Effectiveness analysis of a novel rectangular tunnel boring machine with planetary transmission for box jacking

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Effectiveness analysis of a novel rectangular tunnel boring machine with planetary transmission for box jacking

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Traditional rectangular tunnel boring machines have low tunneling efficiency, poor soil mixing effects, which has hindered the construction of long-distance and large-section box jacking projects. To overcome these limitations, a new type of full-face excavation boring machine was developed based on a planetary transmission mechanism. This machine achieves full-face excavation by utilizing three eccentric cutter heads that revolve around both the central axis of the cutter plate and their individual shafts. The design methodology, feasibility, and principles of this new mechanism were introduced. Furthermore, a successful construction project of an underground highway passage in Japan was presented as a case study to demonstrate the design and application of this tunnel boring machine. The case details include the excavation face support mechanism, optimal cutter-head layout, obstacle removal strategies, and methods for reducing jacking resistance. Monitoring data from the project verified the applicability, reliability, and overall engineering performance of the rectangular shield machine developed using the planetary mechanism. This research demonstrates that the planetary transmission mechanism-based boring machine offers superior performance in terms of ground settlement and tunneling speed, potentially providing a comprehensive solution to the challenges in the development of rectangular shield machines for box jacking projects.

Keywords Box jacking, Full-face excavation, Planetary transmission mechanism, Excavation face stability, Rectangular TBM

The most commonly used methods for underground excavation include open face and hand mining methods, drilling and blasting, cantilever tunnel boring machines (TBMs), and full-face TBMs. The hand mining method is primarily suitable for stable formations but is challenging to apply in urban tunnel projects due to the ground movements and difficult working environment. While drilling and blasting method is mainly used for rock formations and is also difficult to adapt to urban environments due to vibration and noise issues[1]. Additionally, compared to cantilever TBMs, full-face TBMs have become the preferred method for tunnel excavation because of their high advance rate and safety[2]. However, several challenges remain when using conventional full-face TBMs for non-circular cross-sectional excavation in urban geological conditions, such as achieving a higher section excavation ratio, improving excavation and spoil removal efficiency, and enhancing the stability of the overall excavation face.

Rectangular cross-sections offer higher space utilization compared to conventional circular shield methods. However, the development of high-efficiency excavation machinery for rectangular excavation has lagged behind that for circular tunnels. With the emergence of new application scenarios for rectangular underground spaces, such as utility tunnels, underground parking lots, and underground logistics channels[3,4], it is necessary to review the current state of rectangular tunnel boring machines (RTBMs) and develop more efficient equipment for rectangular excavation.

The origin of the rectangular shield machine can be traced back to the Double-O-Tube (DOT) shield[5], which was used to construct subway stations by replacing the parallel twin tunnel or open-cut methods to reduce soil excavation. However, the complex changes in the shield's sectional profile can cause serious friction resistance during advancement, leading to the development of the quasi-rectangular TBM to minimize these

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impacts[6]. Since then, various RTBMs have been developed to further improve the excavation efficiency and ratios, including multi-circle types, eccentric multi-shaft types, eccentric double-shaft types, and cylinder types. However, these boring mechanisms still face challenges in achieving full-face excavation for rectangular cross-sections due to various constraints[7,8]. In addition, the behavior of the rectangular boring mechanism also affects the ground response after excavation. For example, in box jacking, if the RTBM's boring mechanism causes significant disturbance to the surrounding strata during excavation, the arching effect of the overburden may be compromised, leading to substantial ground surface subsidence[9,10]. Furthermore, frictional resistance from pipe-soil interaction tends to be more pronounced than in circular conditions due to ground disturbance and movement, especially under complex geological conditions[11].

Several countermeasures have been proposed to alleviate these problems in box jacking construction, focusing on improving the performance of tunnel boring machines (TBMs) and implementing auxiliary measures[12]. In terms of auxiliary measures, the pipe roof method, for instance, constructs a retaining wall or stress insulation structure above the main tunnel by combining pre-excavations with micro crosssection.[13–15]. However, controlling the deformation of pre-excavated sections during main tunnel jacking remains a challenge. Soil improvement is another approach to reducing disturbance from RTBMs, but its effectiveness is highly dependent on grouting techniques. Additionally, these auxiliary engineering measures can complicate and increase the cost of construction. Therefore, optimizing the performance of RTBMs by improving the boring mechanism is a more fundamental approach to minimizing the environmental impact during excavation.

Developing a new rectangular shield with an advanced boring mechanism to minimize soil disturbance and enhance boring efficiency is critical for successful box jacking. Key parameters, such as face pressure, tail void size, and soil fluidity in the cabin, controlled by RTBMs, need to be reevaluated[16–18]. In this context, the key issues and design limitations of conventional RTBMs are reviewed. Furthermore, a full-face excavation cutter-head developed based on a planetary transmission mechanism is introduced, which demonstrates improved performance in excavation efficiency, mixing efficiency, and adaptability to complex conditions. This design effectively prevents excessive soil movement at the face and minimizes ground disturbance within the soil's elastic limits. Finally, a case study is presented to verify the effectiveness of this new RTBM, particularly regarding its impact on ground stability.

Key technique issues at the excavation face

Maintaining excavation face stability is paramount for all types of RTBMs during underground excavation. Studies have shown that the mechanical performance of RTBMs significantly impacts face stability[6]. Since the 1980s, RTBMs have been designed with various factors in mind, including soil strength, overburden conditions, soil particle size distribution, and groundwater conditions. However, the engineering performance of these RTBMs often varies across projects with similar geological conditions, even when using the same boring mechanism and construction scheme. Initially, this variability in outcomes was attributed to site-specific geological conditions, such as soil mass quality, groundwater conditions, and ground improvements. However, attributing performance issues solely to site geology overlooks potential shortcomings in equipment design and operation. This oversight hinders progress in addressing technical challenges and limits the effectiveness of RTBMs. Actually, the potential incompatibility between the excavation face-forming mechanism on the ground side and the fixed functions on the TBM side is the main reason for these issues. In many cases, the expected performance of the machine is not fully realized, and the stability of the rectangular excavation face is compromised by limitations within the mechanical design of conventional boring mechanisms[19]. Therefore, it is necessary to re-evaluate the actual state of the excavation face and the functionalities of RTBMs before proceeding with any redesign.

Ground looseness

The actual state of the excavation face can be readily assessed in open-shield methods through observations of collapse and ground movement. However, in closed-type box jacking with continuous excavation, directly observing the excavation face is impossible. In this context, achieving and maintaining stability becomes crucial, regardless of soil properties. Once looseness or collapse occurs at the excavation face, it becomes difficult for RTBMs to mechanically prevent soil particle fluidization, especially when the ground has limited self-supporting ability. Therefore, when dealing with soils that have limited self-supporting capabilities, implementing countermeasures to prevent ground looseness at the rectangular excavation face is essential for ensuring stability[16,20]. Table 1 presents the fluidization indicators for sandy soil formations used in Japan [21].

Contradictions of the excavation process

Box jacking is a dynamic process characterized by fluctuations in pressure at the excavation face. The continuous operation of the boring system within the closed cabin—including soil cutting, spoil handling, and muck removal—inevitably disrupts the soil mass at the face. Furthermore, during excavation pauses, a mud film forms at the excavation face, giving the illusion of high water-cutting performance and ground support-ability. However, this film is immediately destroyed by the cutter head when excavation resumes rotation. This cycle

Information origination	Content of Indicators
Japan National Railway Bridge Design Office (1977)	Uniform grain size sand & fine grain content ratio ≤ 10%; Uc ≤ 5, Saturated sand.
Japan Society of Civil Engineers (1977)	Fine-grain content ratio ≤ 10%, Uc ≤ 5.

Table 1. The fluidization indicators for sandy soil ground for pipe jacking.

of mud film formation and destruction within the closed cabin underscores the need to effectively utilize both the fixed bulkhead and the flexible cutter heads to achieve a stable soil-retaining effect. Therefore, the design of RTBMs must address these inherent contradictions in the excavation process.

The primary factor affecting soil-retaining effect is the RTBM's ability to regulate support pressure at the excavation face[22]. Theoretically, the support pressure applied by RTBMs must account for the active earth pressure, groundwater pressure, and the preliminary pressure[23,] all of which directly relate to ground deformation during excavation[24]. If support pressure exceeds the ground's bearing capacity, the jacking force required to propel the machine forward increases significantly. This can overload the RTBM's drive unit and reduce the lifespan of the cutter bits. Additionally, excessive pressure can consolidate the soil within the cabin, decreasing its fluidity and potentially causing blockages in the spoil removal system. In sandy soil condition, excessive pressure may also lead to the uncontrolled soil ejection (spouting) due to partial liquefaction. When soil compressibility reaches 2–4%, the soil in front of the excavation face shifts into a passive earth pressure state, causing serious deformation of the surrounding soil and reducing the RTBM's flexibility.

In practice, RTBM performance should aim to suppress ground deformation and maintain it within the elastic range, allowing the soil to recover its original state once pressure is released. Therefore, relying solely on Rankine's passive earth pressure calculations for determining face pressure in box jacking may have significant drawbacks. Allowing a controlled degree of excavation face deformation can be beneficial for RTBM advancement.

Soil loss around the excavation face

The excavating process disturbs the surrounding soil, leading to its loosening. Existing boring mechanisms mainly use rotating cutter bits to cut the rectangular section. As the soil loosens, the surrounding soil collapses and enters the excavation face, increasing the soil loss rate[20]. Thus, conventional cutting systems struggle to prevent soil loss from the surrounding ground. To address this challenge, four critical areas are proposed for technical improvements that should be prioritized when developing new RTBMs:

1) Shortening mud film formation time at the excavation face
2) Passing through the excavation zone while the ground remains in the elastic state (see the diagram of modified Fenner-Pacher curve in Fig. 1) [25];
3) Reducing the time for mixing and compressing spoil by well-designed cutter-head
4) Identifying a proper cutter bit penetration depth and peripheral speed to promote sediment fluidization

Peripheral speed of the cutter-head

The peripheral speed of the cutter head is a critical factor for spoil processing within the excavation chamber of an RTBM. However, the widely used circular cutter head has limitations in its ability to effectively mix and agitate the spoil as its diameter increases. While a higher peripheral speed on the outer edges of the rotating cutter head can improve cutting rates and mixing forces in peripheral areas, the rotational velocity decreases significantly towards the center, as shown in Fig. 2. This results in a limited mixing zone in the central region referred to as the "blind area".

To achieve adequate mixing and stirring within a short excavation cycle, researchers have focused on optimizing the relationship between torque and the peripheral speed of the outermost portion of the cutter head [26]. However, increasing the rotation speed also presents drawbacks. The inertia of the cutters and the excavated soil they carry increases, leading to greater stress on the surrounding soil. The high-speed rotation of the cutter bits on the outer edges creates a zone of significant disturbance on the far side of the excavation face, as illustrated in Fig. 3. Therefore, it becomes necessary to explore new solutions to address these shortcomings and enhance the performance of cutter heads for box jacking applications.

Brief review of rectangular boring mechanisms

Classification of the rectangular boring mechanisms

The ultimate purpose of the boring mechanism design for RTBMs is to reduce the unexcavated area as much as possible, thereby minimizing resistance from the excavation face. To achieve this, various boring mechanisms have been developed to enhance the adaptability and performance of RTBMs. In light of these efforts, this paper now reviews existing RTBMs with different boring mechanisms (see Fig. 4). These RTBMs could be categorized into 8 specific types: (1) Drum (paddle) rotating type; (2) Wagging excavation type (including arm retractable type); (3) Eccentric rotating type; (4) Planetary cutter type; (5) Boom cutter type (optional excavating); (6) Eccentric rotating shaft type; (7) multi-axis rotation type (multi circular cutter-heads arrangement); and (8) Combined excavation type.

A common feature of these mechanisms is the application of high pressure to induce cracks or collapses in unexcavated areas. However, this approach proves ineffective in exceptionally stable ground conditions. Another prevalent issue is the inconsistency in cutting performance between different cutter heads, which can lead to machine imbalances. Such imbalance may result in excessive torque being applied to the motors (over-torque) and reduced excavation speed. Therefore, next-generation RTBMs must focus on improving the ability of cutter heads to cope with unexcavated areas. Additionally, based on existing equipment experience, employing multiple drive devices is crucial for maintaining consistent excavation capability across the entire cross-section, thereby promoting a balanced machine operation.

Development perspectives

The preceding discussion on the technical challenges of RTBMs aims to illuminate the path forward for equipment upgrades. However, manufacturing these machines requires more than just technical considerations;

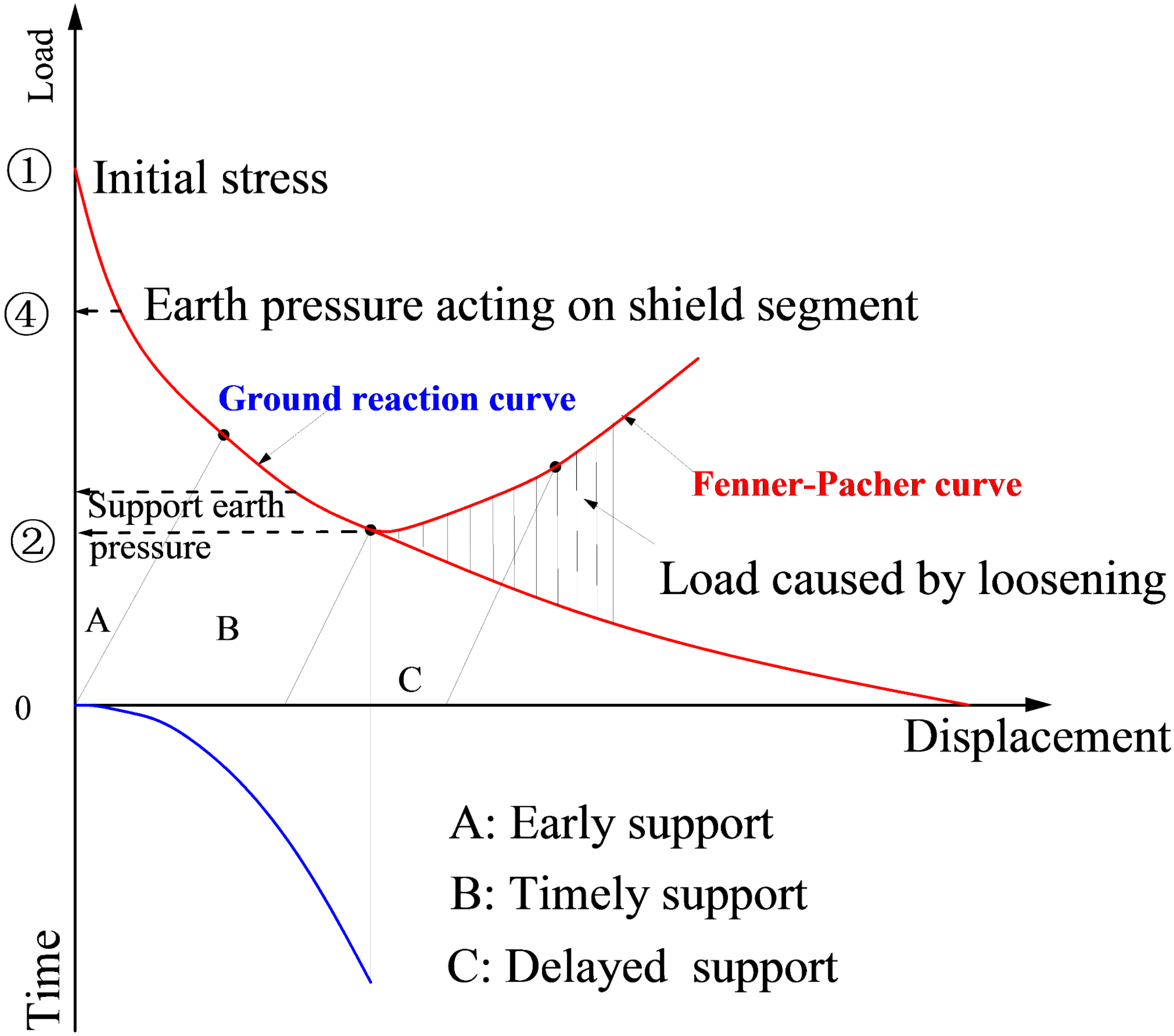

Fig. 1. Diagram of the relationship of the ground reaction curve (GRC) and support reaction curve (SRC) relationship.

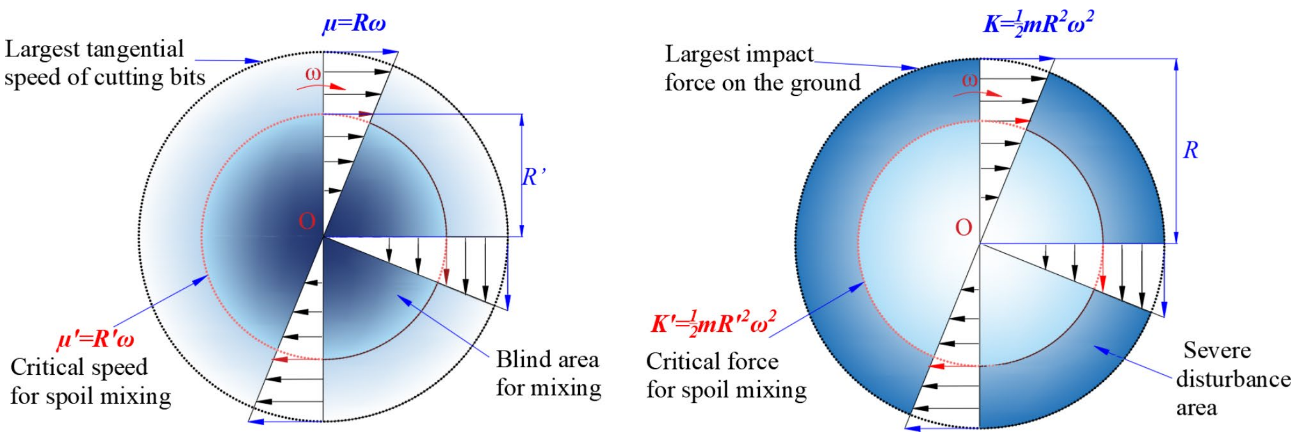

Fig. 2. The schematic diagram of cutting speed differences of circular cutter-head.

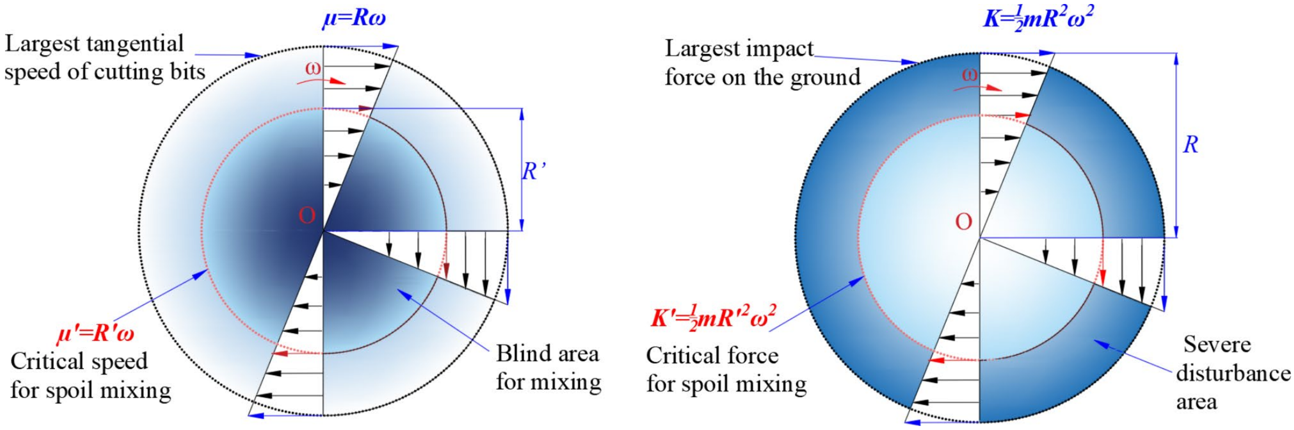

Fig. 3. The schematic diagram of the dynamic cutting impact of circular cutter-head.

it must also adapt to the evolving construction market. Recognizing this dual necessity, this paper addresses both technological and market aspects by proposing six key principles for the development of RTBMs:

1) Relative Superiority: New RTBMs should surpass existing construction methods in terms of cost-effectiveness, speed, environmental impact, and overall performance.
2) Compatibility: Ensuring a smooth transition by leveraging existing technologies and designs, this principle minimizes the need for extensive modifications or entirely new infrastructure.
3) Simplicity: Focusing on user-friendly designs that operators can easily understand and maintain, this principle reduces training requirements and the potential for human error.
4) Experimental feasibility: Highlighting the importance of facilitating empirical testing during development, this principle supports rapid evaluation and improvement of new designs through clear and straightforward testing methods.
5) Ease for observation: Emphasizing the value of clear visual monitoring during operation, this principle enables quick adjustments and troubleshooting by allowing operators to readily observe machine performance.
6) Market alignment: Underscoring the importance of aligning RTBM development with current market demands, this principle ensures that new machines address the specific needs identified by construction professionals.: This principle underscores the importance of aligning RTBM development with current market demands and addressing specific needs identified by construction professionals.

Overall, these six principles offer a comprehensive framework for developing next-generation RTBMs that are not only technically advanced but also user-friendly and commercially viable.

New RTBM based on planetary transmission mechanism

Building on the investigation of existing rectangular boring mechanisms, which revealed limitations in addressing unexcavated areas and face stability, this paper introduces a novel RTBM developed in Japan based on a planetary transmission boring mechanism. This innovative design aims to overcome these challenges and enhance performance in box jacking projects.

Features of the planetary transmission mechanism

The planetary transmission boring mechanism offers several advantages for box jacking projects, including full-face excavation capability and applicability in complex geological conditions. This mechanism features three eccentric cutter heads that rotate around both the central axis of the cutter plate and their individual shafts. Each cutter head is designed and operates in the same rotational path, collectively excavating the entire face of the rectangular opening. Dozens of successful applications in Japan have confirmed the effectiveness of this cutting system, as illustrated by representative RTBMs in Fig. 5. Field investigations further demonstrate that this planetary transmission boring mechanism significantly enhances the performance of RTBMs.

The eccentric cutter-head excavation system offers high excavation efficiency and strong adaptability across various geological conditions. Unlike traditional concentric circular cutter heads, the eccentric design allows the cutter bits to move along different paths, which reduces the cutting area for each head. This design decreases the likelihood of blockage or jamming by debris, including larger pebbles, compared to traditional designs. The eccentric heads also do not push obstacles forward into the ground; instead, they guide these obstacles to break against each other and then discharge them effectively. Furthermore, this system exhibits exceptional mixing and stirring efficiency. Triangular plates positioned on the backside of the cutter-head, enhance its stirring capabilities and facilitate the fluidization of spoil within the cabin. Additionally, the hollow-carved design of the cutter-head plate minimizes adhesion phenomena in clay soil, further improving the system's overall performance.

Uneven wear on cutter bits is a common issue due to variations in rotation speed and cutting distance. This design effectively addresses this problem by employing a rotation and revolution method, which equalizes the cutting distance and rotating speed of each cutter bit. As a result, wear becomes more uniform, extending the

Fig. 4. Schematic diagrams of the existing RTBMs.

overall service life of the cutter bits. In terms of full-face excavation, this system minimizes unexcavated areas at the outer corners with the help of the low penetration resistance at the cutting edge's corner points. This design reduces the impact on the surrounding soil and prevents significant collapse at the corners.

Each eccentric cutter head is capable of lateral movement along the outer excavation section during rotation. This lateral movement presses soil particles inwards, preventing them from accumulating on the sides of the outer shell and mechanically reducing the peripheral frictional force. The specially designed cutter bit pedestals

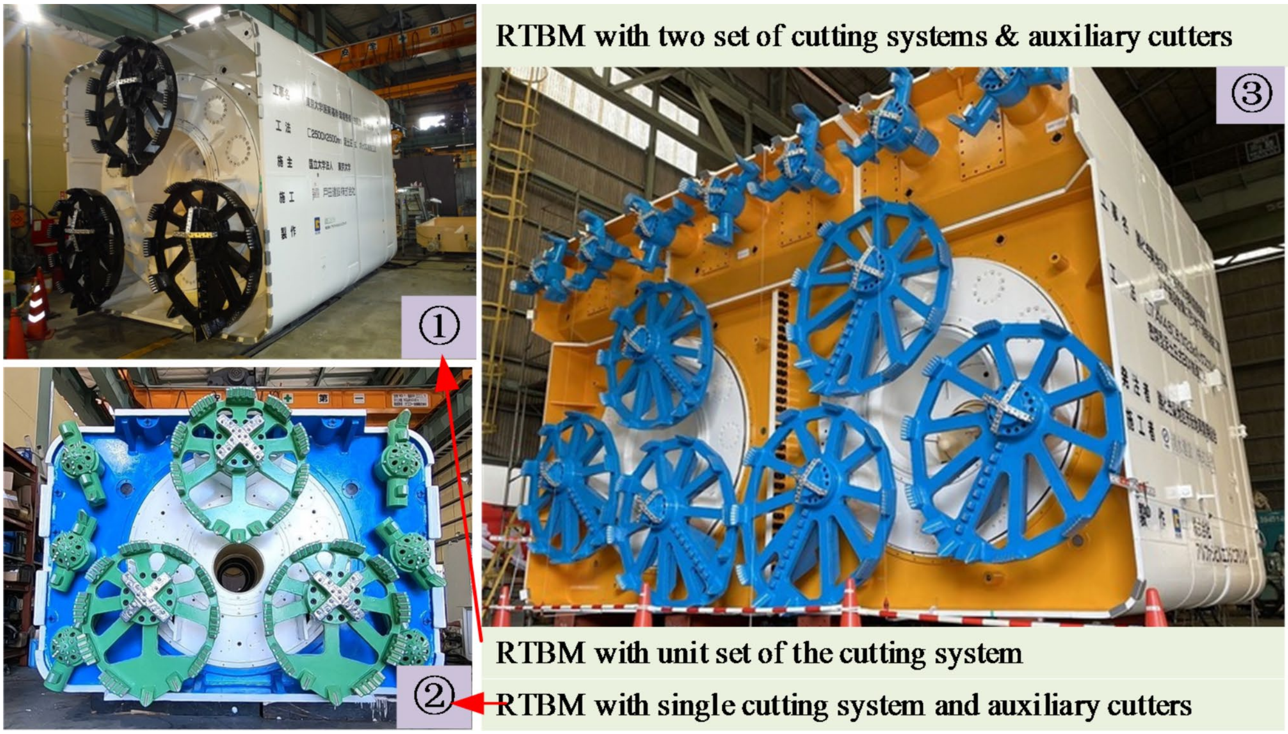

Fig. 5. Schematic diagrams of the planetary transmission mechanism-based RTBM.

on the side surface create an tail void space and a smooth cutting edge, which partially restores the arching effect of the surrounding soil. This design reduces ground resistance and enhances overall efficiency.

Based on the preceding analysis, this RTBM demonstrates greater adaptability to the box jacking method and effectively addresses the limitations of conventional machines, such as challenges with mixed ground conditions and minimizing unexcavated areas. Consequently, it is essential to further promote the adoption of this technology. However, the planetary transmission mechanism is currently limited to excavating only a square section. To achieve large rectangular sections, multiple sets of these excavating units is needed to be combined. Section 5 presents a design example of a large-section RTBM based on this boring mechanism to show the combination method.

Design method

The planetary transmission boring mechanism is depicted in Fig. 6. The motor is mounted on the shield and and transmits power through a rigid connection to the sun gear (drive wheel). A central shaft, fixed to the shield, forms a central bearing for the planetary carrier (planetary frame). The rear end of the planetary carrier is equipped with a gear ring, which forms a gear pair with the drive wheel. The planetary shaft is attached to both the planetary gear and the cutter head. The planetary gear meshes with a large gear ring that is mounted directly on the shield. During operation, as the motor drives the sun gear, the planetary carrier rotates due to the interaction of the meshing ring gears. Simultaneously, the eccentric connection between the carrier and the planetary shaft causes the entire shaft to revolve around the machine's central shaft. Additionally, the planetary gear's meshing with the large gear ring on the shield forces the cutter head to rotate on its own axis. The relationship is illustrated in Fig. 7.

For the purpose of analysis, we assume that the rolling contact point (*Pi*) between the cutter-head and the edge of the rectangular cross-section must traverse all sides of the cross-section by the principle of contour tangency. Additionally, we assume that for each traversal of a side, *Pi* completes one full revolution counterclockwise around the cutter-head contour. Based on the geometric relationships:

$$|OP_i| = r + R \tag{1}$$

$$|OP_i|\, cos\alpha\ = l \tag{2}$$

thus,

$$r = \frac{l}{cos\alpha} - R,\ \alpha\ \in\ (-\frac{\pi}{4}, \frac{\pi}{4}) \tag{3}$$

where R is the radius of the planetary frame (the distance of $|OO_0|$), l is the length of the half side of the rectangular cross-section, α is the rotation angle of the cutter-head around the central axis, β is the rotation

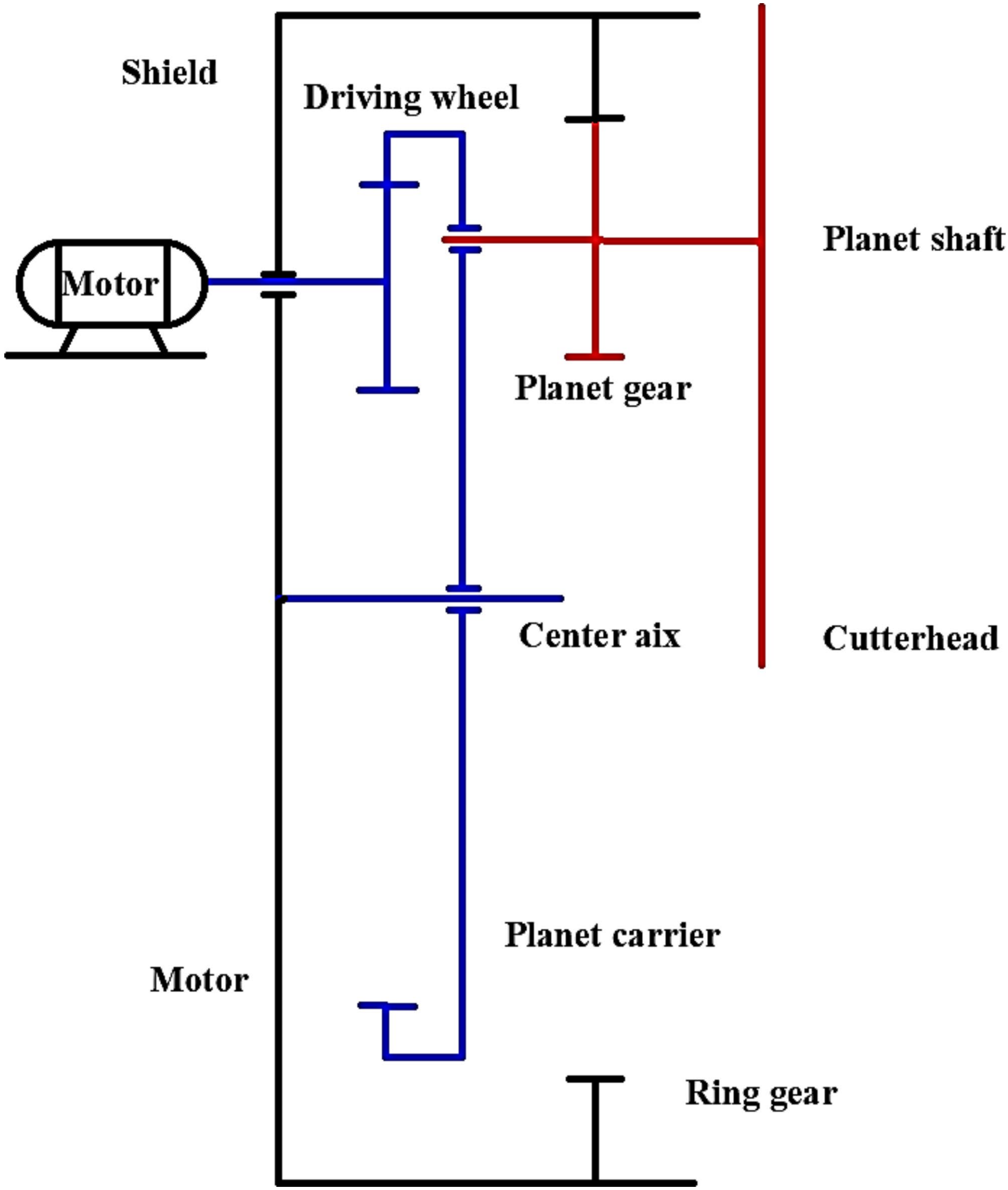

Fig. 6. The framework of the planetary transmission boring mechanism.

angle of the cutter-head around its axis θ is the expansion angle of the cutter-head, and r is the radius of the cutter-head.

The equation for the cutter-head contour in the fixed coordinate system $O_0x_0y_0$ can be derived:

$$x_0{}^2 + y_0{}^2 = \left(\frac{l}{cos\left(\frac{\theta}{4}\right)} - R\right)^2, \ \theta \in \ (-\pi, \pi) \tag{4}$$

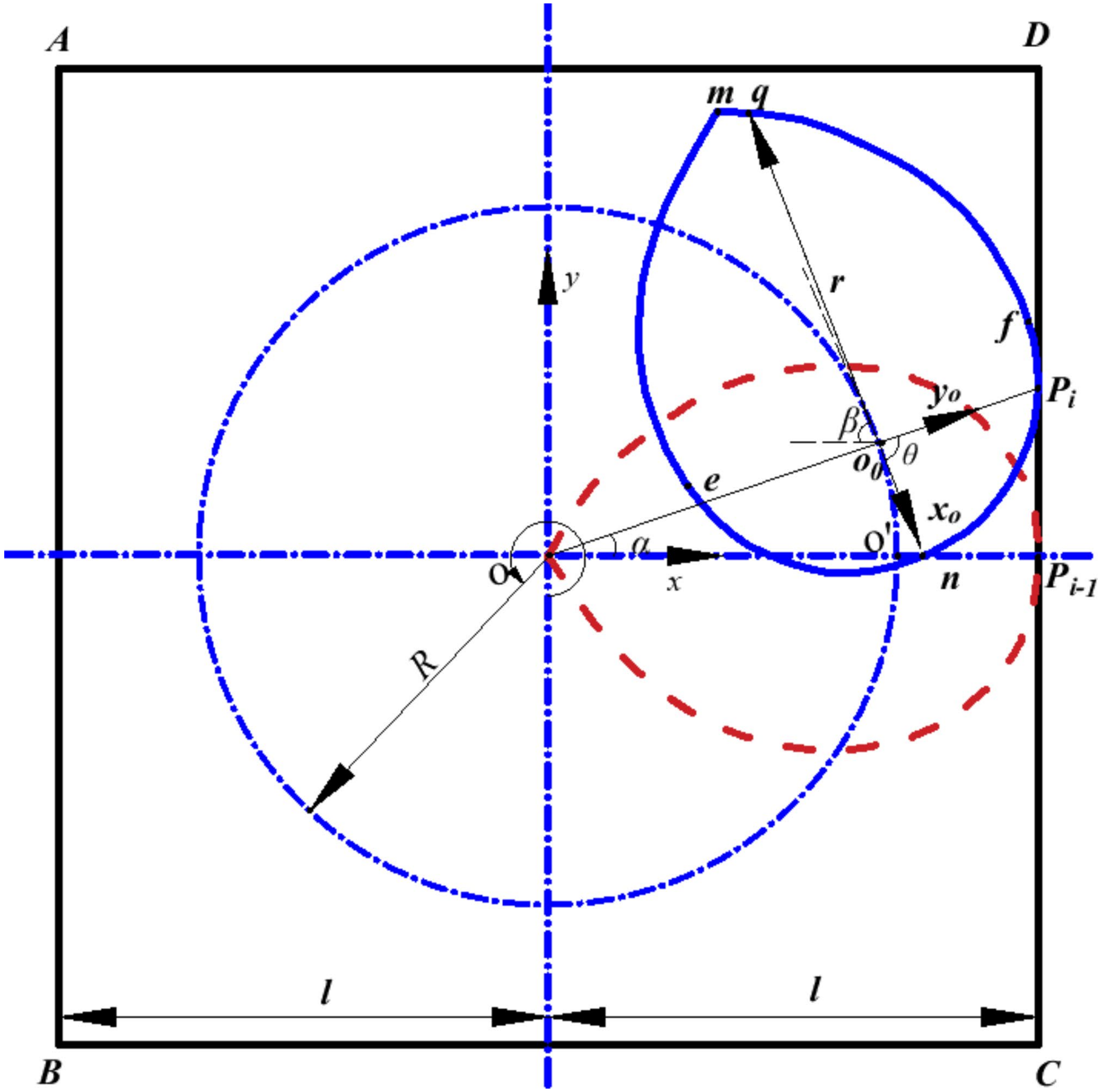

Fig. 7. The geometric relationship of the planetary transmission boring mechanism.

Given that q is any point on the cutter head contour, its position in the absolute coordinate system OXY can be expressed as follows:

$OC = OO_0 + O_0C$ (5)

$$O_0C = \left(rcos\left(\beta - \theta\right), -rsin\left(\beta - \theta\right)\right) \tag{6}$$

considering the difference in rotation speed:

$\beta = 3\alpha$ (7)

$$OO_0 = \left(Rcos\alpha, Rsin\alpha\right) \tag{8}$$

thus, the cutter-head cutting trajectory can be calculated as:

$$\begin{cases} x = Rcos\alpha + rcos(3\alpha - \theta) \\ y = Rsin\alpha - rsin(3\alpha - \theta) \\ r = \frac{l}{cos(\frac{\theta}{4})} - R - \omega \\ \theta \in (-\pi, \pi) \\ \alpha \in (0, 2\pi) \end{cases} \quad (9)$$

where ω is an optimization factor that is a function of θ, and can be approximately $0.11L$. Based on the above analysis, the relationship between l and R has a significant impact on the cutting trajectory of the cutter-head. Based on Eq. (9), the full-face excavation can be achieved when the value of R is equal to $\frac{\sqrt{2}}{2}l$. The trajectory of the three feature points of the cutter-head can be visualized in Fig. 8.

The analysis of the transmission ratio of the planetary transmission mechanism reveals that the cutter-head completes one full rotation for every 120° of revolution around the central axis. Similarly, the central axis completes four revolutions for every rotation of the cutter-head around its own axis. Based on this relationship, three cutter-heads can be evenly spaced at 120° intervals to complete the excavation of the entire cross-section through their combined cutting motion. A comparison between three or four cutter-heads configurations indicates that the three cutter-head layout is more effective for several reasons. First, with three cutter-heads, there is more space for movement of excavated material (soil and rock fragments) within the excavation chamber. Secondly, the symmetrical phasing of the cutter-heads is crucial. In a four-head configuration, when a cutter bit at the far end of each cutter-head reaches a corner of the rectangular section, the far ends of the other three cutter-heads are simultaneously positioned at the remaining three corners. This creates a situation where large rocks (boulders) could become lodged in the central area of the cutting plate due to limited space for movement within the closed chamber. Consequently, the three-cutter-head configuration proves more efficient for both soil mixing and muck transportation.

Application case

Despite the successful application of rectangular shield machines using the planetary transmission mechanism in Japan, there remains a lack of clarity regarding their performance in terms of excavation efficiency, stability, and wear on components under complex conditions. Additionally, the design considerations for this mechanism are not well understood. Therefore, this study aims to analyze the applicability, reliability, and overall engineering performance of this full-face excavation boring mechanism, using a shallow-buried rectangular pipe-jacking

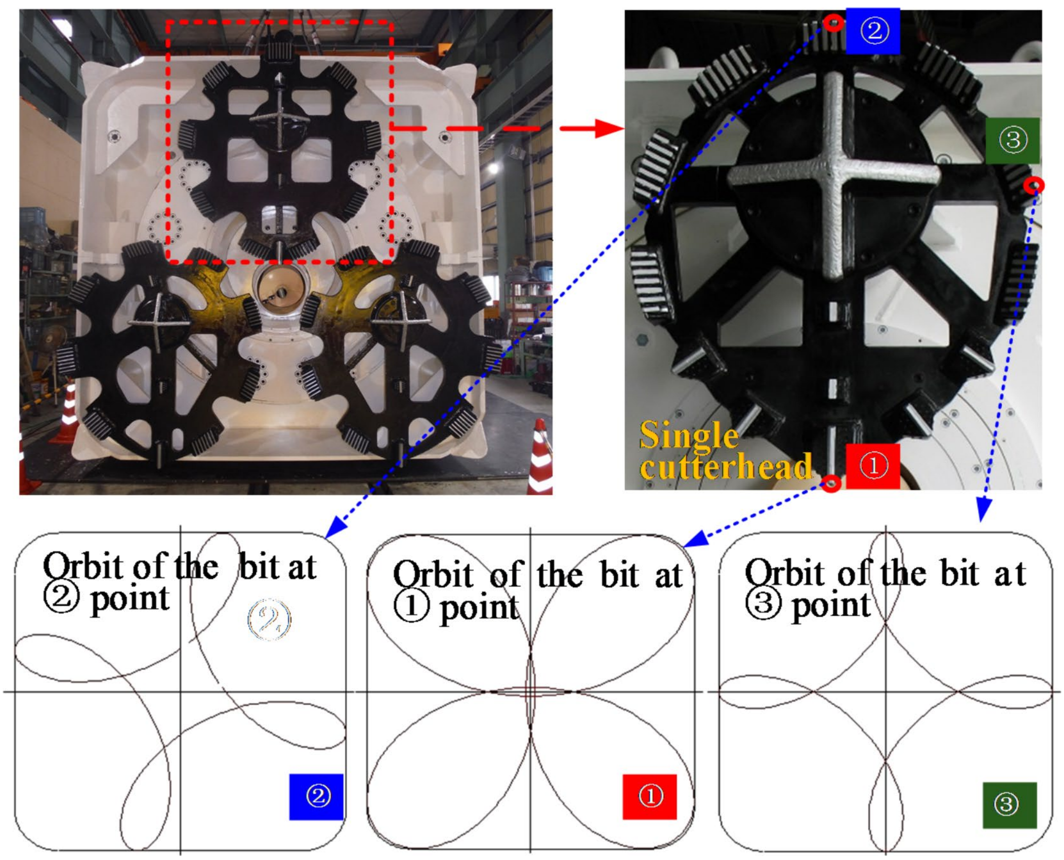

Fig. 8. Diagrams of the cutter bits and their rotating trajectory[27].

tunnel passing through a highway as a case study. The primary technical characteristics of this rectangular shield machine are elaborated below, providing a valuable reference for the further development and application of this type of RTBM in future projects.

Project overview

One of the largest RTBMs using the planetary transmission mechanism was employed for the construction of an underpass beneath National Highway No. 6 in Hitachinaka City, Ibaraki Prefecture. This project represented the largest cross-section box jacking project in Japan, with a dimension of 6.3 m in height and 5 m in width. The shield machine jacked 35 m eastward from underneath National Highway No. 6. The geological conditions encountered during this project are detailed in Fig. 9. The underpass's main body was situated within the embankment layer (Bs layer), which consisted of human-made fill material 9 to 11 m thick, containing scattered pebbles throughout the layer. The average overburden was only 1.6 m, indicating a very shallow burial depth. The tunnel's bottom section consisted of cohesive soil (Ac layer) and saturated organic humus layers (Ap layer). The specific physical properties of the soil are presented in this dissertation [19].

Design of multi-cutter-head excavation system

The design and manufacture of the RTBM must consider the field conditions, particularly the challenges associated with shallow depth and specific soil compositions. Since each excavation unit developed from the planetary transmission mechanism is only suitable for excavating square-shaped cross-sections, multiple units are required to achieve higher coverage of the whole excavation face. Determining the optimal layout of these excavation units involves considerating the cutting ratio, operability, and manufacturing capabilities of the equipment. Typically, unified excavation units are preferred due to their lower manufacturing cost. However, in cases like this project, it is not feasible to excavate the entire face using units with the identical specifications.

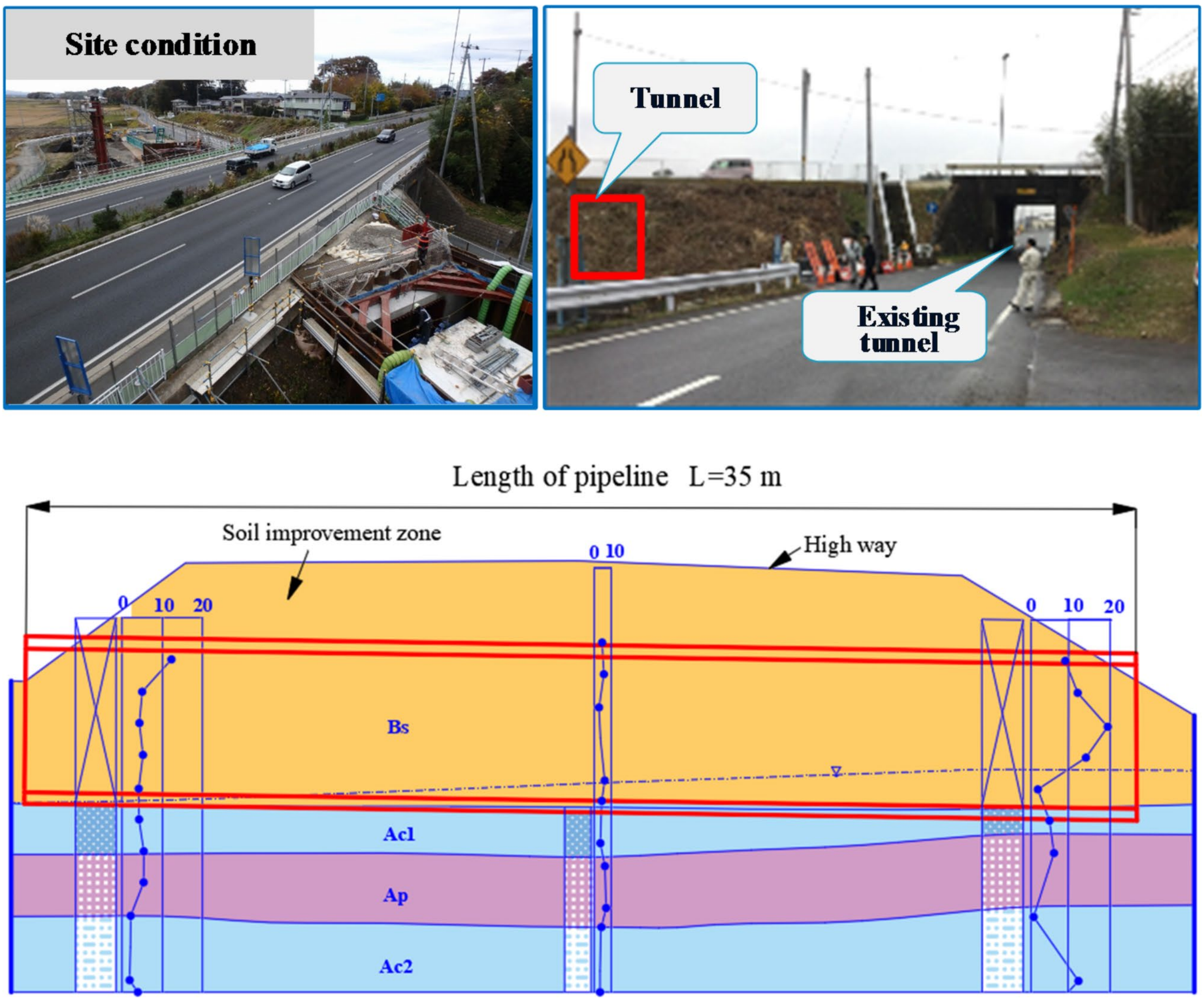

Fig. 9. Geological profile of this tunnel.

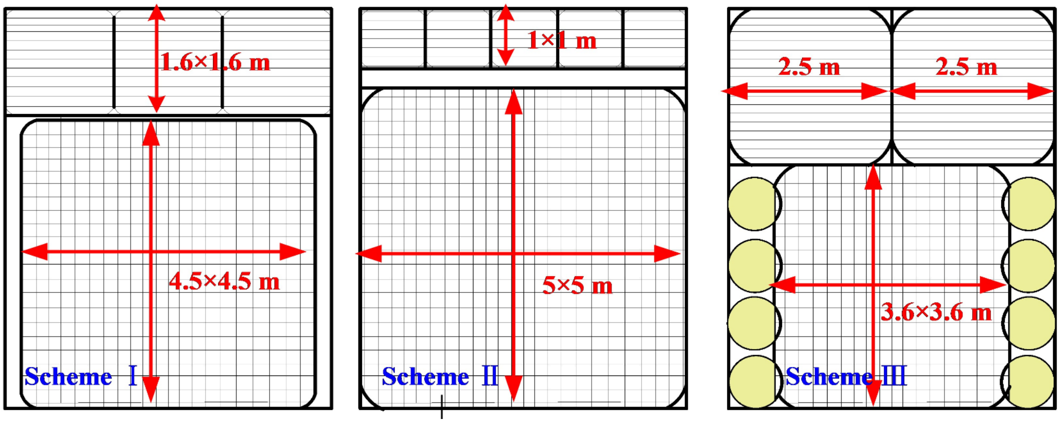

Fig. 10. Combination schemes of excavating systems and layouts.

Fig. 11. Diagrams of the new RTBM developed in this project.

Therefore, based on the principles of minimum unexcavated areas and reducing costs, the following three excavation layout schemes were proposed (see Fig. 10).

Scheme I utilizes a large 4.5×4.5 m excavating unit for the lower face, but completing the upper portion requires three smaller 1.6×1.6 m excavation units. This scheme employs a total of four units and achieves an cutting ratio of 93% (the percentage of the total excavation face that can be directly cut by the units). Scheme II uses a larger 5×5 m excavating unit, offering a higher excavation ratio of 95%. However, it necessitates the installation of five additional smaller 1×1 units for the upper part, bringing the total to six units. Scheme III combines a mid-sized 3.6×3.6 m excavating unit with two 2.5×2.5 units, resulting in an cutting ratio of approximately 87%. While Scheme II's larger size increases the cutting ratio, it presents significant engineering challenges. For units exceeding 5 m in size, a split structure will be necessary, .which can be complex to assemble.

Comparing Schemes I and III, Scheme I offers a higher initial cutting ratio of 93% but requires four units. Scheme III has a more manageable structure with easier manufacturing. To improve its lower initial excavation ratio (87%) necessitates the use of eight additional auxiliary cutting units (side cutters) to boost the overall excavation ratio to 94%. Given the trade-off between excavation efficiency, manufacturing complexity, and the cost of additional units, Scheme III was ultimately adopted. The machine developed based on Scheme III is illustrated in Fig. 11.

The key components of this machine and the construction process are illustrated in Fig. 12. A significant innovation in this machine is found in the design of the upper and lower excavating units. These units are equipped with features specifically engineered to address challenges posed by obstacles within the excavation face, including bypass channels to divert debris to prevent blockages and disruptions, which could otherwise stall the tunneling process. This design is particularly advantageous for the shield jacking method, ensuring smoother and more efficient excavation of large rectangular sections.

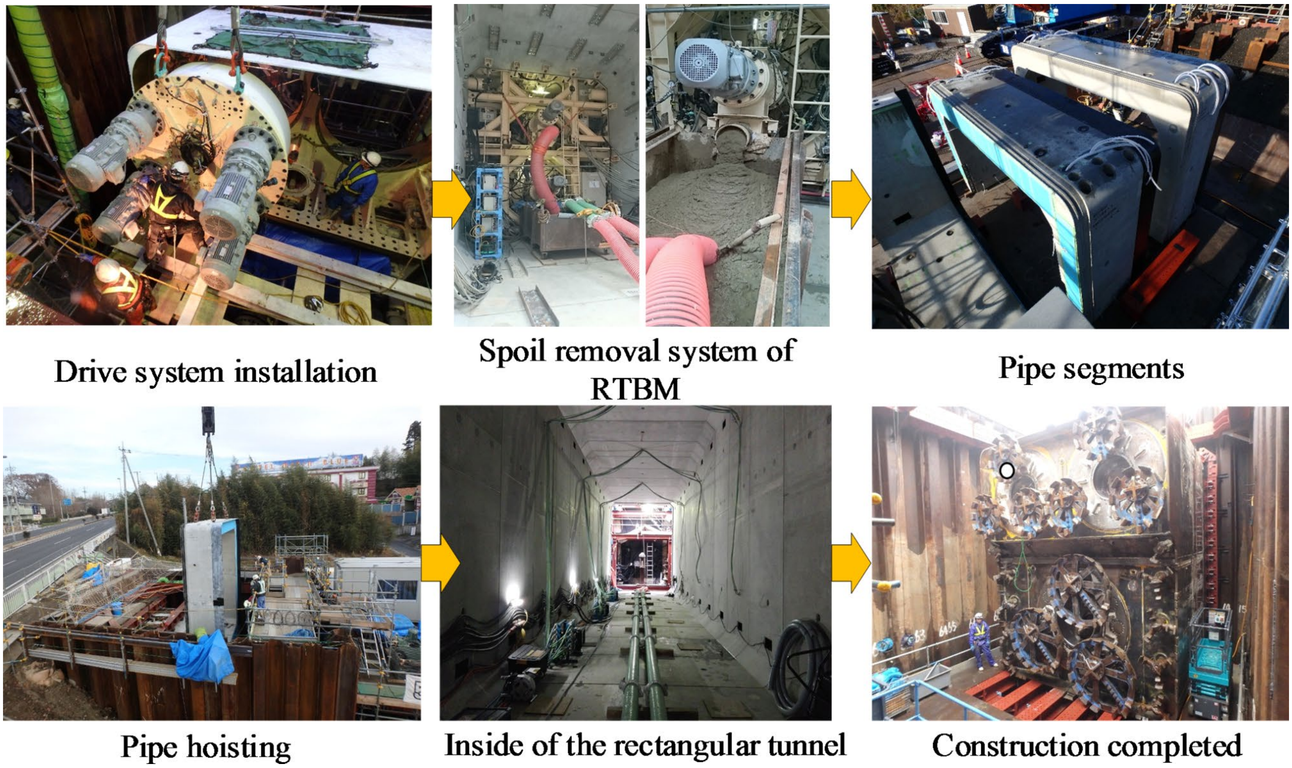

Fig. 12. Key components of the RTBM and the construction process.

Countermeasures for highway settlement

Ground deformation is a significant concern for this project, particularly due to the shallow depth beneath the highway. In such cases, auxiliary construction methods, such as temporary pipe roof structures to support the overlying soil, were typically supposed to mitigate these effects. However, the presence of a Nippon Telegraph & Telephone pipeline buried within the road embankment made it impossible to implement this method. Additionally, considering the heavy traffic on the national highway, the Japan Society of Civil Engineers has established a strict limit of 30 mm for maximum allowable subsidence to ensure smooth traffic flow. As a result, the adaptability and performance of the new RTBM under these challenging conditions became a critical focus during construction.

To monitor settlement during the pipe-jacking process, a comprehensive monitoring scheme was employed for the highway surface, as shown in Fig. 13. This system utilizes a non-prism type of automatic measuring instrument to observe 64 sensitive points on the national road surface, enabling the detection of even minor ground deformations.

The engineering conditions of this project offered an excellent opportunity to evaluate the disturbance control performance of the new RTBM. To minimize ground settlement, it is crucial for the RTBM to effectively manage soil loss during excavation. Typically, the size of the tail void, which directly related with the ground loss ratio, ranges from 25 mm to 50 mm to reduce pipe-soil friction. In this case, a smaller tail void of just 15 mm was selected, leveraging the advantage of the planetary transmission mechanism-based RTBM. This design minimizes soil disturbance and reduces soil loss, making it particularly suitable for the shallow-depth conditions of this project.

To further control highway settlement, auxiliary countermeasures were implemented in conjunction with the new RTBM. In this case, a two-part solidified filler material, specifically designed for its high strength, excellent filling properties, and minimal volume change, was developed to be injected into the tail void to prevent subsequent settlement. To facilitate the grouting process, injection holes were incorporated into the four walls of the RTBM.The components of the injecting materials are shown in Table 2. Considering the high advancement speed of this RTBM, the grouting material needs to possess a short gel time and high strength. Therefore, the type II material was selected as the injection material for this project to minimize ground subsidence.

Effective evaluation

1) Effectiveness in settlement control

The effectiveness of the planetary transmission mechanism-based RTBM was evaluated through on-site monitoring data, specifically targeting ground settlement. A comparative analysis was conducted on highway settlement before, during, and after tunneling. Figure 14 illustrates the vertical displacement of the highway surface as the machine's cutter-head passed beneath the median strip (the center dividing section of the highway),

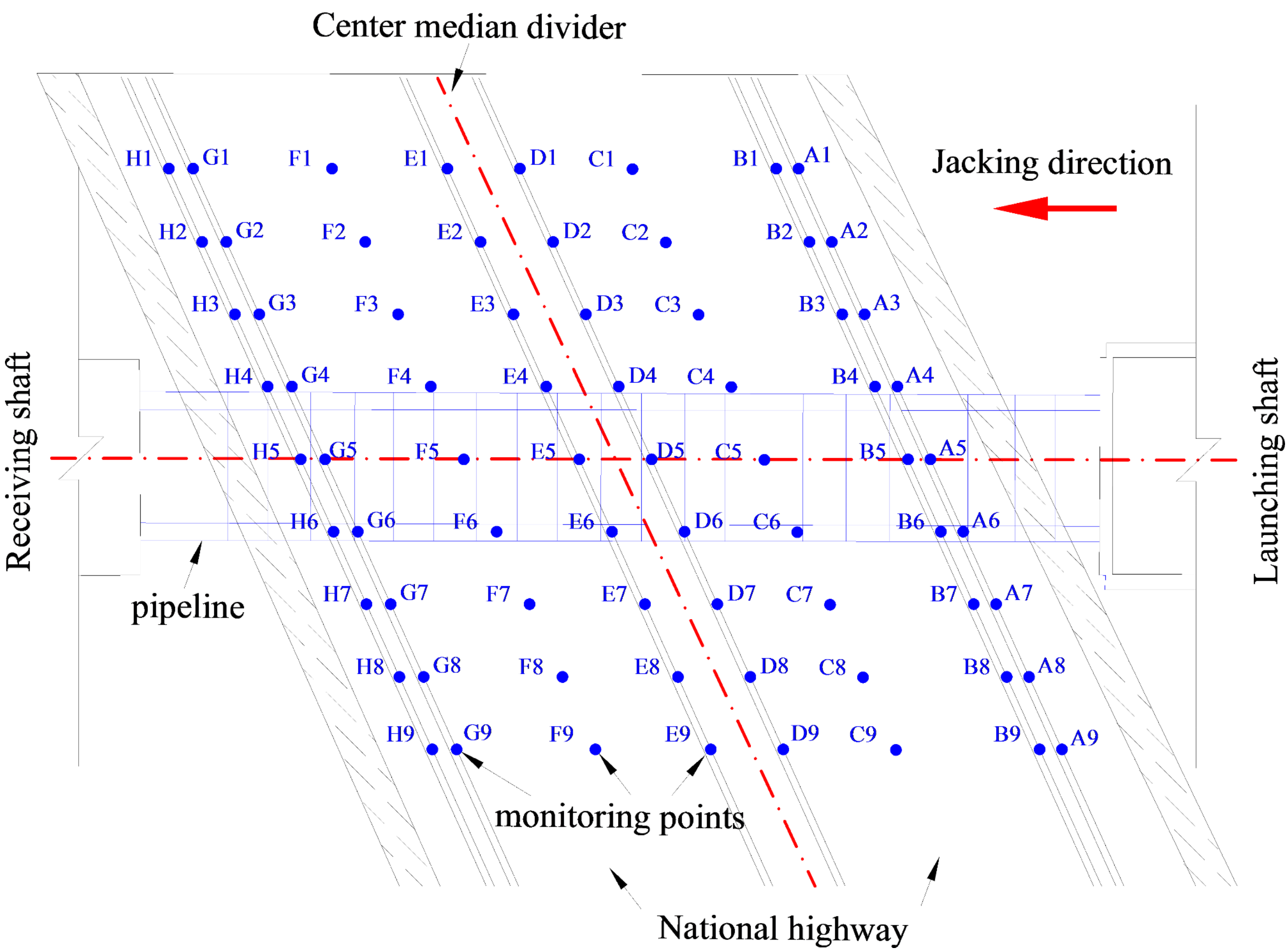

Fig. 13. The diagram of the highway monitoring scheme.

Content	Standard type	High-strength type I	High-strength type II
Liquid A			
Cantor SS-A	36 L	54 L	90 L
Water	164 L	146 L	110 L
Liquid B			
Cantor SS-B	20 kg	20 kg	20 kg
Tackifier	-	-	5 kg
Kasaoka Special Clay	-	-	30 kg
Water	-	-	170 L
Gel time	41.6s	17.2s	16.2s
Qu strength	18kN/m^2	20kN/m^2	50kN/m^2

Table 2. Comparison of ground soil retaining materials with trial test.

located approximately 16 m from the launching shaft. The data indicates that average subsidence behind the excavation face ranged from – 8 mm to -10 mm. Although a small, temporary elevation of the road surface was observed directly in front of the excavation face, this had a minimal impact on traffic flow and overall stability.

After the completion of the jacking construction, settlement trough curves for three key monitoring sections are presented in Fig. 15, while Fig. 16 illustrates the overall settlement distribution across the monitored highway area. As anticipated, the majority of the settlement occurred directly above the tunnel. The maximum recorded settlement was 13.1 mm, observed near the receiving shaft and slightly skewed toward the right side of the tunnel, in the direction of the receiving shaft. This settlement value remains well within the allowable deformation limits established for the project. Regarding horizontal ground disturbance, the data revealed that most of the disturbance was concentrated between monitoring Section 3 to Section 7, corresponding to a lateral disturbance zone of approximately 3 m on either side of the jacked tunnel. The performance of this RTBM is demonstrably

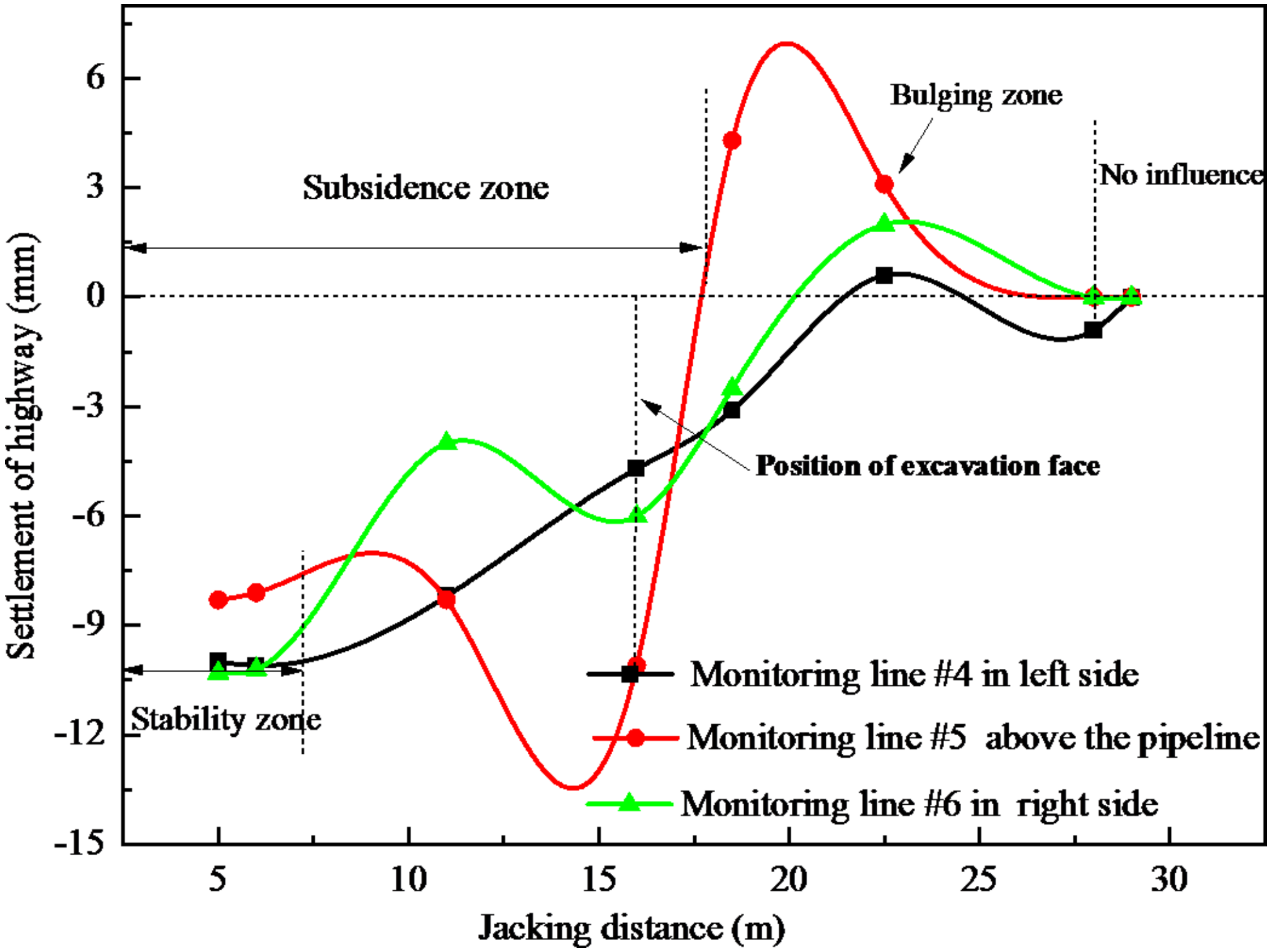

Fig. 14. The vertical displacement of the highway surface along the center line of the jacking pipeline (the excavation face was 16 m from the launching shaft).

superior to conventional RTBMs used under similar shallow burial conditions[28], highlighting the exceptional adaptability of this new RTBM for shallow overburden projects.

2) Effectiveness in excavation speed and resistance reduction

In terms of jacking speed, the new RTBM achieved an average excavation speed of 3 to 8 mm per minute in areas requiring soil improvement, and around 10 mm per minute in normal soil conditions. This project set a record for the fastest jacking speed for a large rectangular section in Japan, reaching 10 mm per minute over 36 days of construction. This performance demonstrates significantly improvement in excavation efficiency provided by the planetary transmission mechanism.

The jacking force fluctuated around 5,000 kN, approximately 54% of the theoretical maximum jacking force predicted prior to reaching the improved zone (as shown in Fig. 17). This indicates that the soil surrounding the tunnel remained stable, minimizing frictional resistance between the soil and tunnel. Consequently, the RTBM proved highly effective in reducing resistance during the jacking process.

3) Effectiveness of attitude control

Maintaining proper alignment is crucial for the successful operation of RTBMs. In this project, real-time monitoring was employed to track the elevation of the machine's bottom plate and detect any deviations from the intended axis. The results are presented in Fig. 18. During the jacking process, the maximum recorded horizontal deviation was 31 mm, while the maximum vertical deviation was 36 mm—both of which are well within the project's specified tolerances. Upon completion of the jacking construction, the final deviations in the horizontal and vertical directions were reduced to 12 mm and − 11 mm, respectively, which are significantly below the maximum permissible limit of 50 mm.

These findings demonstrate that this new RTBM exhibits excellent performance in maintaining proper alignment, even under complex geological conditions. This highlights the machine's capability to navigate challenging environments while preserving the structural integrity of the tunnel.

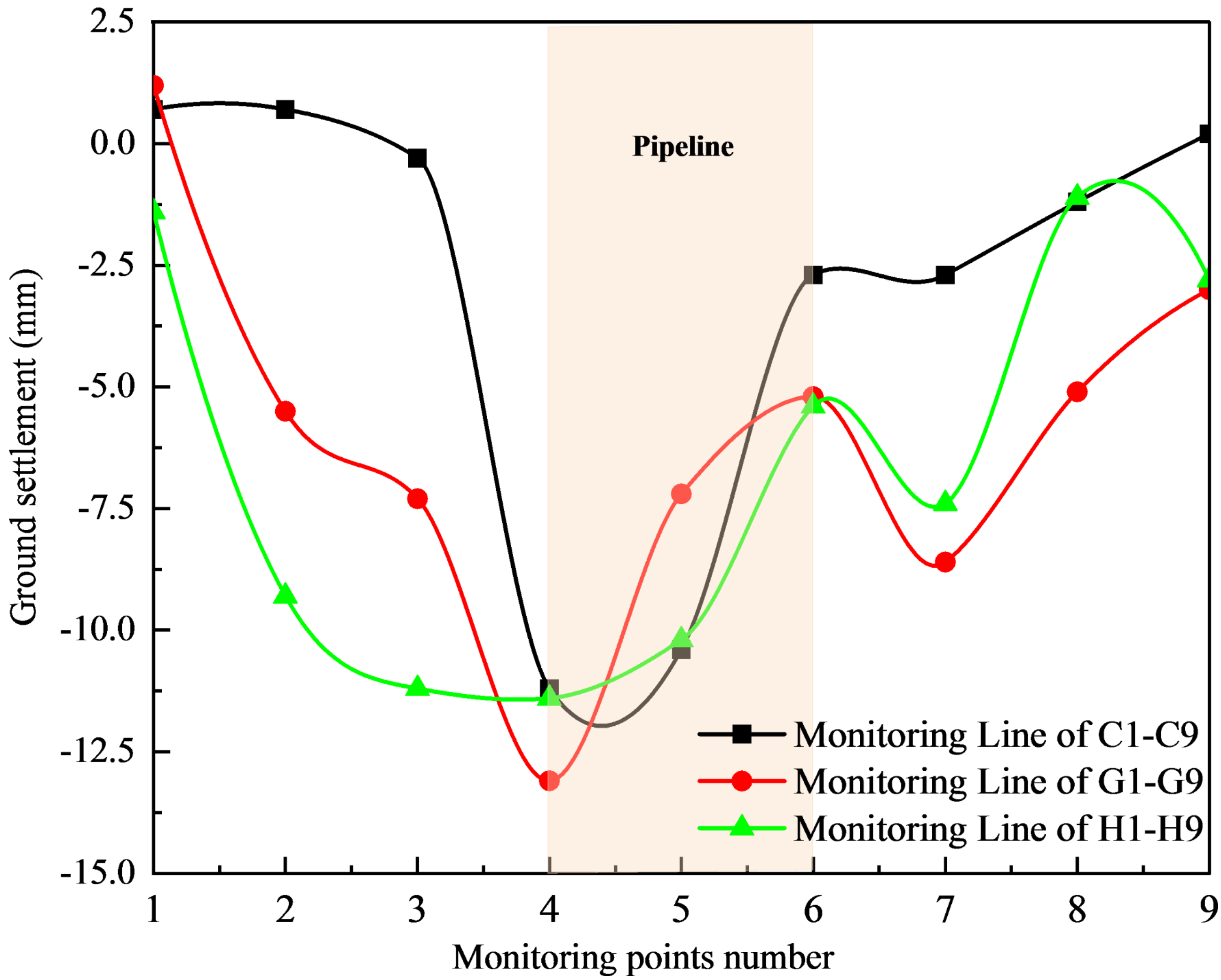

Fig. 15. The vertical displacement of the highway surface along different monitoring sections.

Discussions

The development and deployment of the RTBM based on a planetary transmission mechanism mark a significant advancement in tunneling technology, particularly for box jacking applications. This study aimed to investigate the engineering performance, adaptability, and effectiveness of this novel machine, particularly under challenging conditions such as shallow overburden and complex ground compositions. The results demonstrate notable successes, but they also highlight areas for further refinement and optimization.

1) Performance of the planetary transmission mechanism

The use of planetary transmission mechanisms in RTBMs is expected to solve some technical problems in box jacking construction. The system's ability to facilitate both rotation and revolution of the cutter-heads allowed for more efficient cutting and mixing of materials, reduced unexcavated areas, and improved adaptability to varying geological conditions. Unlike conventional machines, which often struggle with mixed soils or obstructions like pebbles and boulders, the new RTBM's design effectively minimized blockages and improved spoil discharge.

These characteristics make the RTBM a promising option for future projects where mixed or unstable ground conditions are prevalent. However, the use of the planetary transmission mechanism also imposes some limitations, particularly in relation to scalability. As discussed in Sect. 5, achieving large rectangular cross-sections requires the combination of multiple excavation units, which increases both the complexity and cost of machine manufacture. In particular, Scheme II, which proposed the use of a large 5×5 m excavating unit, encountered significant engineering challenges due to the need for split structures. While this layout offered a higher excavation ratio, the complexities in assembly and the potential for increased mechanical wear may limit its practicality in large-scale projects. A balance must be struck between excavation efficiency, machine operability, and cost, which is why Scheme III was ultimately adopted.

2) Settlement control and ground disturbance

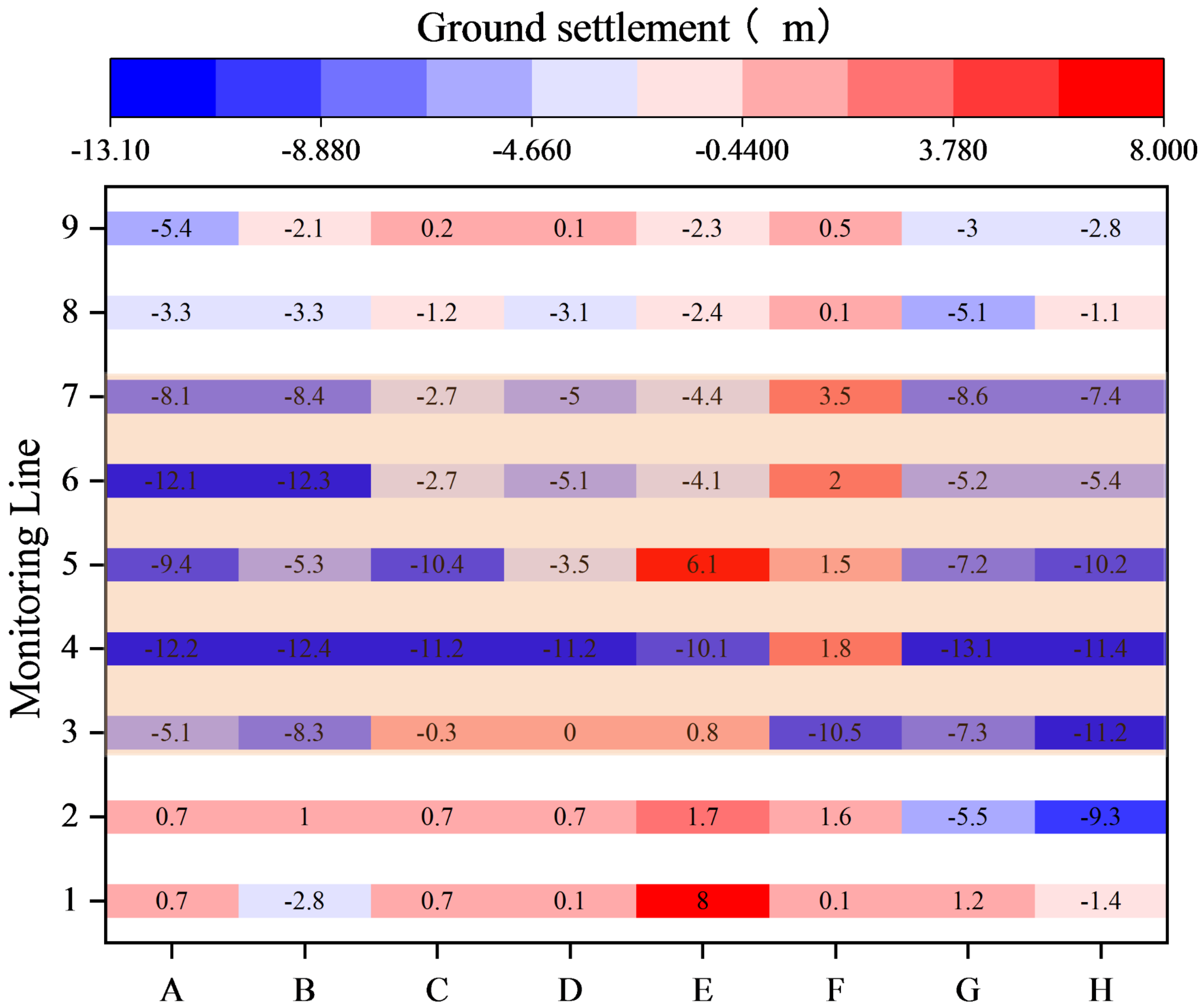

Fig. 16. The settlement distribution of the vertical displacement of the highway surface.

Ground deformation is a critical concern in shallow-buried tunneling projects, particularly under high-traffic areas such as National Highway No. 6. In this case, the RTBM demonstrated excellent performance in minimizing settlement, with maximum recorded subsidence of just 13.1 mm—well below the allowable limit of 30 mm. This success can be attributed to several factors, including the optimized tail void size, the use of high-strength filler material, and the RTBM's ability to minimize soil disturbance through its innovative cutter-head design. However, there are trade-offs associated with these design choices. For example, reducing the tail void size to just 15 mm helped minimize soil loss but increased peripheral resistance. While this trade-off was acceptable in this project, it may not be suitable for deeper or more complex tunneling operations, where greater friction could hinder machine progress and require more frequent maintenance or adjustments.

To further validate the performance of the RTBM in controlling ground settlement and minimizing disturbance, construction records from 22 projects utilizing this type of RTBM across Japan were collected and analyzed. These projects have collectively achieved a total jacking distance of 4.518 km, some of them as detailed in Table 3. In the majority of the projects, settlement was kept within 10 mm, a benchmark that is difficult to achieve with conventional RTBMs. Even in sandy soil conditions, the machine demonstrated the ability to maintain minimal settlement, ensuring that ground traffic was not adversely impacted. This further validates the RTBM's advantages in both settlement and disturbance control. The settlement data from these projects confirm the RTBM's effectiveness in controlling surface settlement under various engineering conditions, particularly excelling in challenging environments such as shallow overburden.

3) Applicability to other projects and geotechnical conditions

While the results from this case study are promising, further investigation is needed to determine the broader applicability of this RTBM technology in different geotechnical environments. The machine's performance under varying ground conditions, such as highly cohesive soils or fractured rock, remains to be thoroughly

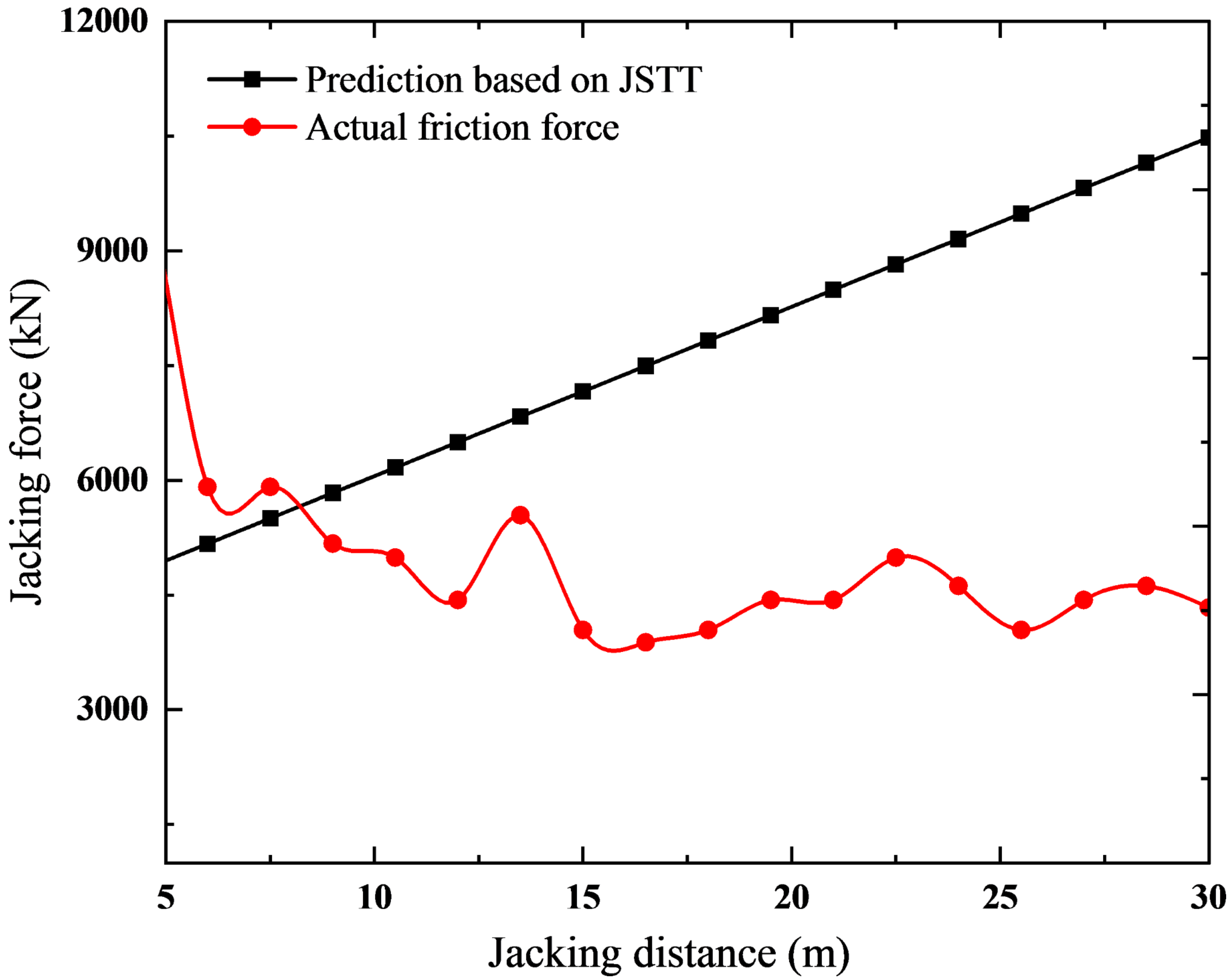

Fig. 17. Jacking force in this project.

tested. Additionally, the long-term durability of the RTBM components, especially the cutter bits and planetary gears, should be evaluated through further operational use in projects of longer duration and greater complexity. Moreover, while the machine was able to handle the specific challenges posed by the shallow-buried conditions in this project, it is essential to explore its performance in scenarios involving deeper tunnels or more uneven load distributions.

4) Future design considerations

The modularity of the RTBM design presents both opportunities and challenges. On one hand, the ability to tailor the number and size of excavation units to specific project requirements provides flexibility. On the other hand, this modularity can lead to operational complexities, particularly in terms of assembly, maintenance, and alignment during operation. For instance, larger units such as those proposed in Scheme II would require split structures, which not only complicate the manufacturing process but also introduce potential weak points in the machine's overall structural integrity.

In future iterations of the RTBM, efforts should focus on simplifying the modular design without sacrificing performance. Advances in material science, particularly in the development of lighter and stronger materials, could allow for larger excavation units without the need for split structures. Additionally, further research into automation and machine learning could enable more precise real-time adjustments during the excavation process, optimizing cutter performance and minimizing the risk of blockages or wear.

5) Implications for the industry

The success of the RTBM in this project demonstrates its potential as a viable alternative to conventional circular boring machines for certain applications, particularly in urban environments with stringent settlement control requirements. The machine's ability to maintain alignment and minimize ground disturbance highlights its suitability for use in shallow-buried projects. As the demand for more efficient and adaptable tunneling

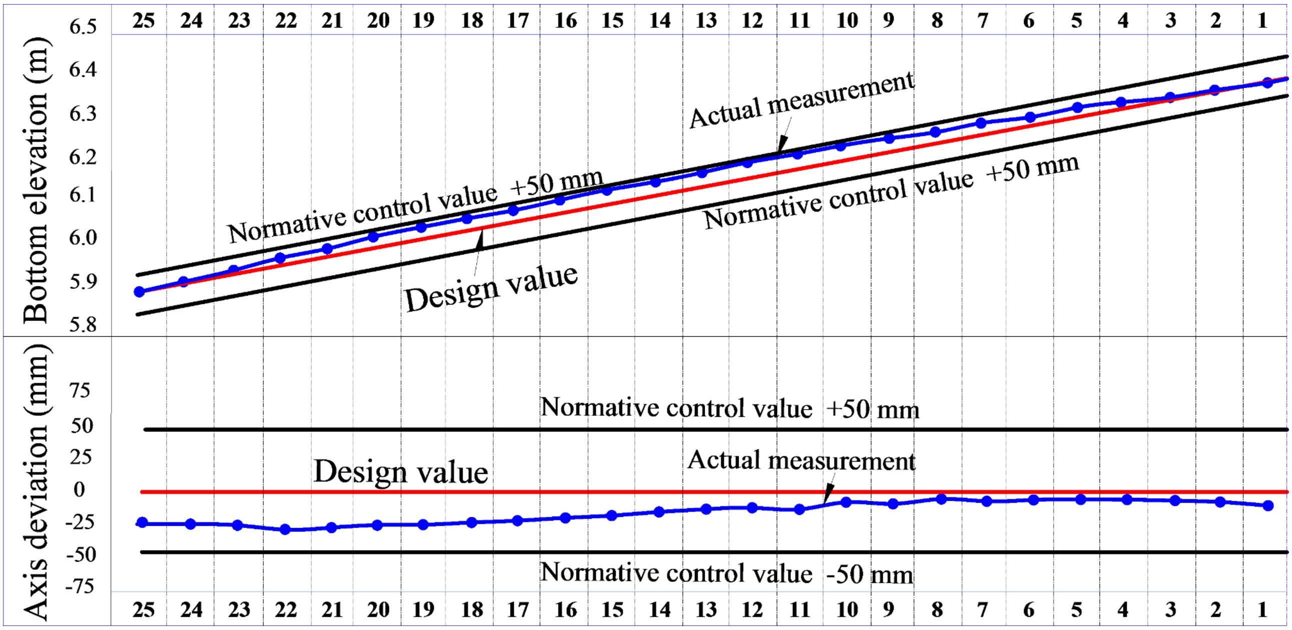

Fig. 18. The deviations in horizontal and vertical directions during the jacking construction.

technologies continues to grow, particularly in urban infrastructure development, the RTBM with a planetary transmission mechanism offers a novel solution. However, its adoption on a broader scale will require further demonstration of its versatility in different soil conditions and project types. Future research should also focus on reducing manufacturing and operational costs to make the technology more accessible for a wider range of applications.

Summary and conclusions

This paper addressed the challenges and limitations of current rectangular tunnel boring machines (RTBMs) used in box jacking projects. A systematic review of existing rectangular boring mechanisms was conducted, and practical considerations for the development of next-generation RTBMs were proposed. The design, implementation, and performance of a novel RTBM equipped with a planetary transmission mechanism were analyzed. Furthermore, a case study evaluated the feasibility of the RTBM in a challenging, shallow-buried project beneath National Highway No. 6 in Hitachinaka City, Japan. Several key takeaways were identified from the study:

1) The mechanical performance of conventional RTBMs significantly impacts the stability of the excavation face. It is crucial to prevent excessive soil movement around the face and minimize ground disturbance during the jacking construction. Additionally, the uneven peripheral speed of conventional circular cutter heads negatively affect both the mixing of excavated spoils and the stability of the surrounding soil.
2) The planetary transmission-based RTBM demonstrated significant improvements in cutting efficiency, soil mixing, and overall excavation performance compared to conventional machines. The ability to control the rotation and revolution of the cutter-heads allowed for more uniform cutting and reduced unexcavated areas, making it highly adaptable to challenging ground conditions.
3) One of the critical challenges in box jacking under shallow highway conditions is controlling ground settlement. The RTBM employed in this study successfully minimized ground deformation, with maximum settlement staying well within the allowable limits. This was achieved through the optimization of the tail void size, the use of high-strength filler materials, and the machine's ability to reduce soil disturbance.
4) The study compared different excavation unit layouts to determine the most efficient and cost-effective configuration. Scheme III, which utilized mid-sized and auxiliary cutting units, proved to be the most practical choice, balancing high excavation coverage with manageable manufacturing and operational complexity.
5) The performance of the RTBM in shallow-buried conditions, coupled with its ability to handle mixed soil compositions, underscores its adaptability. The machine's innovative cutter-head design and ability to manage both small and large obstructions without significant blockages position it as a robust solution for future urban and shallow-overburden projects.

In conclusion, the planetary transmission mechanism-based RTBM offers a promising advancement for box jacking projects, particularly in urban environments with strict settlement requirements. However, further research and development are needed to refine the machine's scalability, cost-effectiveness, and adaptability to a broader range of geotechnical conditions. Future iterations of the machine should focus on simplifying modular designs and incorporating automation to enhance its operational efficiency and reduce manufacturing complexities.

Year	RTBMs	Size/mm	Jacking distance/m	Buried depth ratio/m	Soil condition (*N*-value)	Ground average settlement/mm	Excavation speed/ mm/min
2002		882 × 882	972.4	18.71 m 21.21D	Sand and silty N:0 ~ 18	0.6	20–25
2008		2800 × 2520	36	1.92 m 0.76D	Sandy soil N:0 ~ 8	2	15
2010		3300 × 2500	220.97	0.97 m 0.39D	Sandy soil N:0 ~ 13	16	25
2012		3600 × 3600	57.00	2.68 m 0.74D	Silty soil N: 0 ~ 10	8	15
2013		3000 × 3180	50.08	1.37 m 0.43 D	Clay soil N: 2 ~ 13	3	20
2014		2390 × 3310	29.57	2.78 m 0.84 D	Sand soil N: 1 ~ 7	5	25
2017		3000 × 3000	224.78	2.50 m 0.83 D	Silty sand N: 2 ~ 8	7	30
2017		5000 × 6300	32.00	1.60 m 0.25D	Gravel sand N: 5 ~ 20	13	10
2017		4900 × 6150	40.50	1.78 m 0.29D	Gravel clay N: 10	10	35
2019		4700 × 2200	146.16	1.56 m 0.71 D	Sand soil N: 2	17	16
2021		2360 × 1600	281.14	4.00 m 2.50 D	Clay and gravel N: 3 ~ 68	10	20
2022		7400 × 4600	122.20	7.50 m 1.63 D	Sand clay N: 0 ~ 2	8	15
2021		5300 × 2900	19.00	0.30 m 0.10 D	Gravel sand N: 5 ~ 28	3	35

Continued

Year	RTBMs	Size/mm	Jacking distance/m	Buried depth ratio/m	Soil condition (*N*-value)	Ground average settlement/mm	Excavation speed/ mm/min
2023		4000 × 3900	121.33	2.88 m 0.74D	Gravel sand N: 5 ~ 28	13	20
2023		3500 × 2000	10.80	3.17 m 1.59 D	Rhyolite/Soft rock N: 50/27 ~ 50/15	5	25

Table 3. Statistical analysis of some engineering cases constructed by the new RTBMs.

Data availability
All data generated or analyzed during the study are included in this manuscript.

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Author contributions
Peng Ma and Yahong Zhao wrote the main manuscript, and Hideki Shimada provided the resources and case data. Hou Zhou revised the manuscript. All authors reviewed the manuscript.

Declarations

Competing interests
The authors declare no competing interests.

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