China starts the world's hardest "Sky-High Road" project: Challenges and countermeasures for Sichuan-Tibet railway

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In China, a new "epic project" named the Sichuan-Tibet railway linking Chengdu and Lhasa is in the construction phase. This 1,592-km-long railway passes through the western Sichuan basin, subsequently climbing 5,000 m and running across the "roof of the world" Tibet plateau, which is dubbed the "Sky-High Road" (Figure 1).[1] Over the past decades, the region along the Sichuan-Tibet railway was recognized as the "forbidden zone" for railway projects, resulting from the world's

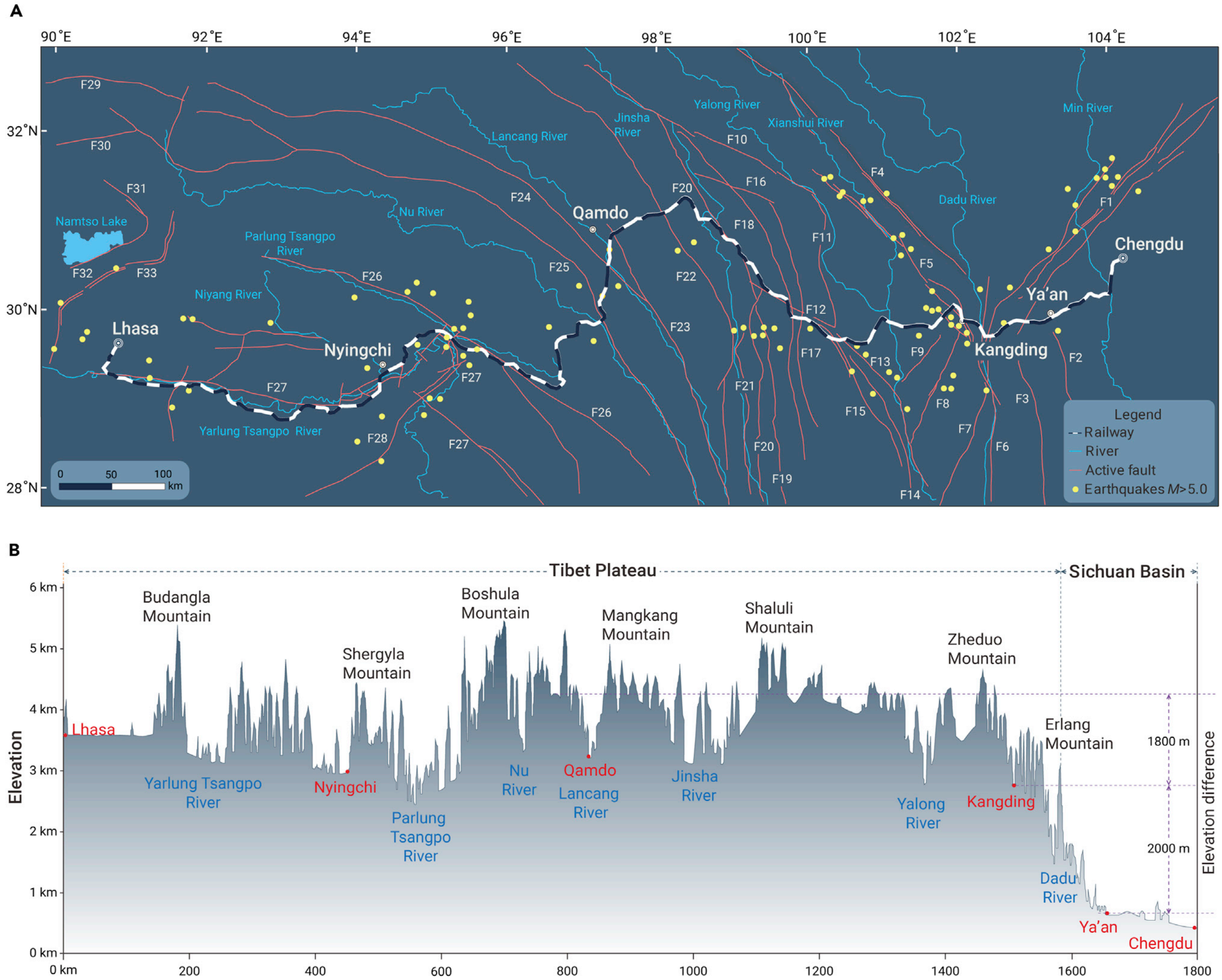

Figure 1. Diagrammatic maps related to the Sichuan-Tibet railway in China (A) Sichuan-Tibet railway and its adjacent active faults. The names of active faults are listed as follows: F1, Longmenshan fault zone; F2, Ebian fault; F3, Ganluo-Zhuhe fault; F4, Huarongshan fault; F5, Xianshuihe fault zone; F6, Anninghe fault; F7, Xiaojinhe fault; F8, Yunongxi fault; F9, Shade fault; F10, Ganzi-Yushu fault zone; F11, Ganzi-Litang fault zone; F12, Litang-Yidun fault; F13, Mula fault; F14, Chazhong fault; F15, Litang-Dewu fault; F16, Maisu fault; F17, Zengke-Shuoqu fault; F18, Dege-Xiangcheng fault; F19, Dingquhe fault; F20, Jinsha River fault zone; F21, Batang fault; F22, Zigasi-Deqin fault; F23, Lancang River fault zone; F24, Baqing-Leiniaoqi fault; F25, Nu River fault zone; F26, Jiali-Chayu fault; F27, Yarlung Tsangpo River fault zone; F28, Maniweng fault; F29, Anduo-Sewa fault; F30, Dongqiao fault; F31, Bengcuo fault; F32, Namucuo fault; F33, Yadong-Gulu fault. (B) Topography along the Sichuan-Tibet railway.[1–3]

most remarkable topographic relief, the most active tectonic movement, the most numerous mountain hazards, and the most vulnerable ecological environment.[2,4] This unprecedented railway program is thus acknowledged as the world's toughest problem—technically, economically, and environmentally.

High altitude and great topography relief

From Ya'an to Lhasa, the average altitude along the Sichuan-Tibet railway remains at 3,800 m, while the elevation differences range from 2,000 to 5,000 m (Figure 1B).[4] The high altitude is accompanied by plateau hypoxia and extreme climate. The great variation in topographic relief results in inconvenient transportation and weak electricity/communication infrastructures. These extreme conditions, indeed, impose enormous challenges for railway construction and maintenance.

Given the wide disparity in topography relief, more than 70% of the railway is composed of tunnels with great depth (>1,000 m), widely affected by the problems of high geostress and high geotemperatures.[1,4] Specifically, the high geostress results in frequent and severe rockburst hazards in tunnels, threatening the safety of construction personnel and equipment.[1] Moreover, the high temperature exerts a severe threat to workers' health and machines operating in the tunnel.

Numerous active faults and intensive earthquakes

Because the Indian plate collided with the Eurasian plate about 50 million years ago, the Tibet plateau has suffered from the world's most active tectonic movement. Hence, numerous active faults are widespread over the regions covering the Sichuan-Tibet railway (Figure 1A). Most of the active faults are characterized by a large motion rate and frequent seismicity. One notable example is the Xianshuihe fault zone, which slips at a rate of 9–12 mm year^{-1} and has experienced more than 10 earthquakes of $M > 6.5$ over 1,700 years.

The severe challenges for Sichuan-Tibet railway, generated by active faults, are reflected in three main aspects. First, the railway could be dislocated by its intersecting active faults. This dislocation depends not only on the continuous fault creep-slip, but also on the surface rupture caused by earthquakes. Second, a devastating earthquake could destroy the railway structures, including bridges, tunnels, and station buildings because of tremors.

Finally, fault motion could trigger chains of geological hazards. Specifically, fault creep-slip and seismic activities could form and widen cracks on mountain crests or flanks, increasing the frequency of rockfalls, landslides, or debris flows.[5] Landslides could block rivers and cause huge lakes, subsequently collapsing and flooding downstream areas. Previous seismic hazard events imply that the hazard chains will affect the Sichuan-Tibet railway for much longer than the relatively brief quake tremors from earthquakes.

Numerous mountain hazards and increasing hazard chains

Along the Sichuan-Tibet railway, the steep topography and densely fractured lithology arise from interactions among tectonic uplift, valley incision, and fault motion, eventually triggering the world's most numerous mountain hazards. Large-scale mountain hazards are readily encountered along the railway, reflected by 418 rockfalls, 580 landslides, and 1,132 debris flows.[3] Meanwhile, mountain hazards are clustered in a much wider corridor along the active fault.[1] These hazards could destroy the railway, the infrastructures, and the ecosystems, impeding railway operation and probably provoking hazard chains.

Moreover, the increasingly extreme weather increases the frequency of hazard chains along the railway. Climatic warming is promoting glacial ablation and forming many glacier lakes, which could collapse later and generate floods, probably evolving into debris flows. Also, extreme drought can damage the vegetation cover. The exposed rock is sensitive to rainstorms causing more debris flows than would occur normally. Also, extreme rainfall events can trigger rockfalls and landslides. Landslide debris on slopes can be further remobilized by rainfall and generate debris flows.[5]

Complex ecosystem and vulnerable ecological environment

The Sichuan-Tibet railway passes through the Chinese Loess Plateau-Sichuan-Yunnan ecological barrier, the Tibet plateau ecological barrier, the Qionglai mountain biodiversity reserve, and the Gonggashan national natural reserve. Nearly 100 rare plant and animal species live in these areas.[4] The Tibet plateau is the source of many rivers and also plays an important role in regulating the climate of the Northern hemisphere. Thus, the ecosystem is complex, and ecological environment protection is the top priority during railway construction.

Corresponding to the wide-ranging topography relief and extreme weather, rocks on the Tibet plateau can be weathered rapidly, which makes the ecological environment prone to soil erosion, land desertification, and mountain hazards. As such, the ecological environment along the Sichuan-Tibet railway is the most vulnerable in the world and easily affected by socio-economic activity.

More specifically, the construction of the railway by building bridges, excavating tunnels, and cutting off hillslopes may destroy the vegetation, eventually leading to soil erosion and geological hazards. Vegetation recovery is notoriously tricky for biodiverse areas. Also, railway construction may impede the migratory route of wild animals. Thus, the vulnerability of nature will create unprecedented challenges for the preservation of the ecological environment.

Next step for the countermeasures

Regarding the successful construction of the Sichuan-Tibet railway, the National Natural Science Foundation of China, the Ministry of Science and Technology, the Ministry of Ecology and Environment, the Ministry of Natural Resources, the National Development and Reform Commission, and the China State Railway Group first conducted correlated research decades ago and started the Special Funds Project in 2019. Here, several countermeasures are also recommended to transcend some of the existing challenges.

To anticipate the short- or long-term hazard risks, an "aerospace-aeronautics-ground-underground" integrated monitoring and early warning system is required to be built using IoT (Internet of Things) and intelligence artificial technology. Global positioning satellites, remote sensing, unmanned aerial vehicles, ground SAR (Synthetic Aperture Radar), and sensor integration technology will be used for monitoring the precursor information of mountain or underground geological hazards. The gathered data can be subsequently processed through artificial intelligence, where the hazard alert level can be identified. Finally, the hazard forewarning information will be published in real time.

Concurrently, new building materials and structures are required to resist earthquake fault dislocation. The new material can automatically heal the seismic cracks by releasing polymer composites. The new building structures for tunnels, using flexible joints that comprise hyperelastic and self-reset shape memory alloy (SMA) elements, can potentially resist the fault dislocation. Also, the self-reset SMA dampers can expend the impact energy of earthquakes. Moreover, to protect the ecological environment, the rock/soil dreg field should be kept away from rare wildlife habitats and water resource regions. Restoration of vegetation in dreg fields is necessary to prevent soil erosion and secondary geohazards.

Overall, to transcend the existing challenges, new catastrophe theories, materials, and structures will have to be developed; and humankind needs to focus on learning how to realize harmonious intergrowth of nature and railways. All these innovations will promote the scientific and technological development of China and eventually the world.

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