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Research on Multi-functional Excavation Trolley for Single-track Tunnel Face

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Abstract: The construction of the tunnel face is a critical aspect of tunnel excavation, and its supporting equipment mainly includes drilling jumbos, arch installation trolleys, wet spraying manipulators, and anchor bolt trolleys. To address the issues of high construction costs and the need to replace equipment for different processes, this paper designs an economical and practical multi-functional integrated trolley based on engineering cases. This trolley is suitable for various construction methods such as full-face excavation and benching method, and integrates functions such as drilling and blasting holes, anchor bolt holes, advance grouting holes, pipe roof construction, charging, anchor bolt installation and grouting, and arch mesh installation. It reduces the number of operators, improves the tunnel working environment, lowers construction costs, and enhances construction efficiency.

Keywords: Single-track tunnel; Tunnel face; Excavation trolley; Full-face excavation; Benching method

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1. Introduction

Tunnel construction is gradually moving towards mechanization, automation, and intelligence to improve construction quality, safety, and efficiency [1–3]. For complex strata, to achieve requirements such as "quality, safety, progress, and environmental protection", it is necessary to comprehensively consider factors such as tunnel length, section size, surrounding rock geology, excavation method, schedule requirements, environmental and site conditions, and to configure construction machinery in an economically applicable and overall efficient manner. Currently, the equipment used for tunnel face construction has issues such as poor adaptability, single functionality, low overall efficiency, and high cost:

(1) Most equipment can only meet the needs of full-face and two-bench excavation methods, resulting in poor adaptability [4].

(2) Apart from the three-arm drilling jumbo, which can handle both excavation and anchor bolt construction, other equipment generally only has one function [5, 6].

(3) Different equipment needs to be replaced for different work procedures, leading to more ineffective working time and affecting overall efficiency [7, 8].

(4) The equipment is costly, resulting in high construction costs. To address these issues, it is necessary to further improve the construction technology of the tunnel face, optimize and upgrade existing equipment, or develop new multi-functional equipment to enhance the overall efficiency of tunnel face construction and reduce construction costs.

In response to the aforementioned issues, a multi-functional tunnel construction equipment that integrates various functions such as tunnel drilling and arch installation is developed. This equipment not only facilitates workers to load explosives but also allows other process equipment to pass through the gantry, significantly improving the efficiency of tunnel excavation using the drilling and blasting method. Compared with traditional equipment, this multi-functional equipment can effectively reduce equipment procurement and maintenance costs for tunnel construction, facilitate equipment scheduling in narrow tunnels, and save time and labor. The adoption of integrated equipment will significantly increase excavation speed, ensure construction safety, reduce operational complexity caused by excessive equipment, optimize construction processes, improve construction accuracy, and ensure the quality of tunnel sections.

2. Scheme design and key technology research

2.1. Scheme design

The single-track multi-functional excavation trolley mainly consists of a traveling mechanism, a platform frame, a movable arch frame, an arch frame lifting mechanism, an arch frame hoisting mechanism, an arch frame transfer cart, an arch frame installation cart, an anchor bolt auxiliary drilling mechanism, auxiliary mechanisms, an electrical system, and a hydraulic system. **Figure 1** shows the movable arch frame in retracted state, while **Figure 2** shows the movable arch frame in an extended state. This equipment is suitable for both full-face and benching method construction, integrating tasks such as assisting manual pneumatic drilling and blasting holes, anchor bolt holes, charging, anchor bolt installation and grouting, and arch mesh installation.

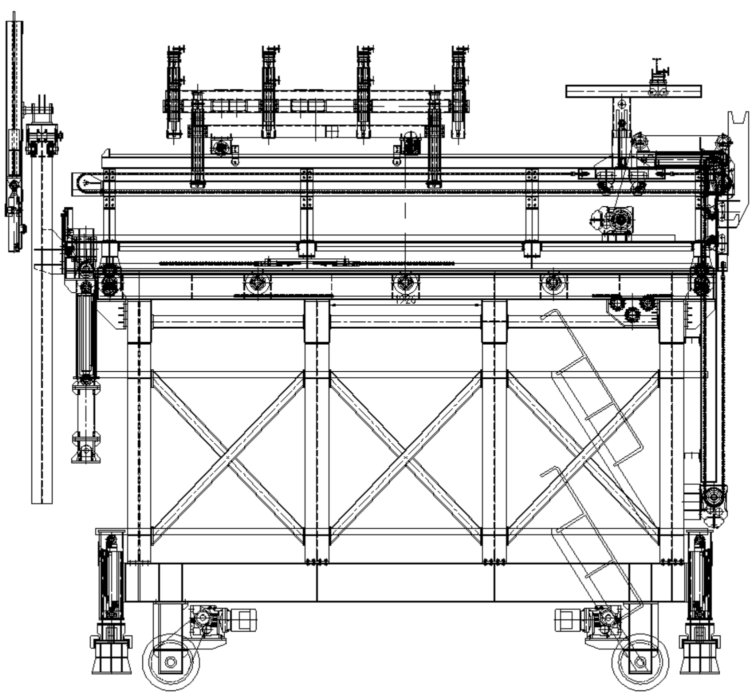


Figure 1. Mobile arch frame in retracted state

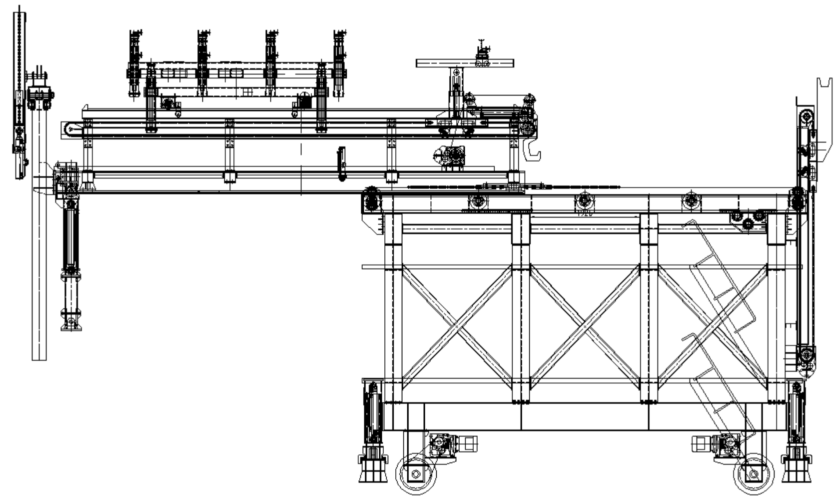


Figure 2. Mobile arch frame in extended state

2.2. Key technical research

(1) Research on telescoping arch frame

The mobile arch frame consists of a frame structure composed of 4 sets of arch frames and longitudinal beams (**Figure 3**). The lower end of the arch frame is equipped with a load-bearing track connected to the gantry beam. The load-bearing track is equipped with tug wheels and reverse hanging wheels, which are driven by chains to achieve relative movement between the arch frame and the gantry. The front end of the arch frame is equipped with telescoping legs. During stepped construction, the arch frame extends to support the upper step.

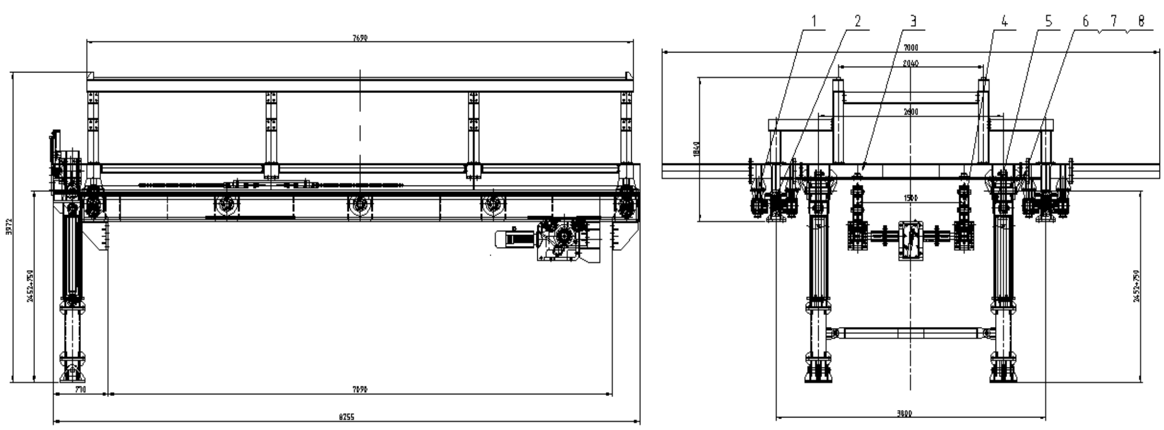


Figure 3. Schematic diagram of telescoping arch frame

(2) Research on arch frame transfer

The arch frame transfer mechanism includes a lifting mechanism (**Figure 4**), a transfer cart, and an installation cart. The arch frame lifting mechanism consists of a guide frame, a lifting cart, and a driving mechanism, with a total of two sets installed on the rear columns of the trolley platform, mainly used to lift the arch frame from a low position to a high position, facilitating the transfer of the arch frame on the platform by the arch frame transfer cart. The effective lifting height of the mechanism is 2.5m.

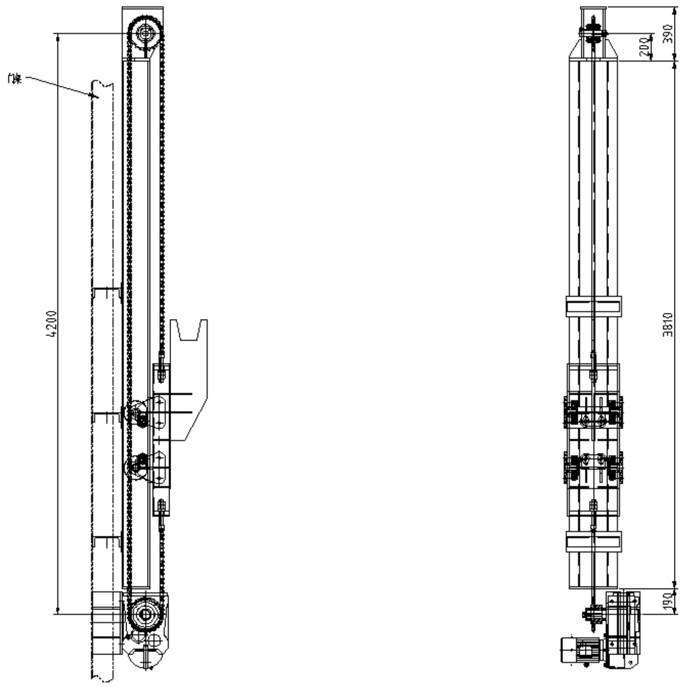


Figure 4. Schematic diagram of arch frame lifting mechanism

The arch frame transfer cart (**Figure 5**) mainly consists of a running track, a driving mechanism, and a cart, with a total of two sets installed on both sides of the mobile arch frame. It is mainly used to transfer the arch frame from the lifting mechanism to the arch frame installation cart.

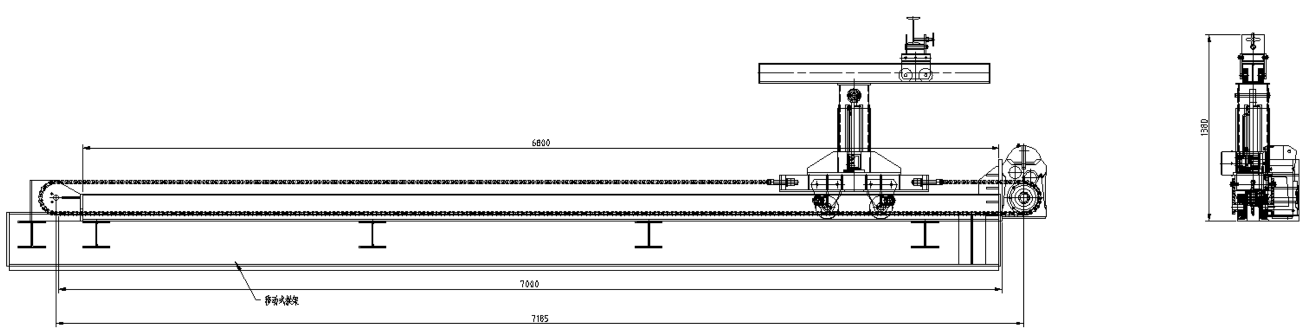


Figure 5. Schematic diagram of arch frame transfer cart

The arch frame installation cart (**Figure 6**) mainly consists of a running mechanism, a cart frame, an arch frame lifting mechanism, and an arch frame swing mechanism. It is mainly used for the storage and installation of arch frames, realizing the adjustment of different spacings, lifting, and small-scale swinging of the arch frames.

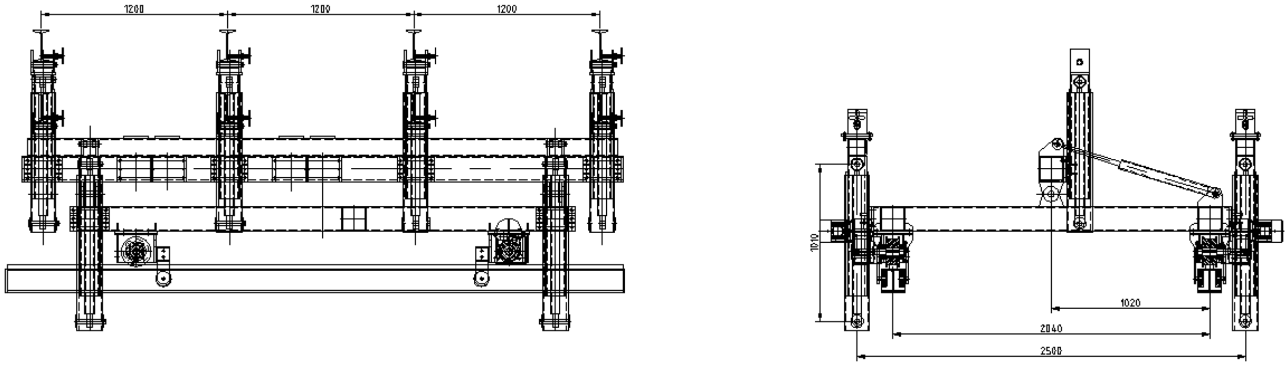


Figure 6. Schematic diagram of arch frame installation cart

2.3. Calculation of mechanical parameters

Steel is Q235B steel with a gravity density of 78.5kN/m3, an elastic modulus of 206Gpa, an allowable tensile and compressive stress of 140Mpa, and an allowable bending stress of 156Mpa (with a safety factor of 1.5). Some moving mechanism parts are made of 45# steel with an allowable tensile and compressive stress of 210Mpa. The construction load consists of the structural self-weight load and the weight of the steel arch frame, with a single steel arch frame weighing 500kg.

Focusing on the large cantilever state of the telescoping arch frame, the stiffness and strength of the platform and telescoping arch frame structure are checked. At this time, the equipment has completed the lifting of 4 steel arch frames, and the front legs have not yet supported the ground to form a stable structure. The equipment is in the most unfavorable stress state overall. **Figure 7** shows the finite element model of the trolley in working condition.

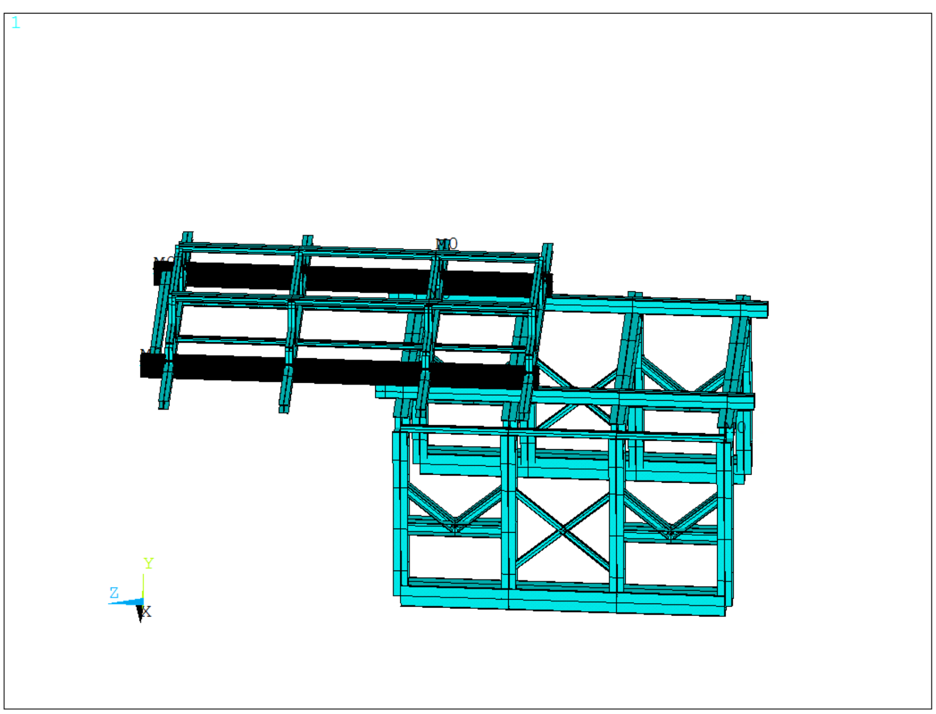
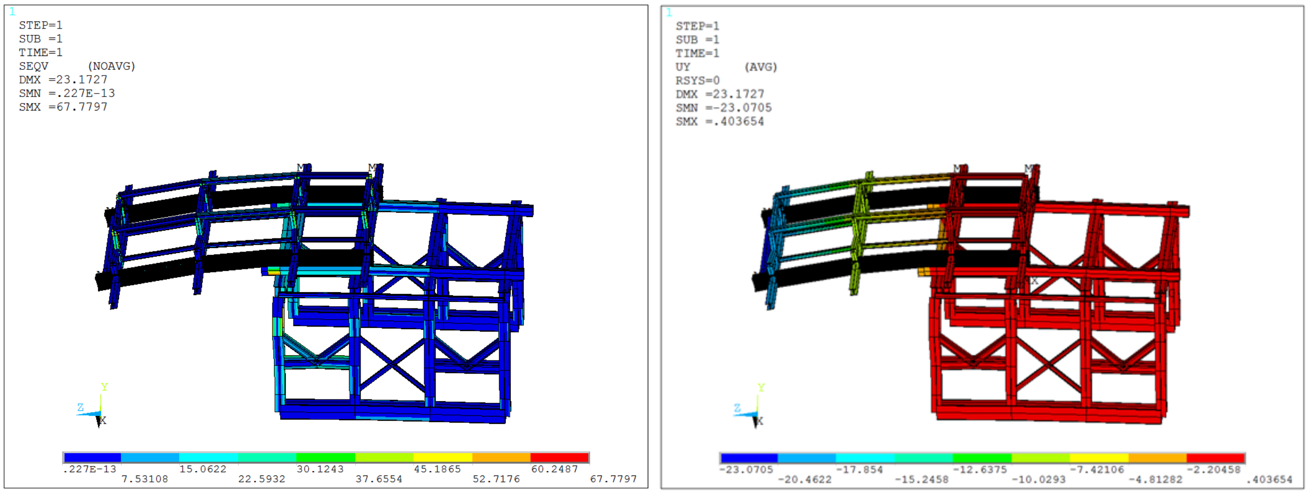


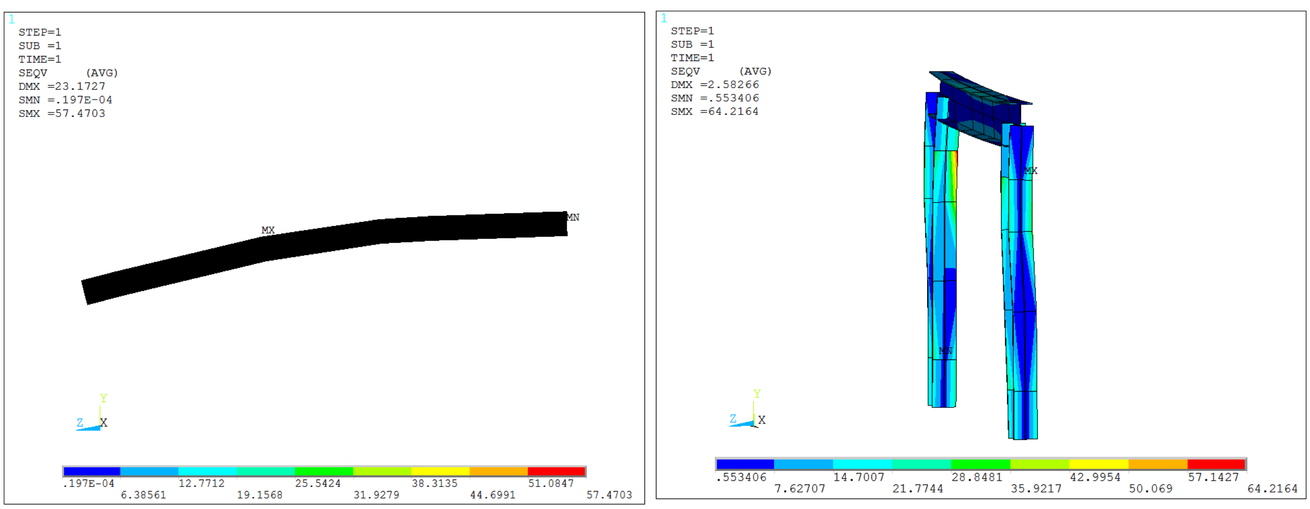
Figure 7. Finite element model

When the equipment is in a horizontal state, the finite element calculation results are shown in **Figure 8(a)** and **Figure 8(b)**, and the stress calculation results for key structures are shown in **Figure 9(a)** and **Figure 9(b)**. The maximum stress is 68Mpa, and the maximum deformation is 23mm, which meets the usage requirements.



(a) (b)

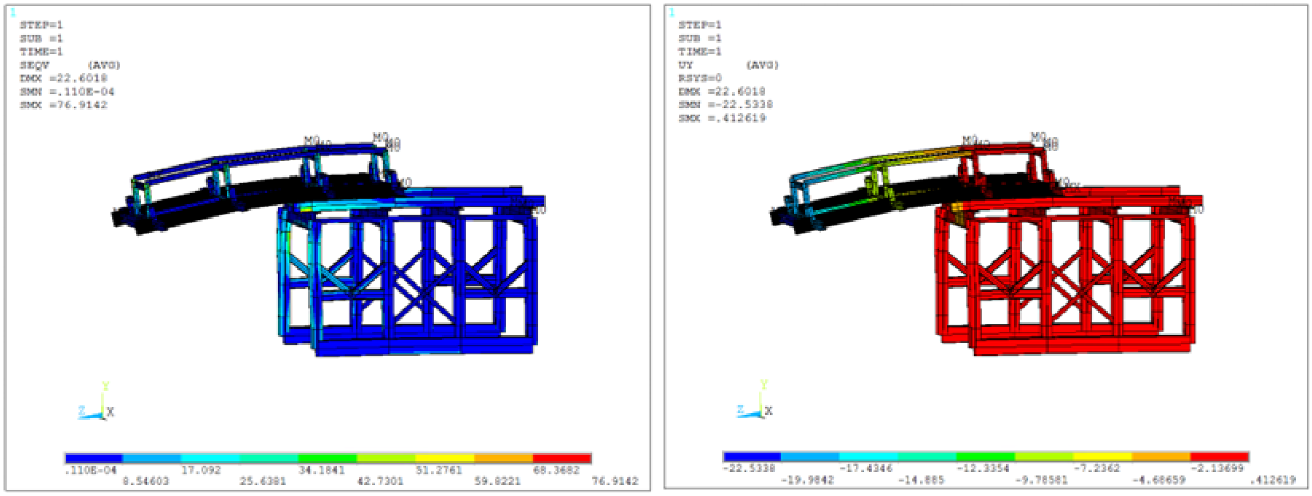
Figure 8. Finite element calculation results when equipment is in horizontal state, (a) Stress calculation results for the complete machine; (b) Deformation calculation results for the complete machine



(a) (b)

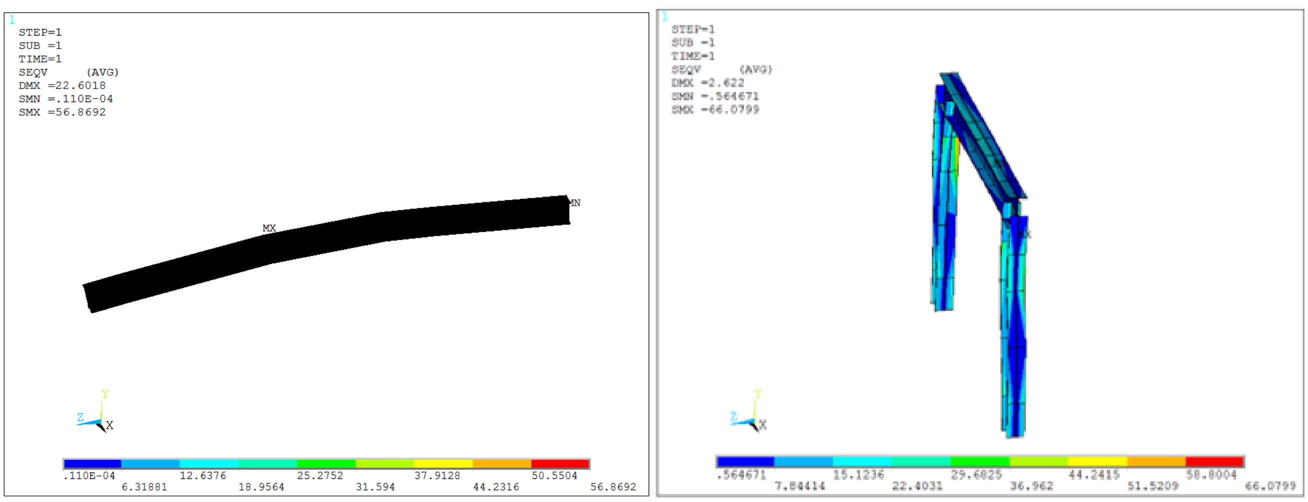
Figure 9. Stress calculation results for key structures when equipment is in horizontal state, (a) Calculated stress for the front longitudinal beam; (b) Calculated stress for the first gantry frame

The road conditions of the tunnel face are complex, with large slopes, and a maximum slope of 11%. The stress conditions of the equipment when climbing an 11% slope are calculated. The finite element calculation results are shown in **Figure 10(a)** and **Figure 10(b)**, and the stress calculation results for key structures are shown in **Figure 11(a)** and **Figure 11(b)**. The maximum stress is 76Mpa, and the maximum deformation is 22.6mm, which meets the usage requirements.



(a) (b)

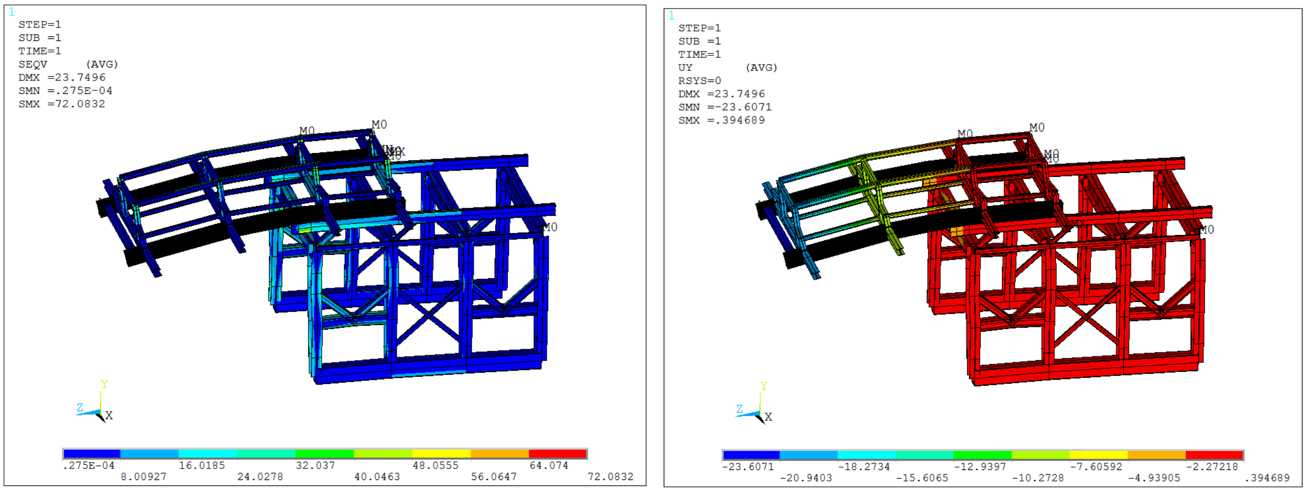
Figure 10. Finite element calculation results of equipment when climbing at an 11% slope, (a) Stress calculation results for the complete machine; (b) Deformation calculation results for the complete machine



(a) (b)

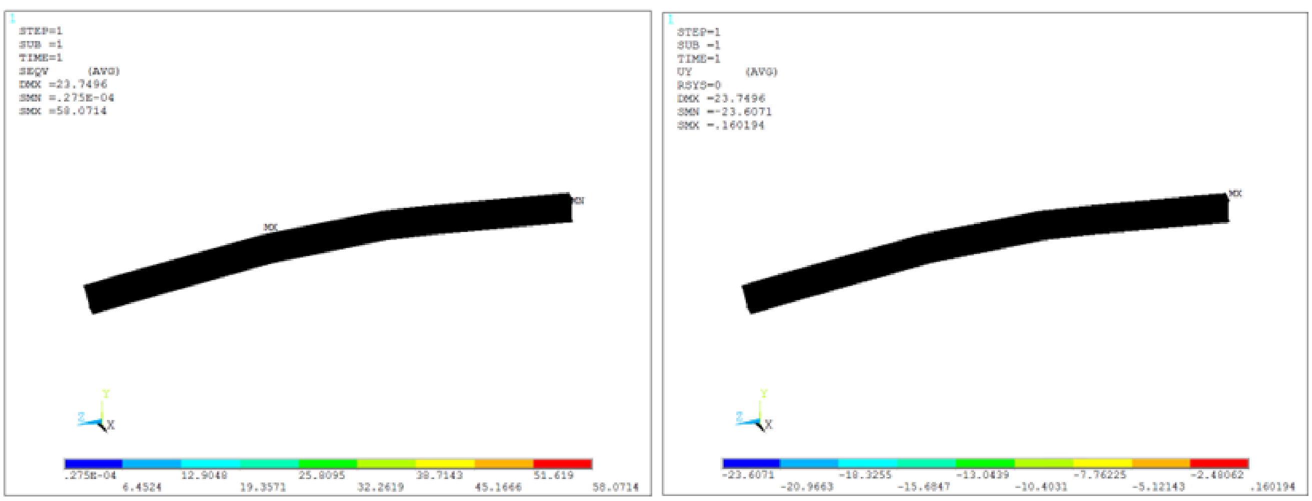
Figure 11. Stress calculation results for key structures of equipment when climbing at an 11% slope, (a) Calculated stress for the front longitudinal beam; (b) Calculated stress for the first gantry frame

The stress conditions of the equipment when descending an 11% slope are calculated. The finite element calculation results are shown in **Figure 12(a)** and **Figure 12(b)**, and the stress calculation results for key structures are shown in **Figure 13(a)** and **Figure 13(b)**. The maximum stress is 72Mpa, and the maximum deformation is 23.6mm, which meets the usage requirements.



(a) (b)

Figure 12. Finite element calculation results of equipment when descending at an 11% slope, (a) Stress calculation results for the complete machine; (b) Deformation calculation results for the complete machine



(a) (b)

Figure 13. Stress calculation results for key structures of equipment when descending at an 11% slope, (a) Calculated stress for the front longitudinal beam; (b) Calculated stress for the first gantry frame

The force models used in the above mechanical analysis process are calculated using simplified methods that tend to be safe. After analysis, all components can meet the stress and deformation requirements.

3. Research on construction technology

3.1. Research on drilling technology for tunnel face

(1) Full-face construction

As shown in **Figure 14**, the mobile arch frame is retracted, and manual drilling operations on the tunnel face are performed using pneumatic rock drills through the working platform of the trolley.

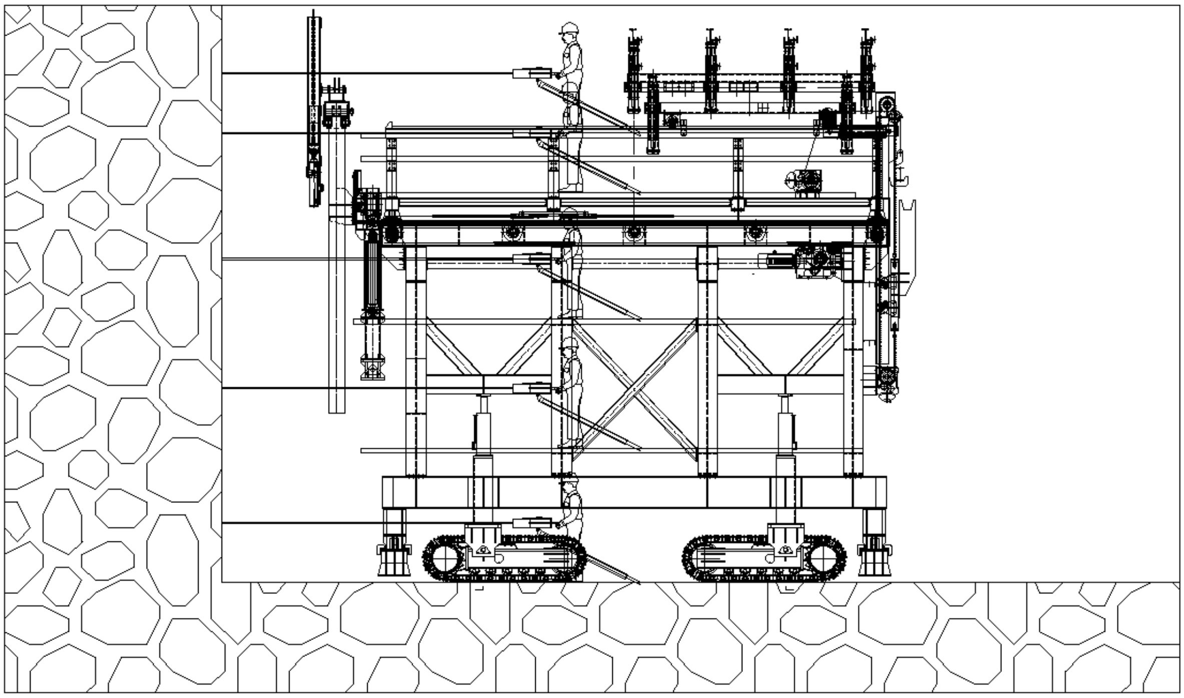


Figure 14. Full-face drilling

(2) Stepped construction

As shown in **Figure 15**, the mobile arch frame is extended, and the front legs of the arch frame are supported on the upper step. Manual drilling operations on the tunnel face are performed using pneumatic rock drills through the working platform of the trolley.

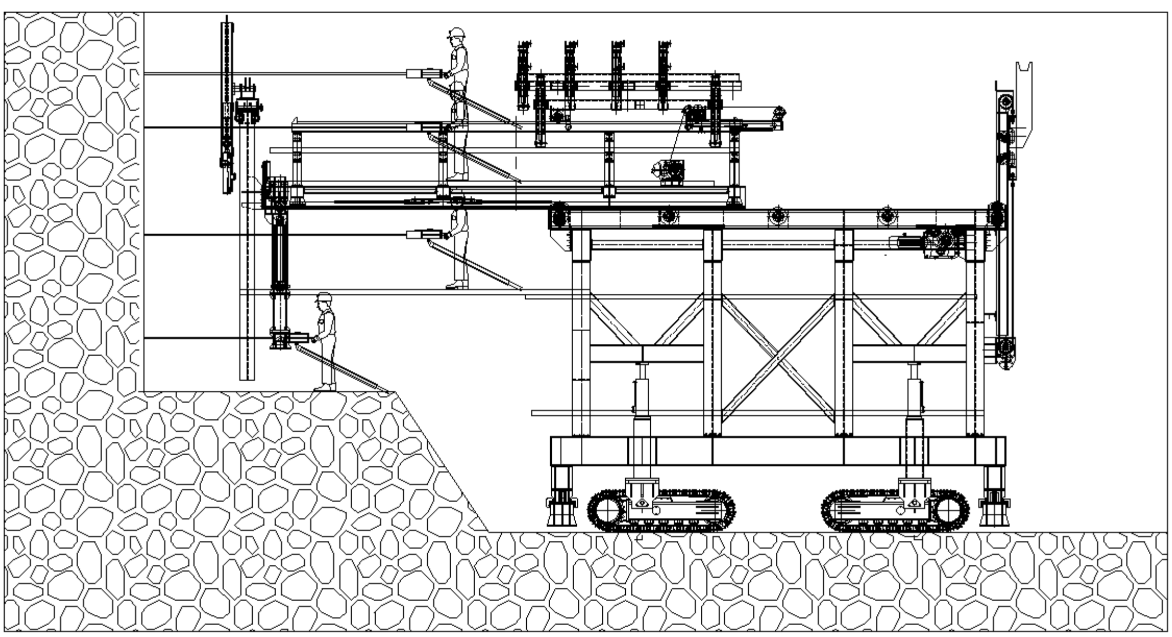


Figure 15. Stepped drilling

3.2. Research on arch frame assembly process

3.2.1. Full-face construction

(1) S1: The multi-functional integrated excavation trolley is positioned away from the tunnel face, and the arch frame is pre-assembled on the ground (excluding the lower part of the arch wall) without affecting the traffic of construction vehicles at the tunnel face.

(2) S2: The pre-assembled arch frame is lifted from the ground to a vertical position using the arch frame lifting mechanism at the rear of the trolley.

(3) S3: After the arch frame is lifted to a certain height by the lifting mechanism, it is placed on the arch frame lifting mechanism with manual assistance and lifted to the highest position.

(4) S4: Once the arch frame is lifted to the highest position, it is moved from the lifting mechanism to a transport cart.

(5) S5: The transport cart continues to lift the arch frame to a higher position and transports it to the installation cart for temporary storage.

(6) S6: Pre-assemble four arch frames following the same steps as above.

(7) S7: When the tunnel face meets the conditions for arch frame installation, the trolley is moved to the vicinity of the tunnel face. The arch frame is then moved to the installation position using the installation cart, and adjustments such as lifting and swinging are made. The side arch frames are pushed to the side walls of the tunnel using a telescoping platform, and the bottom arch frames are installed with manual assistance.

3.2.2. Benching method construction

(1) S1: The multi-functional integrated excavation trolley operates away from the tunnel face, and the arch frame is pre-assembled on the ground without affecting the traffic of construction vehicles at the tunnel face.

(2) S2: The assembled arch frame is lifted from the ground to a vertical position by the arch frame lifting mechanism at the rear of the trolley.

(3) S3: After the arch frame is lifted to a certain height by the lifting mechanism, it is manually placed on the arch frame lifting mechanism, which then lifts the arch frame to the highest position.

(4) S4: Once the arch frame is lifted to the highest position, it is moved from the lifting mechanism to a transport cart.

(5) S5: The transport cart continues to lift the arch frame to a higher position and then transports it to the arch frame installation cart for temporary storage.

(6) S6: Complete the pre-assembly of four arch frames according to the same steps as above.

(7) S7: When the tunnel face meets the conditions for arch frame installation, the trolley is moved to the vicinity of the tunnel face. The arch frame is extended onto the bench, and after the support legs are properly positioned, the arch frame is moved to the installation position using the installation cart. Adjustments such as lifting and swinging are then made. The bottom arch frames on the bench are installed with manual assistance.

3.3. Research on anchor drilling technology

After the completion of the arch frame, the anchor drilling operation is performed using the anchor assist mechanism at the front of the trolley. The anchor drilling mechanism can move back and forth through the telescoping arch frame to complete anchor drilling operations at different locations.

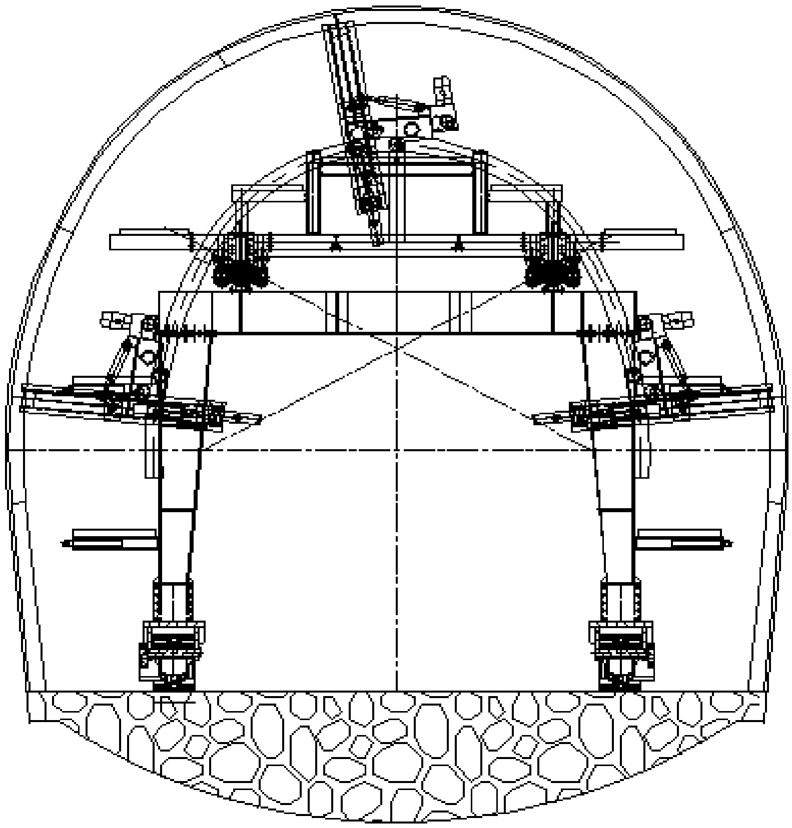


Figure 16. Schematic diagram of anchor drilling

4. Engineering example

4.1. Application situation

The main line of the Sichuan-Tibet Section 7 project is 36.645km long, with a tunnel length of 35.4km, accounting for 96.6% of the total line length. Among them, the Ga'er Temple Tunnel is a key and difficult project of the entire line, with a total length of 18.8km and a maximum depth of 1093m. The main geological problems include fault fracture zones, large deformations in soft rock with high ground stress, high ground temperature, sudden water inrush, and bedding bias pressure. Among them, large deformations in soft rock are the most prominent issue, and the predicted ground stress is the highest along the entire line, reaching 54.8MPa.

The prototype designed and produced based on the scheme of the single-track multi-functional integrated excavation trolley is mainly used for the tunnel face construction of the small-mileage left tunnel of the No.5 inclined shaft of the Ga'er Temple Tunnel in the Sichuan-Tibet Section 7. The equipment arrived at the site in May 2023 and was ready for use at the end of May. **Figure 17** shows the operating status of field equipment.

Figure 17. Operating status of field equipment

4.2. Cost analysis

The initial investment for purchasing a rock drilling jumbo is significant. A three-arm rock drilling jumbo (without a computer) costs over 9 million yuan, while a semi-computerized or fully computerized three-arm rock drilling jumbo can cost over 10 million yuan. (The fully computerized rock drilling jumbo from Railway Construction Heavy Industry costs 11.6 million yuan.)

Table 1 lists the cost of the newly developed multi-functional tunnel excavation platform. It compares the costs of various tunnel machinery currently used in different stages of drilling and blasting construction. Through comparison, it is evident that the multi-functional tunnel excavation platform has a significant cost advantage.

Table 1. Equipment cost comparison table

<table>
<tr><th colspan="2">Equipment</th><th>Three-boom jumbo</th><th colspan="2">Steel arch carrier</th><th>Wet spraying manipulator</th><th>Bolting jumbo</th><th>Total</th></tr>
<tr><td colspan="2"></td><td>1160 × 2</td><td colspan="2">250</td><td>160</td><td>260</td><td>2990</td></tr>
<tr><th rowspan="2">Equipment</th><th colspan="7">Comprehensive excavation platform (Estimated cost)</th></tr>
<tr><th>Framework structure</th><th>Working arm + Drilling hammer</th><th>Hydraulic system</th><th>Control system</th><th>3D laser radar scanning</th><th>Arch installation system</th><th>Total</th></tr>
<tr><td></td><td>100</td><td>50 × 6</td><td>40</td><td>80</td><td>80</td><td>50</td><td>650</td></tr>
</table>

5. Conclusion

In conclusion, the development of a multi-functional excavation trolley for single-track tunnel face construction addresses critical limitations in existing tunnel equipment, including high costs, limited functionality, and operational inefficiencies. By integrating multiple construction processes, such as drilling, grouting, anchor installation, and arch frame assembly, into a single platform, this innovative design enhances construction flexibility, reduces labor intensity, and improves safety and overall efficiency. Mechanical analysis confirms the trolley's structural reliability under various working conditions, and practical application in the Ga'er Temple Tunnel project demonstrates its cost-effectiveness and adaptability in complex geological environments. This research provides a valuable reference for future mechanized and intelligent tunnel construction practices.

Disclosure statement

The author declares no conflict of interest.

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