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Challenges and Thoughts on Risk Management and Control for the Group Construction of a Super-Long Tunnel by TBM

Mingjiang Deng

Xinjiang Association for Science and Technology, Urumqi 830011, China

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ABSTRACT

The total length of the second stage of the water supply project in the northern areas of the Xinjiang Uygur Autonomous Region is 540 km, of which the total length of the tunnels is 516 km. The total tunneling mileage is 569 km, which includes 49 slow-inclined shafts and vertical shafts. Among the tunnels constructed in the project, the Ka–Shuang tunnel, which is a single tunnel with a length of 283 km, is currently the longest water-conveyance tunnel in the world. The main tunnel of the Ka–Shuang tunnel is divided into 18 tunnel-boring machine (TBM) sections, and 34 drilling-and-blasting sections, with 91 tunnel faces. The construction of the Ka–Shuang tunnel has been regarded as an unprecedented challenge for project construction management, risk control, and safe and efficient construction; it has also presented higher requirements for the design, manufacture, operation, and maintenance of the TBMs and their supporting equipment. Based on the engineering characteristics and adverse geological conditions, it is necessary to analyze the major problems confronted by the construction and systematically locate disaster sources. In addition, the risk level should be reasonably ranked, responsibility should be clearly identified, and a hierarchical-control mechanism should be established. Several techniques are put forward in this paper to achieve the objectives mentioned above; these include advanced geological prospecting techniques, intelligent tunneling techniques combined with the sensing and fusion of information about rock parameters and mechanical parameters, monitoring and early-warning techniques, and modern information technologies. The application of these techniques offers scientific guidance for risk control and puts forward technical ideas about improving the efficiency of safe tunneling. These techniques and ideas have great significance for the development of modern tunneling technologies and research into major construction equipment.

1. Project profile and major geological problems

1.1. Project profile and major features

The total length of the second stage of the water supply project in the northern areas of the Xinjiang Uygur Autonomous Region is 540 km. The project's main tunnel is divided into three sections: the Xi–Er tunnel, the Ka–Shuang tunnel, and the Shuang–San tunnel (Figs. 1–3). The lengths of these three tunnels are 141 km, 283 km, and 92 km, respectively, and their total length is 516 km, which comprises 95.6% of the total project length. The tunnel-boring machine (TBM) excavation diameters of the three tunnels are 5.5 m, 7.0 m, and 7.8 m, respectively, so the tunnel diameter ranges from 5.5 m to 7.8 m. The project has the following notable characteristics:

(1) **Deep-buried tunnels**. The average burial depth is 420 m, and the maximum burial depth is 774 m. The tunnel line goes through mid- and low-altitude mountainous areas and hilly areas where the terrain gently undulates. The sea level elevation ranges from 600 m to 1500 m, and the relative height difference is from 150 m to 650 m. The total length of the main tunnel is 516 km; according to the burial depth, the part that is shallower than 450 m is 357.7 km long, the part with a depth ranging from 450 m to 650 m is 96.8 km long, and the part deeper than 650 m is 61.5 km.

(2) **Long-distance tunneling**. The total tunneling mileage of the main tunnel is 569 km; that is, the mileage of the main tunnel itself is 516 km, as mentioned above, and the total mileage of the 49 sub-tunnels is 53 km. There are 24 slow-inclined shafts. Four TBMs

E-mail address: xjdmj@163.com

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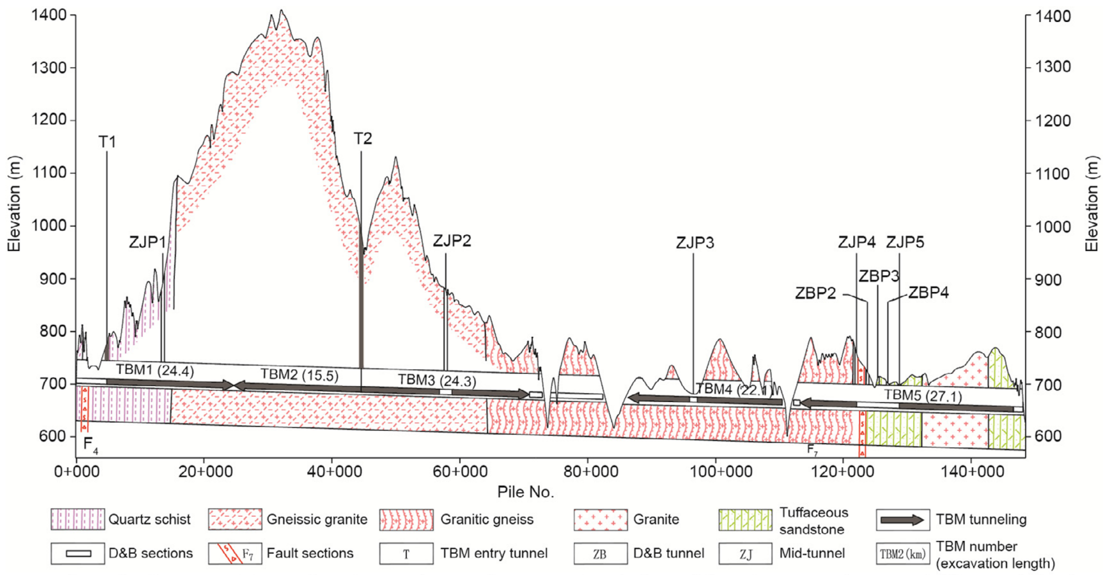

Fig. 1. Schematic diagram of the engineering geology and construction design of the Xi–Er tunnel. D&B: drilling-and-blasting; P: stulm; S: vertical shaft.

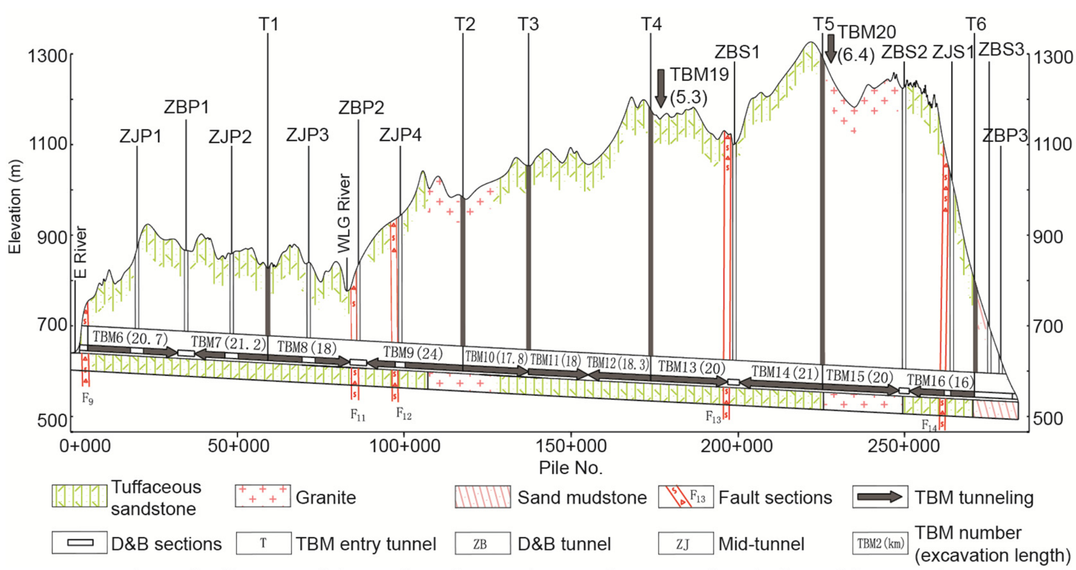

Fig. 2. Schematic diagram of the engineering geology and construction design of the Ka–Shuang tunnel.

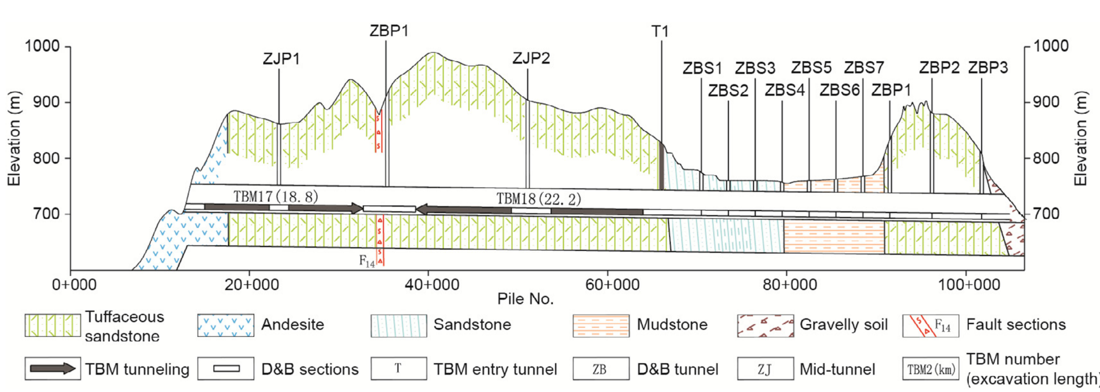

Fig. 3. Schematic diagram of the engineering geology and construction design of the Shuang–San tunnel.

were installed directly in the main tunnel; to install the other TBMs, 14 TBMs had to pass through nine slow-inclined shafts to enter the main tunnel. A total of 18 TBMs are being used for the main tunnel construction. The longitudinal gradient of the slow-inclined shafts ranges from 10.5% to 12%, and the shaft lengths range from 0.86 km to 6.44 km. There are 25 vertical shafts, with depths ranging from 46 m to 714 m.

(3) **TBM group construction**. A total of 20 open-type TBMs are being used in the construction, with 18 of these being used in the excavation of the main tunnel. The TBM tunneling mileage of the main tunnel is 393 km, which accounts for about 80% of the whole, while the drilling-and-blasting method is being used for the remaining 123 km of the tunnel, out of the aforementioned total of 516 km. In addition, the drilling-and-blasting method is being used in large or continuously distributed fractured zones and in the soft rock strata. Two TBMs are being used in the two long slow-inclined shafts, which are 5.2 km and 6.4 km, respectively.

(4) **World-record setting**. The length of the Ka–Shuang tunnel is a continuous 283 km, making it the longest water-conveyance tunnel in the world. The length of continuous excavation by a single TBM ranges from 15.5 km to 24.5 km, and the length of cumulative excavation is 27 km. The world records for the longest single tunnel excavation, the longest continuous excavation by a single TBM, and the longest cumulative excavation will be all broken by this project [1–3].

1.2. Geological structure and formation lithology

(1) **Fault structure**. The construction is located in a fold system of geological structure units. The tunnel passes through eight regional fault structures, where the surface width of the fractured zones ranges from 100 m to 200 m and the widest distance is 800 m. There are 129 secondary fault fractured zones. Along the construction site, the faults and fissures are not developed, and the fissures are mainly in medium or large dip angles. The surfaces of the fissures are filled by quartz veins, and their structural planes mainly have a compress-shear structure. The basic seismic intensity level is VII.

(2) **Formation lithology**. The formation lithology mainly consists of granite, biotite gneiss, tuffaceous sandstone, tuff, and calcareous sandstone. At the rear of the Ka–Shuang tunnel and the Shuang–San tunnel, there is a continuously distributed soft strata including mudstone or sandstone, which is 38 km long. For granite and biotite gneiss, the quartz content is 20%–30%, and for other types of rocks, the quartz content is generally 5%–10%. In the tunnel chamber, 82.7% of the surrounding rock is of class II and III, and 78.5% of the surrounding rock has a saturated compressive strength between 30 MPa and 120 MPa.

1.3. Evaluation of major geological problems in the project

Specific research was carried out to assess the main geological problems likely to affect the project, which included collapse, water inrush, rockburst, soft rock deformation, high geotemperature, radioactivity, high geostress, and active faults. The main conclusions are as follows:

(1) Generally speaking, the surrounding rock condition is good and is suitable for mechanized construction using TBMs. There are 19 tunnel sections where collapse may easily occur, with a cumulative length of 52 km. These areas are mainly located in a regional fractured zone and in a local large secondary fractured zone.

(2) The surface water in the construction area is deficient, and mainly consists of bedrock fissure water. The rock mass is relatively complete, and its water permeability is not strong. The location of the tunnel section where water inrush may easily occur roughly overlaps the location of possible collapse.

(3) Two tunnel sections pass through a moderate rockburst zone: The Xi–Er tunnel contains a tunnel section that is 18 km, with a burial depth of over 500 m; and the Ka–Shuang tunnel contains a tunnel section that is 47 km, with a burial depth that is greater than 650 m. The rock strength-stress ratio is 3–4.

(4) Large plastic deformation may easily occur in the soft rock tunnel section, which has a total length of 38 km.

(5) Issues with high geotemperature, radioactivity, and harmful gas are not present.

(6) The presence of an active fault has a certain influence on the lining structure of the tunnel. Anti-breaking measures that are suitable for deformation should be considered in the design.

2. Project difficulties and risk assessments

2.1. Major difficulties in the project

The general principles for the construction of this super-long tunnel project can be summarized as risk prevention and control, construction safety, high efficiency, and scientific standardization. Six difficult problems are confronted in the construction management of this project [4].

(1) **Excavation evaluation of the TBM and drilling-and-blasting methods and sublevel tunneling**. Given the complicated geological conditions, risk control should be taken as the main principle of the project. As the primary objectives of the construction organization scheme for this deeply buried super-long tunnel, the construction sections should be scientifically and rationally divided, the advantages of the drilling-and-blasting method and TBM tunneling should be fully exploited, and corresponding technical strategies and control management methods should be developed. Based on comprehensive effect factors such as rock-mass characteristics, fault structure distribution, technical equipment capabilities, environmental conditions, construction efficiency, and project investments, the adaptability of a TBM for the geological conditions of the project should be studied, and a technically feasible and economically reasonable construction plan for divided sections should be put forward. The construction channels, branch tunnels, and selection of the position and number of vertical shafts are key in optimizing the design of a construction plan.

(2) **Safety issues regarding TBM entering and tunneling**. It is a very challenging problem for large-scale equipment to pass through vertical shafts, inclined shafts, or slow-inclined shafts ($< 7°$) and other branch tunnels entering a deeply buried underground main tunnel. In addition, the set of technical operations including the assembling, starting, stepping, and dismantling of TBMs inside the tunnel presents further challenges. TBMs can pass through slow-inclined shafts to enter the main tunnel. Rail haulage is then applied in the main tunnel, while trackless haulage is applied in the branch tunnels. Given this comprehensive transportation plan, the key to ensuring the safety and efficiency of the construction is to carry out a design of the supporting system—such as muck removal, ventilation, material transportation, power supply, water supply and drainage, personnel, and transportation—that matches the design of the long-distance and large-slope slow-inclined shafts and of the chamber structure.

(3) **The design and manufacturing of TBMs and TBM intelligent tunneling**. A TBM's adaptability, durability, and reliability enable fast construction, long use, and a long excavation. TBM designers must carefully consider how to comprehensively balance technical advances in the TBMs with economical practicability, and how to carry out an individual design based on the specific engineering geological conditions of a given project. The current devel-

opment directions for modern tunnel construction technologies are: to improve the comprehensive perceptual ability and informatization level of TBMs; to obtain real-time parameters of the surrounding rocks; to change cutting tools in a timely manner; to adjust the tunneling parameters in a timely manner; and to establish an intelligent tunneling control system based on big data and a cloud platform that connects humans, TBMs, and rocks in a workable network.

(4) **Safety and security of TBMs and supporting facilities**. The mechanized construction of a super-long tunnel is a large systematic project. Numerous pieces of equipment are needed for the construction. The information management of TBM groups and their supporting systems—such as detection and diagnosis, maintenance and fault recovery, construction quality, project progress, and so forth—plays an important role in modern tunnel construction. Each of these systems contains major problems that must be solved. One of the problems confronted in construction is the safety and security of supporting facilities, such as muck removal, ventilation, power supply, water supply and drainage, and material transportation. Furthermore, the reliability of equipment performance and the timeliness of danger elimination and first-aid repair are difficult problems in construction.

(5) **Geological prospecting and risk prevention and control**. Fault fractured zones, soft fractured rock masses, water-bearing structures, water inrush, collapse, boulder falling, surrounding rock deformation, rockburst, and so forth are the main geological problems that affect the safety and efficiency of a TBM construction. Because a TBM tunnel is generally extremely long and deeply buried, with complex geological conditions, advanced geological prospecting and exploration should be included in the construction process. Attention should also be paid to disaster monitoring and early-warning systems. Advanced reinforcement and other follow-up construction measures must be done in order to achieve an efficient excavation in a scientific and safe way. Certain incidents that may be caused by adverse geological conditions, such as out-of-control TBM posture or blocked or buried TBMs, should be prevented, and an emergency disposal plan should be created.

(6) **Soft rock deformation and the selection of a construction plan**. Soft rock strata are continuously distributed at the end of the Ka–Shuang tunnel (over 11.7 km of the tunnel) and at the rear of the Shuang–San tunnel (over 26.3 km of the tunnel). In the Shuang–San tunnel, 80% of the soft rock section is extremely soft rock with a saturated compressive strength lower than 5 MPa. The thickness of the rock mass overlying the soft rock ranges from 60 m to 80 m, and the groundwater level is higher than the bottom of the cave by 50 m to 62 m. In these locations, it is very easy to trigger plastic deformation, surrounding rock bulging, and rheologic deformation. Application of the drilling-and-blasting method requires many ancillary measures, and the cost and duration of such an application are difficult to control. Even if soil pressure balance or slurry balance shield construction is applied, high risks remain [5].

2.2. Project construction and classification of construction risks

The major sources of risk in this project include the geology, equipment, construction, environmental protection, and investment. The potential risks can be classified into four levels and 12 categories, based on the possibility and severity of the outbreak of potential safety hazards (Fig. 4).

Level One: Risk sources include major geological hazards, major pieces of equipment, centralized operation channels, and large-group personnel safety.

(1) **Regional fault structure zones**. The tunnel passes through eight regional fault structure zones, which may trigger water inrush, mud inrush, collapse, machine blockage, and personnel safety risks.

(2) **Large plastic deformation of extremely soft rocks**. The Shuang–San tunnel is deeply buried, and the level of underground water is very high. In addition, there are extremely soft cave sections. Thus, there is a risk of large plastic deformation.

(3) **The safety of operation channels**. Super-long tunnels, large-slope slow-inclined shafts, and deeply buried vertical shafts create security risks. Transport systems for wind, water, electricity, muck, and materials are densely arranged, creating a threat to the safety of the operation channels.

Level Two: Risk sources include general geological hazards, major pieces of supporting equipment, and small-group personnel safety.

(4) **Secondary fault fractured zones**. There are 129 secondary fault fractured zones that develop from fault structure zones. These secondary fault fractured zones may cause water inrush, large deformation, collapse, and machine blockage.

(5) **Manufacturing, operation, and maintenance of TBMs**. This process includes the design and manufacturing, properties diagnosis, and fault repair for the overall performance and key components of the TBMs. Operation risks exist in the processes of installation, starting, stepping, dismantling, and other procedures.

(6) **Operation and management of supporting facilities**. Supporting facilities for muck removal, ventilation, power supply, water supply and drainage, and material transportation have the characteristics of safety, reliability, durable stability, energy conservation, and high efficiency. However, potential risks still exist.

Level Three: Risk sources include safety related to ecological protection, the operating environment, project investments, the construction quality, and the construction period.

(7) **Soil and water conservation and ecological protection**. The project passes through natural grasslands with pastoral areas and national ungulate wildlife reserves, and may therefore threaten the soil and water conservation and ecological environmental protection in the area.

(8) **Construction quality, construction period, and investment control**. The total investment in this project is 51.2 billion CNY, and the construction period is 84 months. Great risks are present regarding the construction quality, construction period, investment control, and loans.

(9) **Working environment and labor security**. Potential risks exist in the working environment, such as low ventilation quality around the tunnel face, de-dusting and cooling measures, pollutant emission, and noise control in the tunnel excavation.

Level Four: Risk sources include general construction management safety.

(10) **Run-through survey and traverse-survey control**. The tunnel is divided into 18 TBM excavation sections and 34 drilling-and-blasting tunnel sections. A lack of accuracy and reliability in the ground control net and in the traverse survey of the tunnel will present challenges to the creation of an accurate run-through of the tunnel.

(11) **Spare parts dynamic management**. TBMs and their supporting facilities are numerous, and the system is complex. Risks exist in the operation management of a safety reserve of spare parts, in performance matching, and in ensuring a timely supply of spare parts.

(12) **Hard rock excavation and moderate rockburst**. Granite and biotite gneiss are types of hard rock with a compressive strength greater than 180 MPa and with a quartz content of 20%–30%. These rocks present risks of tool wear and machine blockage. In the deeply buried sections of the tunnel, there is also a great probability of encountering moderate rockburst.

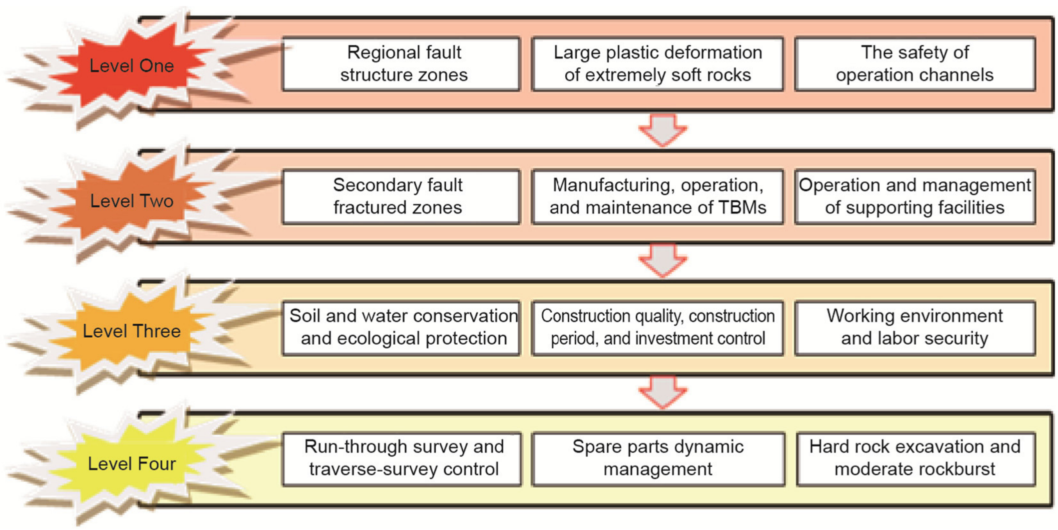

Fig. 4. A block diagram classifying the construction risks for the group construction of a super-long tunnel by TBMs.

3. Risk control and mechanism structure

3.1. General ideas: Level-to-level control of classified risks by responsibility allocation

(1) **Risk control by different responsible parties**. The management of the units responsible for equipment manufacturing, equipment operation and maintenance, engineering construction, material supply, construction supervision, quality inspection, survey and design, and project management should be carried out by different responsible parties.

(2) **Risk control by different levels**. First, it is necessary to establish a risk-prevention-and-control center that involves five sub-centers. Hierarchical control is then implemented according to the risk level. Second, potential risks should be decomposed and construction difficulties should be reduced—for example, by dividing a long tunnel into short construction sections. This is a primary principle for super-long tunnel construction. Construction sections should be rationally divided and construction organization should be scientifically optimized. The advantage of the high efficiency of TBM tunneling should be fully made use of, and the drilling-and-blasting method should also be adopted, according to geological conditions. The drilling-and-blasting method should first be applied to the construction of tunnel sections with rather poor geological conditions, to avoid the risks of TBM construction in these areas.

(3) **Risk control by different classifications**. Risks should be classified and controlled according to different classifications; these may include geological hazards, equipment operation, construction safety, quality assurance, investment control, and environmental protection.

3.2. Management and control principles

(1) **The principle of "515" (i.e., 500 m, 100 m, and 50 m, as described below) full-coverage monitoring, guided by advanced geological prospecting**. In the geological survey stage, geological boreholes were drilled every 2 km, on average. Considering the geological characteristics of the project, a basic geological analysis was performed of the main geological structures 500 m away from the front of every tunnel face. Geological prospecting methods were applied in order to roughly detect the geological structures and water-bearing stratum 100 m in front of the tunnel face, and situations about 50 m in front of the tunnel face were accurately known. As a result, a "long distance–medium distance–short distance, short distance–medium distance–long distance" cyclical prospecting and proactive geological warning mechanism was established.

(2) **The principle of "20 + 120" (i.e., 20 TBM tunneling faces and 120 drilling-and-blasting tunneling faces, as described below) fixed-point control and relying on construction work groups**. The construction risks mainly came from the 20 TBMs and their ancillary equipment, the 49 tunnel faces of the branch tunnels, and the 91 operating tunnel faces in the main tunnels. Therefore, it was necessary to set up and train 140 operating teams, and to establish the most stringent risk-control measures with the support of advanced geological prospecting methods. Using modern information technology and advanced scientific and technological means, an intelligent tunneling system should be established in the near future, through which the goal of rock-machine matchup, human-machine cooperation, and human-machine-rock perception can be achieved, and the possibility and severity of the occurrence of risks can be decreased.

(3) **The principle of "5 support 1" (where 5 refers to the five major systems and 1 refers to the TBM as described below) early warning and monitoring, relying on TBMs and ancillary equipment**. TBMs play a leading role in long-distance tunnel construction. During the tunneling process, incidents often occurred, such as cutterhead sticking, overly high cylinder temperatures, abnormal hob damages, out-of-control operating postures, abnormal damages to the main bearings and to other core components, and so on; if not properly dealt with, these incidents would lead to serious accidents. Therefore, a full-time early-warning and monitoring system must be established, not only for the TBMs, but also for the key equipment of the five major systems, which include muck removal, ventilation, power supply, water supply and drainage, and material transportation [6].

3.3. Mechanism framework

The risk-control mechanism is shown in Fig. 5; its major characteristics are as follows:

(1) **Clarifying the three main responsible parties**. The team in charge of the geological survey and the team in charge of advanced geological prospecting were a professional organization that took

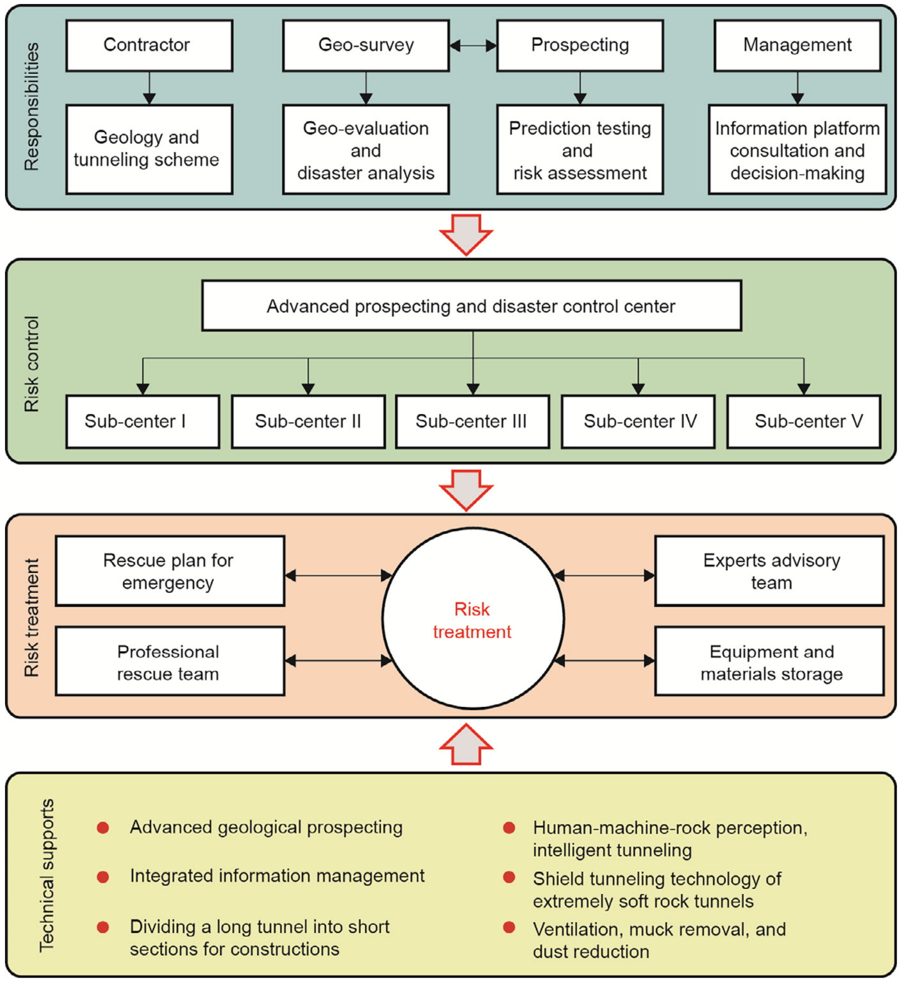

Fig. 5. A block diagram of the risk-control mechanism for super-long tunnel construction.

charge of disaster positioning and proactive early warning. This organization was mainly responsible for geological analysis and disaster assessment. The project employer was responsible for the drilling-and-blasting construction, safe TBM tunneling, the maintenance and operation of auxiliary equipment, and the formulation of risk-prevention procedures and risk control. Finally, the project management team was responsible for establishing an information platform and for comprehensive decision-making management.

(2) **Establishing a prevention-and-control center**. Based on the informatization of the working TBM group, cloud computing, and an Internet platform for big data analysis, a center for advanced prospecting and disaster prevention and control was established. Relying on the project management department, five sub-centers were set up and an expert decision-making and consultation team was formed in order to achieve onsite analysis and decision-making and to establish cloud-based solutions.

(3) **Forming a rescue and maintenance team**. It was necessary to develop a program for emergency rescue and to form a professional construction team and maintenance team, in order to deal with all kinds of geological disasters, TBM breakdowns, the operation and maintenance of auxiliary equipment, and the preparation of personnel rescue. This involved the establishment of preventive measures against possible issues, and the elimination of potential risks at the start of the project. Each rescue team was set up and individually managed by contractors, and would be deployed by the disaster control center in the event of an incident.

(4) **Relying on advanced technology**. Researching, developing, and applying advanced scientific technologies provides an important means of reducing risks. Valuable technologies include advanced geological prospecting techniques with precise and accurate identification; intelligent tunneling technologies with human-machine-rock perception; real-time and rapid early-warning technologies; modern information technology; reliable and efficient technologies for ventilation, muck removal, and dust reduction; and fast and effective water-blocking technologies.

4. Technical support for risk control

4.1. Advanced prospecting of geological disasters

4.1.1. Establishing a comprehensive system of advanced geological prospecting

An important method to ensure safe and efficient TBM tunneling is to scientifically establish an advanced geological prospecting system for the construction by adopting reliable and fast geophysical detection based on geological analysis. Comprehensive prospecting is achieved by combining long-distance, middle-distance, and short-distance prospecting, surface and underground prospecting, drilling exploration and geophysical detection, structure detection, and water content detection, as well as detection with carried equipment and with portable equipment. In this way, the following major goals were realized: automatic and fast advanced geological prospecting with full coverage, information sharing and exchanges; consultation and decision-making; and advanced disaster control.

(1) **Information sharing and exchanges**. In order to solve difficult problems such as too many construction sites, a super-long construction line, and a large number of data formats and images from the prospecting results, a big data platform for information exchange was established, and expert groups that specialized in consultation on advanced geological prospecting were formed. By formulating technical regulations and carrying out technical guidance and professional training as provided by the expert groups, the interaction and standardization of advanced geological prospecting outcomes were achieved, and the efficiency and accuracy of the advanced geological prospecting were improved.

(2) **Consultation and decision-making**. Given the risks of geological disasters and the difficulties in results management, a scientific and effective mechanism for communication, discussion, consultation, and decision-making was established by making full use of big data systems and of an information-based management platform. With a focus on high-risk geo-hazards, disaster identification, risk assessment, and consultation were carried out in order to achieve online, real-time handling of advanced geological prospecting results.

(3) **Advanced disaster control**. To address the threat of potential geological disasters, a 360° omnidirectional rapid-drilling rig was developed and installed, and effective processing measures were worked out. These included advanced reinforcement by grouting, water plugging by grouting, advanced pipe-roof protection, small pipes and roof bolts application, and the use of branch tunnels. Emergency rescue teams were also established. All of these measures were taken in order to achieve safe and rapid TBM tunneling.

4.1.2. The progress of TBM-mounted geological prospecting technology

It is difficult to meet the requirements of efficient and safe TBM tunneling using common geological prospecting methods that are suitable for drilling-and-blasting construction, such as tunnel seismic prediction (TSP), tunnel geological prediction (TGP), tunnel reflection tomography (TRT), and tunnel seismic tomography (TST) [7]. A new trend in theoretical research and equipment development involves studying the new geological prospecting technologies that are suitable for TBM work and applying them in TBM systems. Detection methods are divided into two categories: The first category uses the medium elastic wave impedance difference to detect geological structures such as fault fractured zones and soft intercalated layers; the second uses the medium temperature field, dielectric difference, and polarization characteristics to detect groundwater.

Scholars at Shandong University researched and developed a system that combines three-dimensional (3D) seismic advanced prospecting [8] and 3D induced-polarization advanced prospecting [9]. They used TBM maintenance procedures to run automatic detection, thereby achieving 3D positioning 100 m in front of the tunnel face and an estimation of the water volume of water-bearing structures. The horizontal seismic profiling (HSP) prospecting method and its equipment, which were developed by the China Railway Southwest Research Institute Co., Ltd., use the vibration signal generated by a TBM's cutterhead during drilling to test changes in horizontal acoustic wave reflection and to predict geological structures in front of the TBM without machine shutdown [10]. Rock-mass temperature probing (RTP) technology, which is based on the temperature-field detection of groundwater, can predict the groundwater situation in front of the tunnel face based on the position and range of temperature-field distortions, thus preventing geological disasters such as water inrush and mud gushing [11]. The boring machine seismic tomography (BMST) prospecting method, which was developed by Beijing Tongdu Engineering Geophysics Ltd. Corp. based on the TST system, uses real-time 3D imaging to detect geological structures 30–50 m in front of the tunnel face [7]. Scholars at Huazhong University of Science and Technology developed an online geological exploration system using a current sheathing-focusing method [12]; this method uses the scanning mode of cutterhead rotation to predict the geological situation in front of the tunnel face.

These prospecting methods have their own characteristics and serve different functions; on the whole, they still require further improvement. The goal of research and development of advanced geological prospecting technology is to better achieve TBM group working and automatic and real-time detection. It is believed that in the near future, advanced geological prospecting technologies suitable for TBM construction will be more convenient, more developed, and more scientific.

4.2. Rock-machine perception and intelligent tunneling

4.2.1. Problems

TBM tunneling is prone to threats from adverse geological bodies; at the same time, attention should be paid to equipment adaptability, operating conditions of the components, tunneling parameters, and other factors. Thus far, remarkable achievements have been made in TBM tunneling in many projects; however, the risk of frequent accidents cannot be eradicated, for the following reasons:

(1) **Lack of perception**. A TBM lacks scientific methods and effective means to quickly perceive information about the surrounding rocks and the operating conditions of its equipment and key components; therefore, feedback between the rock and the machine is delayed.

(2) **Lack of decision-making**. Due to a lack of tunneling evaluation and of effective means to make intelligent decisions, practical tasks mainly rely on human experience rather than on scientific bases. This shortcoming may result in low efficiency and resource waste, and may furthermore lead to serious incidents such as collapse and machine blockages.

(3) **Lack of a platform**. Due to the lack of a necessary platform for information exchange and analysis, massive information on TBM tunneling is not saved and analyzed effectively. It is also urgently necessary to develop the use of information technology, the Internet of Things, big data and intelligent algorithms, and other key technologies in TBM construction projects, in order to achieve innovative breakthroughs in platform establishment.

4.2.2. Rock-machine perception and information interaction

Information perception and integration play a fundamental role in TBM intelligent tunneling. It is essential to improve construction safety and tunneling efficiency by exploiting information about rock-machine perception, looking for perceptual patterns, and establishing perceptual models, thus developing an intelligent system and evaluating the perception of the surrounding rocks and equipment condition.

(1) **The perception of information about equipment and the evaluation of operating conditions**. Operation information (such as the forces of the cutterheads, damage to cutter tools, vibration, abnormal alarms, and muck features) and parameter information (such as thrust, torque, rotational speed, and penetration) should be quickly perceived. In order to have a dynamic evaluation of the TBM working conditions and adaptability, a multi-index and multi-parameter evaluation system should be established to grade the equipment; in addition, an evaluation system for geological adaptability should be created.

(2) **The perception of information about surrounding rocks and the evaluation of working conditions**. TBM tunneling

parameters are closely related to rock-mechanics parameters. Geological surveys and advanced geological prospecting can help reveal relational models between drilling parameters and rock-mass parameters; thus, the real-time perception of rock-mechanics parameters during tunneling can be achieved with the help of a digital monitoring system and advanced drilling information. By adopting the rock-machine interaction model, rock-mass parameters were obtained by inverting the equipment parameters. Furthermore, an intelligent information system that infers the rock mass of the tunnel face from the hob force and that infers an image identification of rock muck was developed to enable the real-time perception and evaluation of the rock status during tunneling.

(3) **Rock-machine information exchange and a big data platform**. A big data storage and analysis platform for TBM tunneling was established in order to achieve further integration, in-depth understanding, and systematic analysis. By focusing on knowledge discovery and modeling, information about the surrounding rocks and internal patterns of the rock-machine interaction were revealed, and the TBM working status was determined [13]. The patterns of human-machine-rock information perception and interaction provided a theoretical basis for intelligent construction (Fig. 6).

4.2.3. Intelligent tunneling and decision optimization

The development of information technology has greatly promoted the storage capacity, calculation speed, and quality of information processing, and artificial intelligence is in widespread use. Based on TBM information perception and interaction, intelligent tunneling represents a trend of safe and efficient tunneling.

(1) **Strategies of intelligent tunneling**. When dealing with adverse geological structures, intelligent tunneling should be combined with advanced geological prospecting in order to rapidly perceive and identify the tunneling state; this information should be collected and saved in an expert knowledge base and "experience library." In this way, onsite workers can pre-assess early warnings and optimize plans to keep equipment safe. In conventional strata, intelligent tunneling can intelligently control the tunneling parameters according to the information perceived about the surrounding rocks in order to optimize tunneling goals.

(2) **Intelligent tunneling**. TBM construction is influenced by complex factors and targets. An intelligent tunneling strategy should take full account of the incommensurability between the various targets, and should apply a multi-target dynamic programming method based on accurate rock-machine interaction models in order to comprehensively optimize various factors and thereby realize the goals of being efficient, economical, and energy saving.

(3) **Efficient tunneling**. Taking the main parameters of TBM design, the rock-machine interaction model, and the operating status of the supporting equipment as the limiting conditions, a maximum tunneling speed, $V_{\max}$, was the target. Given this condition, it was necessary to calculate the penetration, P, and cutter's rotation speed, R, and to obtain the minimum value under certain conditions as the theoretical maximum value of the tunneling parameter.

(4) **Economical tunneling**. Based on the monitoring data on cutterhead damages, the correlation between the degree of damage and the tunneling parameters was studied, and a predictive model of cutterhead damage was established. Taking the minimum cutter damage, $\chi_{\min}$, the minimum cutter replacement time, $T_{\min}$, and the maximum drilling footage, $L_{\max}$, as the targets, the tunneling parameters were optimized [14].

(5) **Energy-saving tunneling**. The law of energy consumption of rock cutting under different tunneling parameters was studied, based on indoor cutting experiments and onsite tunneling data. The minimum specific energy necessary for rock breaking and its corresponding optimized parameter were determined.

4.3. An information system for comprehensive management of TBM tunneling

To enhance the construction quality of TBM tunneling, improve project management, and ensure safe construction, it is essential to take full advantage of the technical support that is now available from informatization and intellectualization in modern construction.

The principles of decentralized collection, multi-level integration, on-demand sharing, and hierarchical release were adopted in the establishment of a cloud platform; this platform was used to share information about the management of TBM tunneling.

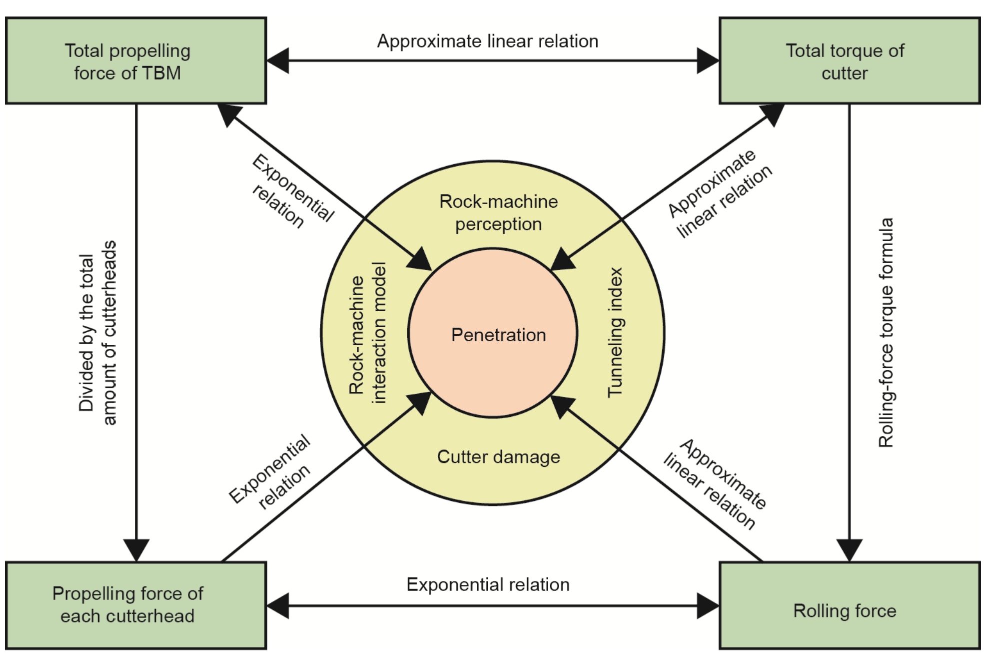

Fig. 6. Diagram of the relations between major tunneling indexes†. †Data was provided by professorate senior engineers Jianbin Li and Liujie Jing.

The same principles were also applied to integrate all the information about the whole project. Using cloud computing and big data technology, the project owner, designer, supervisor, contractor, equipment producer, advisory organization, and other parties were all able to obtain construction information in a timely, systematic, and safe manner. In this way, it was possible to meet the requirements of progress tracking, equipment maintenance, quality management, and risk control.

The platform consists of a monitoring-and-command center, five sub-centers, and nine functional systems (Fig. 7). It enables real-time online monitoring, resource allocation, the issuing of instructions, decision-making, and emergency rescue; in addition, it is linked to the TBM manufacturers' big data center, so that information sharing, fault diagnosis, and online consultation can be achieved. The five sub-centers are responsible for collecting all kinds of monitoring information under the jurisdiction of the project. Through rock-machine perception and information fusion, the sub-centers can instruct efficient and scientific onsite construction. Project participants with user authorization can remotely access the cloud information from the data center, with the help of computers, mobile phones, and other terminals. The goal of building a systematic management and decision-making information platform is to set up a data-sharing mechanism, break down information barriers, and achieve data sharing. This is convenient for big data mining and will promote development and technological progress in the TBM industry. Considering the confidentiality of the project, related technicians should work on network classification and isolation control, in order to ensure system and data security.

4.4. Establishing a risk-control integrated technical support system

Safety, high efficiency, and intelligent tunneling are the general objectives of super-long tunnel construction. Through a strict management mechanism and scientific technical measures, we established a construction technical support system. On the one hand, in light of construction difficulties and major risk sources, it is

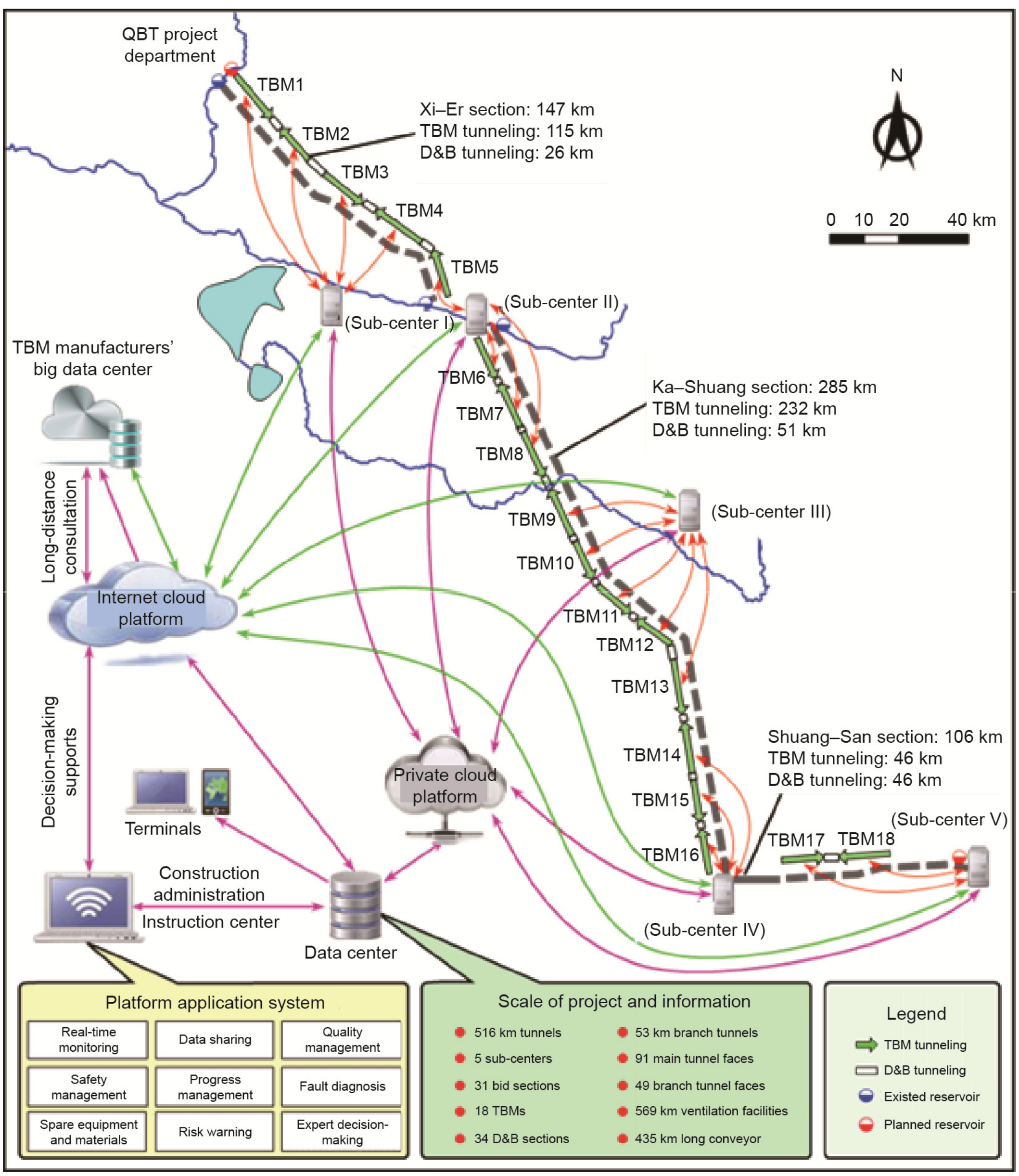

Fig. 7. An information system for management and decision-making for the TBM tunneling of a super-long tunnel.

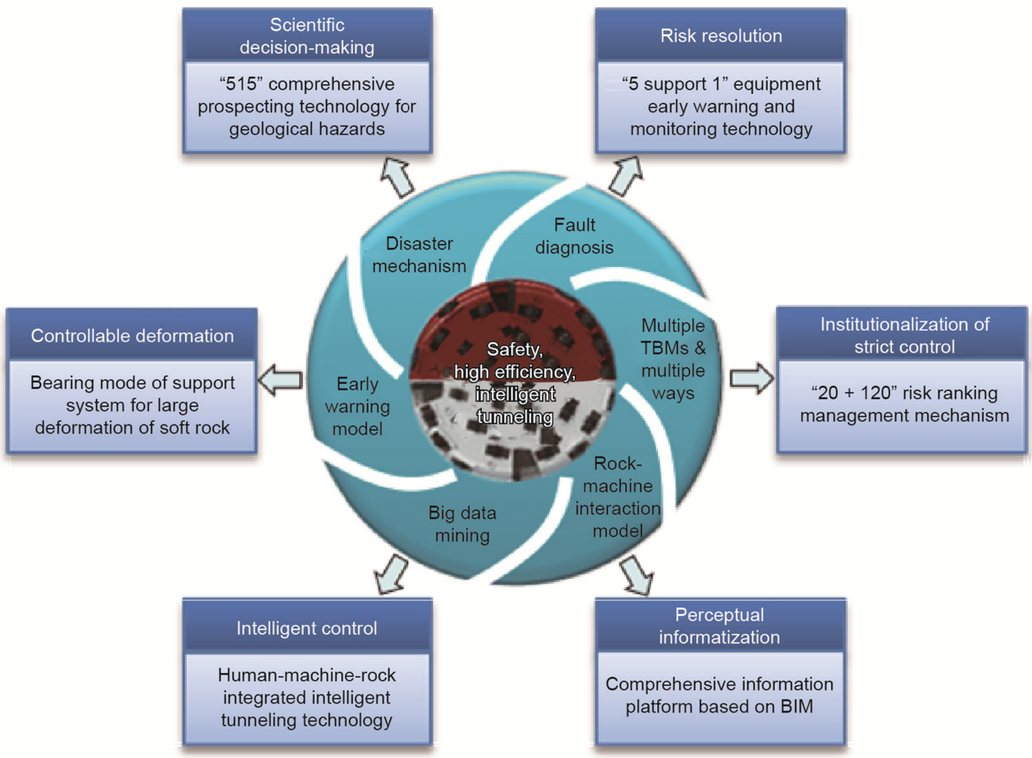

Fig. 8. The six-property comprehensive technical support system for the risk control of the TBM cluster construction of a super-long tunnel.

necessary to establish a strict risk-control mechanism in order to decrease the construction risks; this would include the classification of different categories, levels, and duties. On the other hand, it is desirable to take full advantage of advanced geological prospecting techniques, soft rock large-deformation control-and-support techniques, TBM intelligent-sensing tunneling techniques, and the building information modeling (BIM) cloud platform technique to set up sound technological support and to scientifically avoid risks. The result of the coupling between the management mechanism and the technical measures was a six-property comprehensive technical support system for the risk control of the TBM cluster construction of a super-long tunnel (Fig. 8). These six properties are: institutionalization of strict control, risk resolution, scientific decision-making, controllable deformation, intelligent control, and perceptual informatization.

5. Conclusions

The conclusions of this study are as follows:

(1) The construction of a super-long water-conveyance tunnel involves many aspects, such as geological disaster control and response, equipment operation and maintenance, construction safety, quality assurance, investment control, and environmental protection. Based on the general principles of responsibility separation, incident grading, and classification control, establishing a scientific and effective risk-control mechanism is key in controlling risk and organizing construction.

(2) China has made remarkable progress in the development and application of advanced geological prospecting technology, which has provided a good technical means for risk prevention and control. However, for super-long tunnel construction, it is still necessary to combine geological surveys, advanced forecasting, and rock perception in order to establish a comprehensive geological prospecting system that is suitable for TBM tunneling, and to thereby realize safe and efficient construction. For major geological disasters, a TBM geological prospecting system was established that could achieve real-time tracking and detection; if necessary, advanced geological drilling can verify geological situations and help to establish an emergency response plan.

(3) China has achieved a major breakthrough in the domestic manufacturing technology of TBM equipment; however, due to the characteristics of this project, the risks of TBM manufacturing, operation, and maintenance were still very high. Therefore, continuous research and innovation must be carried out, with particular attention to the research and development of complete sets of equipment and application servicing, in order to enhance the adaptability, durability, and reliability of key components, and to ensure fast, durable, and efficient excavation of super-long tunnels.

(4) Based on technologies such as informatization, the Internet of Things, and big data, rock-machine perception and information interaction can be improved, an evaluation system for operating status and tunneling adaptability can be established, and intelligent control software can developed in order to install a "brain" in the TBMs. This will enable the construction of informatization and intelligentization, which are important measures in moving the risk control of super-long tunnel construction into a new phase.

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