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SUPER ENGINEERING

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"Heavenly Road": The Qinghai–Tibet Railway

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1 Project profile

The Qinghai–Tibet Railway (Fig. 1), which extends from Golmud to Lhasa, has a total length of 1142 km. A 960 km section of its total length is over 4000 m above sea level, and the highest point on Tanggula Mountains is 5072 m above sea level. This railway is known as the "Heavenly Road" and the highest and longest highland railway in the world. The project began on June 29, 2001, and the railway operated on July 1, 2006, with a total investment of 33.09 billion yuan. The frail ecology environment with severe high-altitude anoxia and widespread permafrost was the primary challenge to the construction of the Qinghai–Tibet Railway. A vast number of railway construction personnel achieved technological breakthroughs and innovations. In 2008, the Qinghai–Tibet Railway project won the National Science & Technology Progress Award (special).

2 Innovation and management of Qinghai–Tibet Railway project

2.1 Key construction technologies for Qinghai–Tibet Railway project in the permafrost region

The Qinghai–Tibet Railway runs from the northern foot of Kunlun Mountains to the southern foot of Tanggula Mountains, where a permafrost region of about 550 km, patchy permafrost, deep seasonal frozen grounds, marshy wetlands, and slope wetlands are well developed. The permafrost on the Qinghai–Tibet Plateau at middle-low latitude is mainly characterized by large proportions of ground ice and high-ice-content permafrost, poor permafrost thermal stability, high sensitivity to climate changes, and obvious aspect effects of solar radiation. On the basis of research achievements, practical experiences, and construction lessons at home and abroad, the Qinghai–Tibet Railway adopts the design idea of "actively cooling subsoil and protecting permafrost" by overcoming the constraints of traditional concepts and making full use of natural cold energy to protect permafrost. This design idea has shifted the analysis of the permafrost environment from static to dynamic, the permafrost protection from passive insulation to active cooling, and the permafrost treatment from a single measure to a combination of measures, thereby achieving comprehensive control and maintenance of the subsoil's stable state.

Railway route selection must avoid permafrost areas with complex geological conditions as much as possible, and a railway should run through areas of land with dry surfaces and relatively high elevations to prioritize embankment-based sub-grade by digging more but filling less. The sub-grade structure and material are changed to regulate solar radiation, air convection, and heat transfer or to exercise comprehensive regulation and achieve cooling of the permafrost under the railway. Five engineering test sections were built in accordance with different permafrost characteristics and engineering measures before the full-scale construction of the railway. Through the test sections, the characteristics of ground temperature changes in the permafrost district were further mastered, the application effects of permafrost engineering measures were inspected, different structural forms of permafrost conditions and sub-grades, bridges, culverts, and tunnels were determined, and a reasonable construction process was achieved.

The permafrost sub-grades use many air-cooled riprap embankments (or rubble slopes) and thermal conductive rods (Figs. 2 and 3). The air-cooled riprap embankment (Fig. 4) is a rubble layer with a certain thickness (~1.5 m) and porosity (block diameter of approximately 0.2–0.4 m) above the sub-grade cushion. Under the natural condition that air temperature changes periodically, the rubble layer acts as a thermal semiconductor that cools the subsoil under the rubble layer. The action mechanism of the rubble slope (1.6 m sunny slope and 0.8 m shady slope) is similar

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Fig. 1 Qinghai–Tibet Railway.

Fig. 2 Sub-grade with thermal conductive rods.

Fig. 3 Sub-grade with rubble slopes.

to that mentioned above. The thermal conductive rods belong to a system that uses two-phase conversion (gas–liquid) of the medium inside seamless steel tubes, relies on the temperature difference between the buried part (condenser) and the part exposed to the atmosphere (evaporator), and achieves heat transfer via convective circulation. The thermal conductive rods (length of 12 m and diameter of 83 mm) are arranged at a spacing of 1.3–1.5 m to reduce the subsoil temperature. Vent pipes, sunshades, or thermal insulation materials are used in several areas, and viaducts are designed at particularly complex locations. The foundations of bridges and culverts are mainly composed of bored piles. The tunnel lining has waterproof and insulation layers. The permafrost observation system designed for the Qinghai–Tibet Railway has shown that the sub-grade deformation of the railway is controllable (an annual average settlement < 2 cm), and all bridges and tunnels are structurally stable. Hence, safe train operations are ensured. All Chinese and foreign experts who attended the Sixth International Symposium on Permafrost Engineering agreed that the Qinghai–Tibet Railway successfully uses key technologies for road construction in the permafrost region and reflects the international advanced level of permafrost technology.

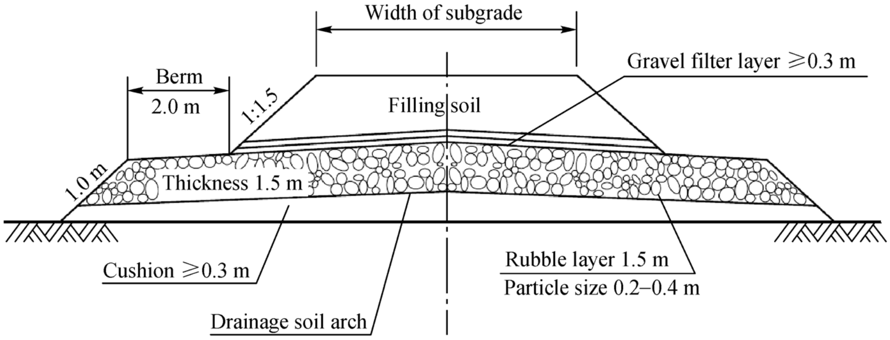

Fig. 4 Cross section of the air-cooled riprap embankment.

2.2 Environmental innovation and management of Qinghai–Tibet Railway

The Qinghai–Tibet Plateau is the only unique ecological environment system in the world and an important origin and differentiation center of mountain biological species. The construction of the Qinghai–Tibet Railway adopts the concept of sustainable development and emphasizes that relevant national environmental protection standards must be implemented throughout the entire project period. In particular, protecting the environment through laws, implementing national environmental laws and regulations, completing an environmental impact assessment, and applying all environmental protection measures at all levels are vital. In addition, the environmental awareness of all workers should be enhanced, construction workers should consciously protect the ecology, and environmental management systems must be reformed. Moreover, the environmental management system that is led, designed, constructed, and established by the owner should be improved, and new environmental engineering technologies, such as alpine vegetation restoration and reconstruction, water pollution prevention for rivers and lakes, and passage for wild animals, should be developed. The construction protects the plateau permafrost environment, wetlands, natural landscape, and wildlife. Drawing from the successful experiences of "environment-friendly railway construction based on advanced technologies", this project has become a typical representative of national key environmental protection projects (Fig. 5). In 2006, the Qinghai–Tibet Railway won the China Environmental Protection Award.

Fig. 5 Completed sub-grade at the south foot of Tanggula Mountains (green corridor).

2.3 Health guarantee for construction

To ensure the safety and health of construction personnel, the construction of the railway adopted the idea of humanism, adhered to the policy of "putting safety first and giving priority to prevention", and established a complete health guarantee system and a perfect epidemic prevention mechanism. Medical examination-based admission, step-by-step acclimatization, and labor protection have been established for construction workers entering the plateau. Site medical institutions have been set up to strengthen healthcare management, and new ideas and measures for treating high-altitude sickness have been explored. In the Fenghuoshan Tunnel with an altitude of 4900 km, a large oxygen plant with a capacity of 24 m^3 pure oxygen per hour was successfully developed. The plant provides a diffusion-type oxygen supply for the tunnel, improves the operating environment, increases the tunnel's working efficiency by more than 1.5 times, and reduces the number of outpatients by 44% and the incidence of acute altitude sickness by 90%. The entire line has 17 large oxygen plants and 25 high-pressure oxygen chambers, which have yielded good results. During the five-year construction period, 530000 patients, including 470 cases with high altitude cerebral edema and 931 cases with encephaledema, were recorded. All patients were treated effectively, with "zero death" from high-altitude sickness and "zero transmission" of human plague. Experts who attended the Sixth International Conference on High Altitude Medicine praised the construction profusely after a field investigation and pointed out that the construction provides successful health protection in long-term large-group construction at high altitudes. They recognized its great contribution to the world's plateau medicine.

In addition to overcoming the three problems mentioned above, the Qinghai–Tibet Railway has also obtained many technical innovations. In terms of earthquake resistance and prevention, the distribution characteristics of high-seismic-intensity areas and seismic active faults along the route have been ascertained. In addition, proper measures have been taken to pass through a fault zone with a low embankment and a large angle and to adopt a simply supported beam structure with reinforced concrete bridge piers and collapse-proof systems when building a bridge. For concrete durability, DZ concrete admixtures that strictly meet the requirements of durability have been developed. With regard to sandstorms, a gale warning system has been introduced, and measures for fixing sand and blocking wind have been taken according to local conditions. Moreover, the plateau power supply, wireless communication, and centralized traffic control (CTC) have been addressed. The railway is the first to provide an oxygen supply system for passenger trains. All of these features lay a solid foundation for all-line operations.

The innovation of the Qinghai–Tibet Railway primarily includes the project legal person responsibility system implemented for public welfare projects to ensure a scientific, standardized, efficient project management, fully consider transportation needs, and prepare for operation. The project is the first to propose a complete project management theory system. Guided by an advanced construction idea, the project follows the basic rules of construction, adopts the correct organizational structure, strengthens the support and support system (including contracts, resources, information, innovation, risk, and cultural management), establishes effective operation mechanisms (e.g., decision making, coordination, performance evaluation, incentives, and constraints), and ensures that the project's targets (e.g., quality, safety, environmental protection, duration, and investment) are fully realized. The project management experience of Qinghai–Tibet Railway has been widely promoted in railway construction in China and has played an important role in improving the construction management of railway engineering.

3 Conclusions

The completion and operation of Qinghai–Tibet Railway ended Tibet's no-access history and fulfilled the long-cherished wish of all ethnic groups. The merits of the railway have been verified by engineering practitioners. The railway continues to demonstrate excellent performance and safe operation, even with the passenger–cargo traffic increasing significantly. This railway accounts for 78.6% of inbound and outbound freight traffic and 34.4% of passenger volume, thus becoming the main mode of comprehensive transport in Tibet. The Qinghai–Tibet Railway is called the "Happy Road" by all ethnic groups due to its remarkable comprehensive benefits that include economic, social, and environmental merits. The railway has considerably contributed to the economic and social development of Tibet and Qinghai and played an exemplary role in the construction of major projects.