

Article

The Principles and Evaluation of Green Construction of Tunnels in Frigid Plateau Regions

Jing Li ¹, Qingguo Liang ^{1,*} , Tao Zhao ^{1,2}, Haining Li ³, Caigui Zhou ⁴ and Xiaopan Xue ⁴

¹ School of Civil Engineering, Lanzhou Jiaotong University, Lanzhou 730070, China

² School of Urban Railway Engineering, Shaanxi Railway Institute, Weinan 714000, China

³ Yindajihuang Construction and Operation Bureau of Qinghai Province, Xining 810001, China

⁴ Northwest Water Conservancy & Hydropower Engineering Co., Ltd., Xi'an 710100, China

* Correspondence: lqg_39@163.com or liangqingguo@mail.lzjtu.cn

Abstract: Green construction is an advanced concept and development trend in engineering construction. It is cold and arid in frigid plateau regions in western China, where the ecological environment is vulnerable to engineering constructions and other human activities. Hence, the time and cost for environmental remediation are much larger than in other areas. Based on the principles and category of green construction, this paper discusses the overall and partial relationship between green construction and green construction operation, presents the technical construction process of the green construction of a tunnel, and puts forward the key points of green construction with the construction practice for tunnels in frigid plateau regions as the engineering background. The main contents and results are as follows: (1) The breakthrough points of the research on green construction include five first-level evaluation indicators of savings the land, energy, water resources, materials, and human resources, as well as protection for personnel health and environment, i.e., five savings and two protections. A comprehensive evaluation system suitable for green construction is proposed and established. (2) The paper summarizes the following essential aspects: the fine classification and safety evaluation of surrounding rock, the changes in the seepage field in the construction process, and the establishment of a standardized construction system. (3) A green construction evaluation was conducted on the tunnel of the Yindajihuang Project, and the green evaluation results were obtained. The evaluation results are basically consistent with the actual situation. In addition, intelligent construction technology should be the orientation of green construction for tunnels. The research would be helpful to the implementation of green construction ideas and technologies for tunnels in frigid plateau regions and the persistence of green and sustainable development.

Keywords: tunnel; green construction; evaluation system; surrounding rock classification; environmental negative effect evaluation; seepage characteristic



Citation: Li, J.; Liang, Q.; Zhao, T.; Li, H.; Zhou, C.; Xue, X. The Principles and Evaluation of Green Construction of Tunnels in Frigid Plateau Regions. *Sustainability* **2023**, *15*, 15153. <https://doi.org/10.3390/su152015153>

Academic Editor: Antonio Caggiano

Received: 12 September 2023

Revised: 12 October 2023

Accepted: 13 October 2023

Published: 23 October 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Green construction is defined as “Following the requirements of green development, through scientific management and technological innovation, construction methods that are conducive to saving resources, protecting the environment, reducing emissions, improving efficiency and ensuring quality are used to achieve engineering construction activities in which humans and nature coexist in harmony”, which is specified in the Green Construction Technical Guideline (For trial Implementation) issued by the Ministry of Housing and Urban-Rural Development of the People’s Republic of China in 2021. In recent decades, the vigorous advancement of China’s infrastructure construction has inevitably caused severe energy consumption and environmental damage. In 2021, 56% of the total Chinese energy consumption came from coal, while non-fossil energy consumption only accounted for 16.6% [1]. In 2019, China’s CO₂ emissions were 9.826 billion tons, ranking first globally [2]. Therefore, China has adopted many policies, measures, and actions to promote green and

sustainable development to reduce energy consumption and carbon emissions. At the same time, green construction is also developing rapidly in China [3].

In recent years, many experts and scholars have researched green construction. Xiao and Feng [4,5] proposed green construction technology's concept and development direction in building engineering. Sun et al. [6] proposed a new understanding of green status, mechanisms, and culture based on the connotations of green railway engineering. You et al. [7–9] systematically explained the concept of green construction of urban integrated pipe corridors, effective ways of realization, construction experience, suggestions and problems, and future development trends. Rooshdi et al. [10] established an evaluation model for green highways in the design and construction activities category. You [11] also put forward the concept and implementation method of green construction in shield tunnel engineering. Zhang [12] constructed a green evaluation system for high-speed railways. Jiang et al. [13] clarified the concept of the green tunnel and its "human-oriented" connotations. Luo et al. [14] pointed out that the existing research on green building pays more attention to the operation stage, resulting in a lack of the necessary knowledge and tools to control the environmental impact at the construction stage. Shi et al. [3] revealed through a questionnaire survey that the three most critical barriers associated with green construction are "additional cost", "incremental time" and "limited availability of green suppliers and information". Qiu et al. [15] established a sustainable evaluation indicator system for railway tunnels in China. García-Trenas et al. [16] analyzed how changes in the vegetation of the portal gate surrounding an Alpine environment can contribute to saving energy from lighting installation. Lehner and Hrabova [17] evaluated concrete to determine which mixtures exhibit better sustainability parameters. Chi et al. [18] found much room for enhancement in construction technology, which can guarantee better structural waste minimization performance. Li et al. [19] introduced green technical methods of tunnel-muck reduction design and resource utilization. Barla and Insana [20] proposed an energy tunnel to reduce carbon dioxide emissions. Phillips [21] applied an established mathematical model of sustainability to determine the sustainability of a tunnel. De La Fuente et al. [22] developed a method for analyzing the sustainability of different concrete and reinforcement configurations for segmental linings of TBM tunnels. Hrabova et al. [23] used the sustainability approach to concrete mix assessment via the sustainability-potential indicator. In addition, green construction technology is applied to many engineering fields, such as underground railways [24], water supply construction [25], and the metallurgical industry [26].

With the rapid development of transportation and water conservancy in China, a large number of tunnels have been and will be constructed. The construction of such large-scale tunnels will cause serious resource consumption [27] and environmental problems [28,29]. Against the policy background of vigorously promoting the construction of ecological civilization and a "Western Development" strategy, making the construction of tunnels and the ecological environment develop harmoniously through advocating green construction is an inevitable way to implement sustainable development strategies.

Although many studies on green construction have been carried out, there are few studies on green construction for tunnels, especially in frigid plateau regions. The climate in frigid plateau regions is harsh, and the ecological environment is fragile, so green construction should be actively practiced. Therefore, in combination with the regional characteristics of "high altitude, cold and drought" in western China, the concept of green construction of a tunnel and its technology are proposed. Furthermore, a comprehensive evaluation system of "Five savings and Two protections" (energy-saving, material-saving, water-saving, land-saving, human resources-saving, environmental protection and personnel protection) suitable for the green construction of a tunnel in the western frigid plateau region has been constructed, and the corresponding secondary evaluation indicators have been presented. This system can compensate for the deficiencies of most existing studies, which have only carried out a green evaluation from the perspectives of soil and water conservation and environmental impact. This paper evaluates the green construction of the tunnel in the

Yindajihuang Project and proposes the development orientation of future green construction technology. This work might greatly benefit the smooth implementation of green construction of tunnels in frigid plateau regions and related tunnel projects. In addition, this work would provide helpful ideas and solutions for the sustainable development of green strategies for tunnel construction and social and economic development.

2. Green Construction

2.1. Concept and Connotation of Green Construction

Green construction takes sustainable development as the starting point and applies the green concept to the overall project construction cycle. According to the construction process, the whole life cycle of “green construction” can be divided into five phases: planning, design, construction, operation and maintenance, and demolition [30], and the first three phases are called green construction. Green construction operation is the core content of green construction. The revised relationship between “green construction” and “green construction operation” is shown in Figure 1.

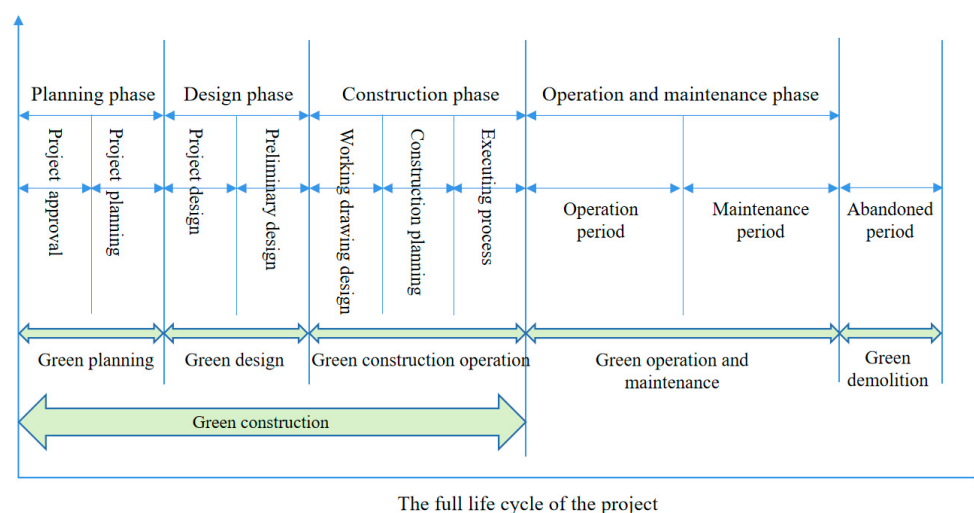


Figure 1. The concept and relationship of green construction and green construction operation (after: [5,7,30]).

Under the premise of ensuring project quality and safety, the green construction of tunnels considers the whole life cycle itself, persists in the concept of sustainable development, and focuses on the three aspects of “green planning, green design, green construction operation”. At the same time, based on scientific and technological advancement and innovations at the management level, green construction saves resources and protects the environment as much as possible. In order to realize the basic concept of “environment-friendly, resources-saving, process-safety, and quality-assurance” [5], the green construction of tunnels should be based on the “Four savings and One protection” (energy-saving, material-saving, water-saving, land-saving, and environmental protection) in the engineering construction process. If we add human resources saving and personnel protection, we ultimately form “Five savings and Two protections”.

Taking engineering safety and quality assurance as guides, the green construction of tunnels focuses on environmental protection and resource conservation. The resource conservation element of the green construction concept is based on the premise of environmental protection, which is different from the simple cost-saving and high economic benefits of the traditional pattern. Based on realizing the integrated development of planning, design, construction, and operation and maintenance, the proposal of the new concept of green construction will play a driving role in changing the traditional construction mode, improving the construction quality of tunnels, and enhancing green awareness in engineering. Green construction will be an effective way to improve management, promote

technological innovation, reduce production costs, and achieve cost control, which can also reduce environmental and legal risks and improve industry competitiveness.

2.2. Green Construction Technology for Tunneling

The implementation of green construction technology has a very significant effect on resource conservation. For example, muck disposal is an inevitable requirement during the tunnel excavation process. In China, single-track tunnels generate approximately 70,000 m³ of tunnel muck per kilometer, while double-track tunnels generate approximately 200,000 m³ of tunnel slag per kilometer [19]. The total cost of maintaining the waste disposal site in the later stage is CNY 40–50/m³. In the green construction technology of tunnels, tunnel muck can be used as a material source for machine-made sand, saving energy and resource consumption. From the literature [31], it can be seen that the Hehua Tunnel is a single-track tunnel, with approximately 39,300 m³ of tunnel slag per kilometer (with a density of 2.5 t/m³) used as a machine-made sand material source, with a utilization rate of about 56%, saving a lot of energy and resource consumption. It can be seen that green construction technology for tunnels can efficiently save resources and achieve the concept of green construction.

According to the current practice in the construction stage of tunnels in China, the construction procedures are mainly classified into six parts: portal engineering; excavation and support of the main tunnel; ventilation and muck disposal; temporary support; lining engineering; and auxiliary engineering. The types of impact of each construction stage, and the process on green construction are preliminarily defined, and the representative and targeted influence factors on the green construction of tunnels can be summarized, as shown in Figure 2.

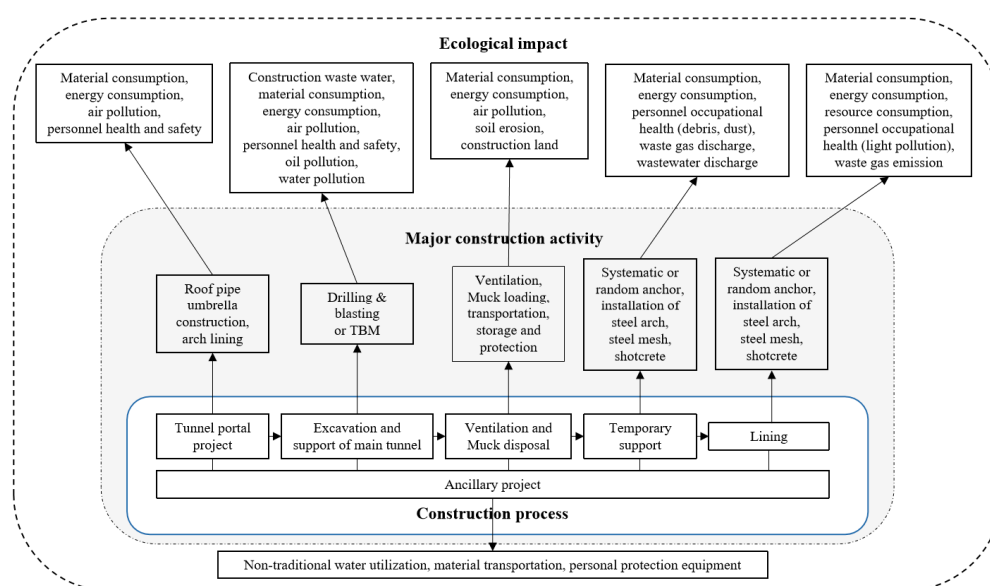


Figure 2. Influencing factors of green construction for tunnels.

Considering the particular characteristics of “high altitude, cold, drought” of the area, the frigid plateau tunnel project adopts a non-excavation slope for tunneling. It uses the roof pipe umbrella method after cleaning up the perilous rock. Based on the on-site investigation research on the implementation of green construction, the proper excavation method is selected according to the geological conditions after finishing the portal section. After blasting and ventilation, the ballast is loaded and transported, and the initial support is implemented to complete a cycle. After the tunnel excavation is completed, the secondary lining of the tunnel is cast. Considering the preparation, construction, and operation and maintenance phases, the tunnel’s technical procedures for green construction are summarized, as shown in Figure 3.

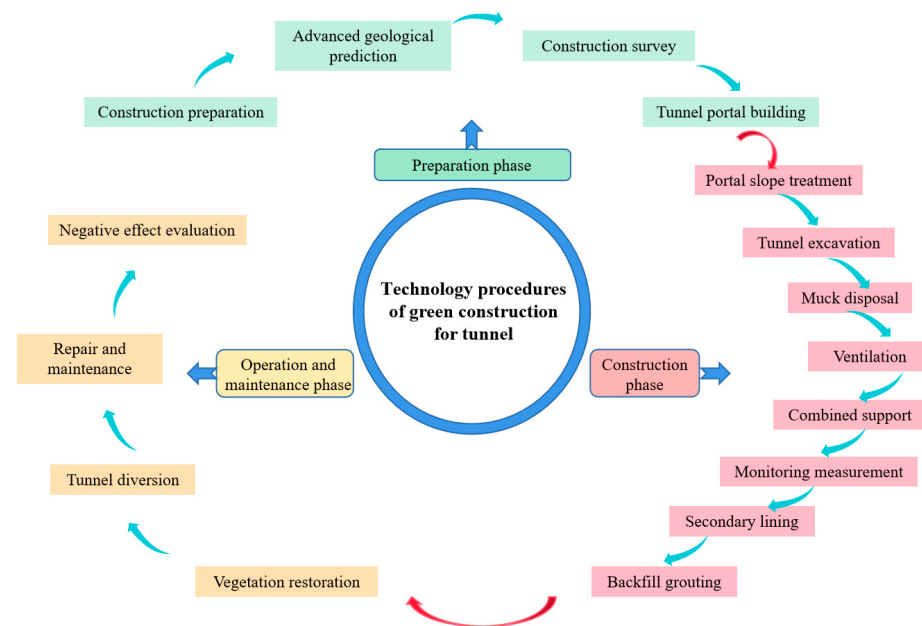


Figure 3. Technological procedures of green construction for tunnels.

Based on the tunnel's green construction technology process, the critical construction concerns regarding the drilling and blasting method widely used in China are listed in Table 1.

Table 1. The key construction concerns regarding the drilling and blasting method.

SN	Construction Stage	Method or Countermeasures	Goals	Five Savings or Two Protections
1	Pre-excavation	Using the comprehensive geological forecast to optimize the pre-support and excavation parameters	Improve the efficiency of the excavation, slow the loss, and extend the service life of construction machinery Reduce the overbreak in excavation, reduce the consumption of explosives, detonators, and other blasting materials, improve the blasting and crushing effect and loading and transportation efficiency	Energy, Personal health and safety
2	Tunnel excavation	Improving the drilling techniques and parameters		Energy, Material, Personal health and safety
3	Ventilation	Selecting the ventilation fan and supporting air duct that are conducive to energy saving and environmental protection	Establish a ventilation system that meets the health requirements of the construction environment	Energy, Personal health and safety, Environmental protection
4	Monitoring measurement	Based on the integrated information platform, carrying out research on the accurate and rational management of labor, machinery, and equipment, updating and analyzing critical data such as labor, machinery and equipment, various resources, materials, and construction quality in real-time	Realize dynamic monitoring and optimization of mechanized construction and refined management	Energy, Personal health and safety, Human resource, Land resource, Material, Water resource
5	Negative effect evaluation	Strengthening the construction management and safety supervision, optimizing construction organization, management, and design, improving the emission detection and disposal of three wastes (wastewater, waste gases, and residues)	Reduce environmental pollution and ecological disturbance, evaluate the negative effects on the ecological environment	Environmental protection

2.3. Key Points of Green Construction for Tunnels

Considering the unique climate characteristics, natural resources, and environmental conditions, the critical points of green construction techniques for tunnels are summarized as follows.

2.3.1. Refined Classification and Safety Evaluation of Surrounding Rock

Most of China's western region has apparent environmental and geographical features of high cold and high altitude. The traditional construction method and organized management technology in the plains area no longer apply to western China. At the same time, the low-temperature environment will also affect the quality of concrete construction and the safety and stability of tunnels. Therefore, through research before and during tunnel construction, such as stability analysis of surrounding rock, fine classification of layered rock mass, optimization of supporting structure parameters, construction information feedback, disaster prediction, early warning and prevention, and lining load characteristics during operation, it is possible to develop the technology for safe tunnel construction in high altitude and cold regions. These research findings and technologies can compensate for the relative lag in green construction and safe construction technology in this field.

In tunnel engineering, classifying the surrounding rock is the main task of theoretical research and the preliminary survey and design stage. There are more than 200 classification methods for surrounding rock, and the classification methods and standards are also different [32–36].

For railway tunnels, highway tunnels, and large caverns (groups) in hydropower projects, the span or equivalent radius is mainly between a few and tens of meters. In the surrounding layered rock, massive rock with a thickness of more than 1 m is rare in practice. Its integrity is outstanding, so the continuum theory can be used for calculation and analysis. The consideration of geological structure is limited to significant discontinuities or faults. Therefore, whether the thickness and occurrence of surrounding rock are considered in the existing codes has minimal influence on the surrounding rock's classification and stability analysis results. The different layer thicknesses and dip angles will significantly influence the classification results of surrounding rock, especially the stability analysis results, so it is vital to improve the surrounding rock classification.

The layered strata are widely distributed in the area through which the tunnel project crosses. The difference between the layered rock mass and other rock masses lies in defect media such as strata and joints. Moreover, the deformation and strength of the layered rock mass are anisotropic, and the failure mechanism is also different. Studying the refined classification method and stability of the surrounding rock of a layered rock hydraulic tunnel is of great value. However, the current surrounding rock classification method needs to be more accurate for the surrounding rock classification of complex geological bodies. Therefore, based on the national standard BQ classification method in China, the hardness of the rock and the integrity of the rock mass are adopted as the main controlling factors. Groundwater, the attitude of the weak structural plane, and the initial stress state are the influencing factors. The three influencing factors surrounding rock classification modification coefficients are refined and supplemented.

The mechanical correction of a weak structural plane and rock mass expansion correction are considered for the layered rock mass with a weak structural plane. The refined classification equation of surrounding rock for layered rock mass in a tunnel is given through the comparative analysis of curve fitting and residual verification, as shown in Equation (1) [37], which can provide more accurate and precise classification suggestions for surrounding rock for similar projects.

$$[BQ]SM = BQSM - 100(K'_1 + K'_2 + K'_3) - 50(K_4 + K_5) \quad (1)$$

where $BQSM = 100 + 3R_C + 250K_v$; K'_1 is the groundwater correction factor; K'_2 is the influence correction factor of the attitude of the weak structural plane; K'_3 is the influence

correction factor of the initial stress state; K_4 is the mechanical correction coefficient of a weak structural plane; K_5 is the swelling factor of rock mass; R_C is the uniaxial compressive strength of rock; K_v is the integrity factor of the rock mass. Therefore, the optimization and comparison of tunnel construction methods and support technology, parameter optimization design of tunnel support structure, the optimization of the tunnel support structure, support timing considering the thickness of layered rock mass, and the occurrence factors of weak layered rock mass of tunnels should be further studied. It is of great scientific significance and practical value to use the range analysis method to find the optimal combination scheme of the excavation and support mode of the tunnel by the orthogonal tests considering the excavation length, the thickness of the primary lining, steel arch spacing, and pre-reinforcement measures.

2.3.2. Changes in Seepage Field Caused by Tunnel Construction

During the tunnel construction period, the groundwater leaks towards the excavation surface under water pressure, resulting in a decrease in groundwater level and the loss of water resources [38,39]. Furthermore, the original equilibrium state of the groundwater is destroyed. In the more severe cases, it will cause substantial ecological and environmental damage around the tunnel area. The direction of the seepage flow of the groundwater along the tunnel is illustrated in Figure 4. Liu et al. [40] analyzed the negative effect of the groundwater environment on the drainage of the Gele Mountain Tunnel. They found that tunnel construction would cause problems such as groundwater level drop and collapse in the tunnel site area. Vincenzi et al. [41] analyzed the negative environmental effects of tunnel construction in Italy. They believed that the depletion and drainage of surface water and spring water in the tunnel construction route resulted in massive damage to the ecological environment of the tunnel site. Moreover, the destruction of the groundwater environment is the main factor that causes many geological and environmental problems. Therefore, the study of the seepage field variation caused by tunnel construction under different geological conditions can provide a certain reference for solving ecological and environmental problems.

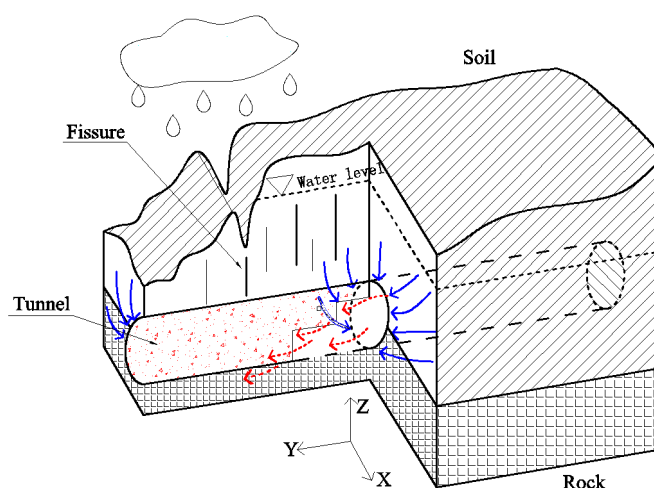


Figure 4. Schematic diagram of groundwater seepage caused by tunnel excavation.

Therefore, the tunnel seepage prediction model, including the groundwater supply provided by rainfall during the construction and operation periods, can be established to predict the seepage and evaluate the impact on the environment at different stages. Calculating the safe drainage of vegetation growth and the volume of the groundwater draining funnel determines the maximum allowable discharge of groundwater, and the evaluation results are quantified. It is a crucial scientific issue and of great importance in practice to put forward the technical guidelines for the green construction of the tunnel, such as evaluation

of the influence on the seepage field of surrounding rock, evaluation of environmental impact and negative effects, monitoring and prediction of the surrounding rock drainage, and investigation and assessment of mountain vegetation and environmental impact.

The environmental load evaluation of a tunnel project should involve its whole life cycle, so it is necessary to evaluate the influencing factors of environmental load in each life cycle stage. The main environmental factors of tunnel projects include air pollution, water pollution, land pollution, solid waste, radioactive pollution, noise pollution, and energy consumption. According to the model of environmental factors in the construction stage, 17 evaluation indicators are selected to construct the tunnel groundwater negative effect evaluation system by screening and optimizing using the Delphi method, among which ten quantitative indicators and seven qualitative indicators are shown in Figure 5. Based on the current research results on the evaluation grade of the negative effect of groundwater [42,43], the classification standard of each evaluation index is determined, which can be divided into five effect grades, namely $S = \{s_1, s_2, \dots, s_5\}$, corresponding to very weak (I), weak (II), moderate (III), strong (IV), very strong (V), respectively.

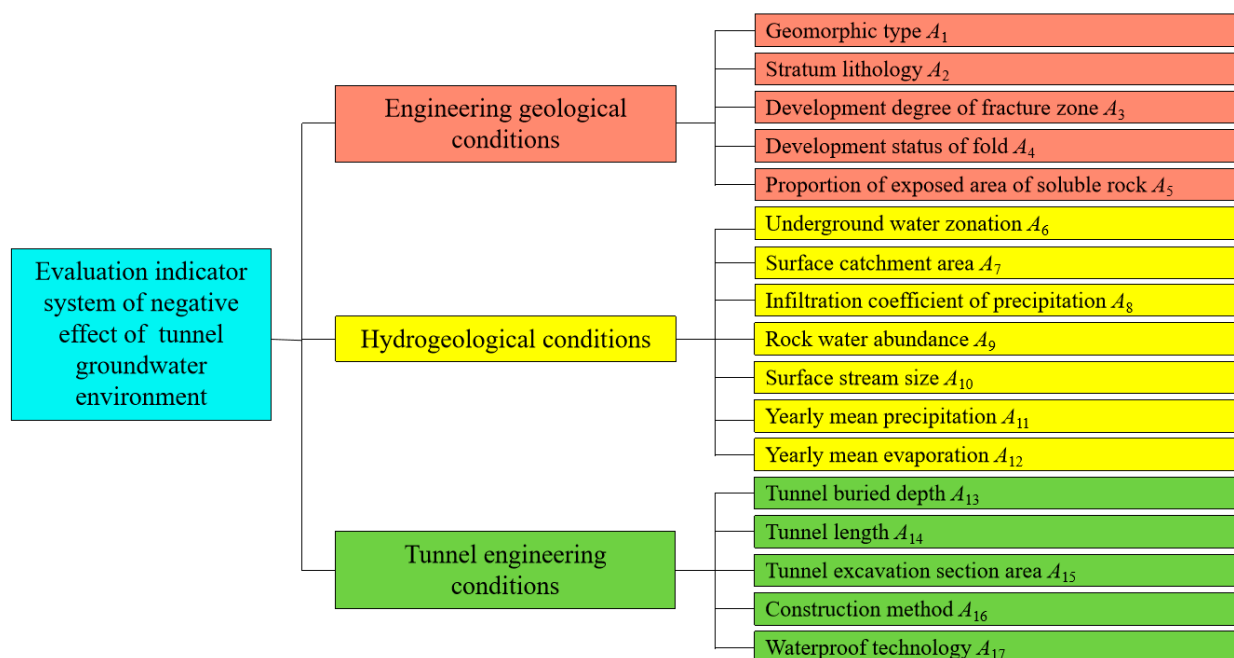


Figure 5. Evaluation system of negative effects of tunnels on groundwater environment.

Combined with the green construction concept for tunnels, based on the investigation of mountain vegetation and environmental impact in the tunnel site area, a qualitative assessment of the environmental impact of tunnel construction on the frigid plateau is carried out. Through the overall design of the evaluation system for the negative effect of the tunnel construction on the environment and the related index system and weight calculation, the evaluation index is quantified, and the quantitative evaluation of the environmental impact is realized. It is an essential scientific issue for ecological and environmental protection to carry out some research, such as statistics on vegetation development in the tunnel site, the drainage situation at the tunnel entrance, evaluation of the effect of engineering construction on the environment, changes of water level and discharge of various surface water bodies in the tunnel site, and research on the ecological restoration technology scheme of the slag field of the tunnel.

2.3.3. Establishment of a Standardized Management System for Tunnels

For a long time, it has been the focus and one of the main tasks of China's standardization development to improve industrial and technological standards and their

standardization level. The standardization of tunnels has become an important indicator to reflect the progress of science, technology, and economic development in the tunnel field. The research on standardization evaluation mainly focuses on the following aspects: judgment of standardization development, standard level, standardization system, and standardization level. According to the natural geography, climate factors, environmental characteristics, and other regional conditions in the high altitude engineering area of the plateau, the quality standardization evaluation index is given through the dynamic management of the construction quality process of tunnel engineering projects. The research on the tunnel standardized management system aims to guarantee construction quality and improve production efficiency, thus comprehensively saving on the overall costs. The standardization system vigorously promotes the implementation of tunnel safety regulations and technical standards through standardization of construction. The all-around, whole-process, and all-staff safety management will be promoted and accomplished by promoting the standardization of tunnel construction.

A complete standardization system of crucial technologies for green construction can be formed by integrating key technical indexes, calculation equations, and engineering applications of safe tunnel construction in frigid plateau regions. According to the characteristics of the natural environment and construction environment, the quality management system, safe and civilized construction system, and construction management standardization system should be established to form the evaluation systems of (a) quality management, (b) safe and civilized construction and (c) construction management standardization. At the same time, overcoming the effects of multiple factors and further considering establishing a standardized system under comprehensive factors are essential and critical scientific issues for constructing frigid plateau tunnels.

3. Evaluation for Green Construction of Tunnels in Frigid Plateau Regions

3.1. Evaluation System

The usual evaluation methods of the current green construction evaluation index mainly include the BREEAM method [44], LEED method [45], and “Evaluation standard for green construction of the building” (GB/T 50640-2010) in China. BREEAM is the world’s first evaluation system to evaluate buildings’ green performance. It divides the evaluation criteria into four grades: “excellent, very good, good, and qualified”. The system has seven evaluation sub-items with a total of 207 points. The LEED certification system is similar to the BREEAM evaluation system and divides the evaluation criteria into four levels: certified, silver, gold, and platinum. The LEED system has scoring sub-items, with a total score of 69 points, but these 69 points do not apply to tunnels. By removing the parts of the LEED standard that do not apply to tunnels, a LEED system suitable for tunnel construction is obtained, which contains 25 points [46]. The “Evaluation standard for green construction of the building” (GB/T 50640-2010) divides evaluation into three levels “unqualified, qualified, and good”. Based on the above systems and standards, five grading standards of very good (V), good (IV), moderate (III), poor (II), and very poor (I) are determined for scoring and evaluation of the green construction level of tunnels.

Considering the climate characteristics, precipitation, and vegetation distribution in the frigid plateau region in north-west China, the related research results both at home and abroad are summarized based on the specifications for green construction operation in China [47–50]. The newly proposed one saving, i.e., saving of human resources, and one protection, i.e., protection of the safety and health of personnel, are added to the traditional green construction of “Four savings and One environmental protection”, which means a new system of green construction with “five savings and two protections of both environment and human resources”. Therefore, 23 secondary evaluation indicators can be expounded and calculated to establish an evaluation system suitable for tunnels in frigid plateau regions.

3.1.1. Evaluation Indicators

The excavation of a tunnel will cause environmental problems, such as ground deformation, groundwater loss, and the withering and death of vegetation. At the same time, the excavation of a tunnel will cause considerable energy and material consumption. For example, to build a 1-m Chinese highway tunnel (horseshoe-shaped section with a width of 12.34 m, a height of 9.69 m and a rock mass of Grade III), 110 kg of steel, 0.036 m³ of wood, 19.7 m³ of water, 716 kWh of electricity and 77.6 kg of explosives are required [27]. Of course, the size of the tunnel cross-section, rock mass grade, geological conditions, excavation method, construction management, and other factors can affect the energy and material consumption of the tunnel. The climate in frigid plateau regions is harsh, and the ecological environment is fragile. So, the savings in green construction in the frigid plateau area can be expanded beyond the traditional green construction conception and content. By optimizing construction technology, protecting the natural environment, and reducing environmental pollution and energy waste during construction, a suitable, comprehensive evaluation system of green construction for tunnels can be established to improve green and sustainable development in the frigid plateau area. The proposed six first-level evaluation indicators, including land saving, energy saving, water saving, material saving, human resources saving and personnel protection, and environmental protection, are referred to as “Five savings and Two protections”. The total saving rate M represents the comprehensive evaluation, and the corresponding 23 second-level evaluation indicators are shown in Figure 6.

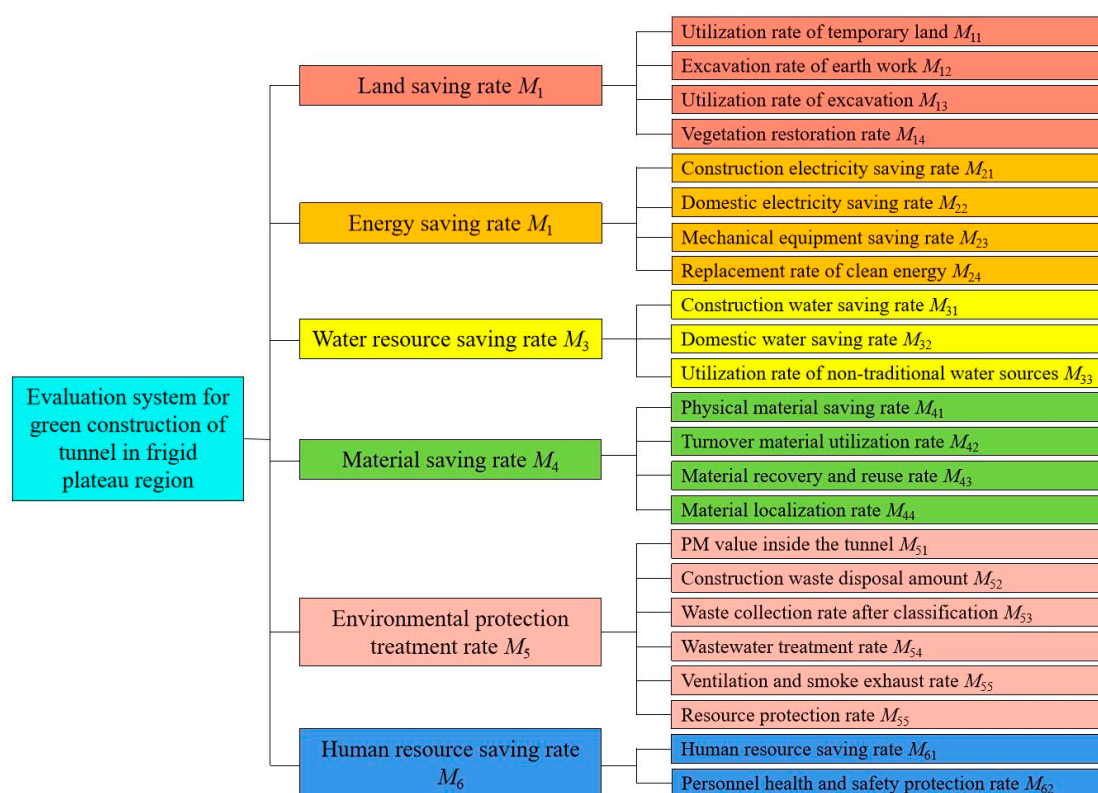


Figure 6. Evaluation system for green construction of tunnels in frigid plateau regions. Note that PM represents particulate matter.

(1) Land resource

The loess widely distributed in the frigid plateau region of western China, where the surface vegetation is sparse and the land is barren, is relatively loose and sensitive to water. The precipitation is low but concentrated between July and September. Under precipitation, the water and soil erosion are exacerbated and cause a vicious circle. Due to the tunnel

construction, the surrounding rock would be disturbed, and the original ecological balance would be influenced. Considering the tunnel construction technology and site conditions, the land conservation rate includes temporary land utilization rate, over-excavation rate of earthwork, excavation utilization rate, and vegetation recovery rate.

(2) Energy

There is a lot of energy consumption in tunnel construction and people's daily work and life. Equipment, electricity, and oil are the primary sources of consumption in tunnel construction. Energy saving is expressed by energy saving rate, including construction electricity saving rate, domestic electricity saving rate, machinery and equipment saving rate, and clean energy substitution rate.

(3) Water resource

The frigid plateau region in western China is a distinct area short of water. The water used in tunnel construction mainly includes construction water and domestic water. Construction water includes concrete mixing station water and vehicle flushing. Domestic water is mainly used for people's daily life. In addition, the construction of tunnels should pay attention to and fully use non-traditional water sources different from traditional surface water and groundwater, including reclaimed water, rainwater, and seawater (only possible in coastal areas). Considering the water-saving methods for tunnels, three aspects, such as construction water, domestic water, and non-traditional water sources, are used as the water-saving effect evaluation indicators of tunnel construction in frigid plateau regions.

(4) Material

The investment in a tunnel project is vast, with the most considerable proportion from materials. There are many ways to save on material, such as optimizing the excavation method and supporting parameters. It can be more cost-effective to improve the utilization rate of materials through proper management methods with the concept of green construction. Considering the construction method and in situ condition of the tunnel, the evaluation was carried out mainly from the four aspects, i.e., physical material saving, material turnover use, material recycling, and material use from the local area or nearest suppliers, i.e., material localization. Therefore, the material saving rate included the physical material saving rate, material turnover use rate, material recycling reuse rate, and material localization rate.

(5) Environmental protection

The frigid plateau region in western China has a harsh natural environment, severe soil erosion, and a fragile ecological environment, so environmental protection is complicated and difficult. The slopes and ground will inevitably be disturbed during the tunnel construction period. The harmful gases produced during blasting and excavation seriously pollute the atmosphere and pose a significant threat to the health of the construction crews. The waste disposal and water discharged during the construction might cause irreversible damage to the soil and underground water and the growth of vegetation. Due to the vulnerable ecological conditions, the impact of tunneling on the mountain and ground might cause further natural disasters, so environmental protection has become an urgent task for tunnel construction in frigid plateau regions. Considering the tunnel construction status, the environmental protection treatment rate includes the PM value inside the tunnel, construction waste disposal amount, waste collection rate after classification, wastewater treatment rate, ventilation and smoke exhaust rate, and resource protection rate.

(6) Human resource, health, and safety

Tunnel construction, mainly including excavation, support, and muck transportation, might be dangerous to a certain extent. Therefore, reasonable allocation and effective management of human resources in tunnel construction can significantly help reduce costs and ensure the safety of workers. So, human resource saving and protection are expressed by the human resource-saving rate and personnel health and safety protection rate.

The calculation method for all the above indicators is shown in Table 2.

Table 2. The calculation methods for each evaluation indicator.

Second-Level Evaluation Indicator	Equation	Explanation
The utilization rate of temporary land M_{11}	$M_{11} = \frac{X_{11a}}{X_{11p}} \times 100\%$	Where X_{11a} is the actual temporary land area, X_{11p} is the planned temporary land area.
Excavation rate of earth work M_{12}	$M_{12} = \frac{X_{12}}{X_{12t}} \times 100\%$	Where X_{12} is the control amount of earthwork over-excavation and under-excavation, X_{12t} is the total amount of earthwork excavation.
The utilization rate of excavation M_{13}	$M_{13} = \frac{X_{13}}{X_{13t}} \times 100\%$	Where X_{13} is the backfilling volume of excavation, and X_{13t} is the total amount of earthwork excavation.
Vegetation restoration rate M_{14}	$M_{14} = \frac{X_{14a}}{X_{14p}} \times 100\%$	Where X_{14a} is the actual vegetation restoration area, X_{14p} is the planned total area of vegetation restoration.
Construction electricity saving rate M_{21}	$M_{21} = \frac{X_{21p} - X_{21a}}{X_{21p}} \times 100\%$	Where X_{21p} is the planned electricity consumption during construction, X_{21a} is the actual electricity consumption during construction.
Domestic electricity saving rate M_{22}	$M_{22} = \frac{X_{22}}{X_{22t}} \times 100\%$	Where X_{22} is the amount of energy-saving lighting fixtures of zoning, timing, and automatic sensing, X_{22t} is the total amount of domestic lighting fixtures.
Mechanical equipment saving rate M_{23}	$M_{23} = \frac{X_{23}}{X_{23t}} \times 100\%$	Where X_{23} is the saving amount of mechanical equipment, X_{23t} is the total consumption of mechanical equipment.
The replacement rate of clean energy M_{24}	$M_{24} = \frac{X_{24c}}{X_{24n}} \times 100\%$	Where X_{24c} is the energy saving of clean energy, X_{24n} is the consumption of non-clean energy.
Construction water saving rate M_{31}	$M_{31} = \frac{X_{31p} - X_{31a}}{X_{31p}} \times 100\%$	Where X_{31p} is the planned water consumption during construction, X_{31a} is the actual water consumption during construction.
Domestic water saving rate M_{32}	$M_{32} = \frac{X_{32}}{X_{32t}} \times 100\%$	Where X_{32} is the number of water-saving devices, X_{32t} is the total amount of domestic water devices.
The utilization rate of non-traditional water sources M_{33}	$M_{33} = \frac{X_{33}}{X_{33t}} \times 100\%$	Where X_{33} is the usage of non-traditional water sources, X_{33t} is the total amount of water used during construction.
Physical material saving rate M_{41}	$M_{41} = \frac{X_{41}}{X_{41t}} \times 100\%$	Where X_{41} is the amount of physical material savings, X_{41t} is the total amount of physical material usage.
Turnover material utilization rate M_{42}	$M_{42} = \frac{X_{42} \times N}{X_{42t}} \times 100\%$	Where X_{42} is the amount of turnover materials, X_{42t} is the total amount of material usage, and N is the usage count of the turnover materials.
Material recovery and reuse rate M_{43}	$M_{43} = \frac{X_{43}}{X_{43t}} \times 100\%$	Where X_{43} is the amount of material recycling and reuse, X_{43t} is the total amount of material usage.
Material localization rate M_{44}	$M_{44} = \frac{X_{44}}{X_{44t}} \times 100\%$	Where X_{44} is the amount of local materials usage, X_{44t} is the total amount of material usage.
PM value inside the tunnel M_{51}	-	Using PM_{10} exposure concentration to represent the air quality inside the tunnel.
Construction waste disposal amount M_{52}	-	A large amount of construction waste is generated during the construction process, including residual concrete lumps, concrete and soil bonding blocks, etc.
Waste collection rate after classification M_{53}	$M_{53} = \frac{X_{53}}{X_{53t}} \times 100\%$	Where X_{53} is the classified collection amount of waste, X_{53t} is the total amount of waste.
Wastewater treatment rate M_{54}	$M_{54} = \frac{X_{54}}{X_{54t}} \times 100\%$	Where X_{54} is the amount of wastewater that has been tested to be qualified after treatment, X_{54t} is the total amount of wastewater.
Ventilation and smoke exhaust rate M_{55}	-	Estimate the ventilation and smoke exhaust rate based on the ventilation conditions of the construction site, on-site cafeteria, vehicles, and equipment exhaust.
Resource protection rate M_{56}	-	Estimate the resource protection rate based on the protection conditions of cultural relics, groundwater, and pipelines within the tunnel construction scope.
Human resource saving rate M_{61}	$M_{61} = 1 - \frac{X_{61a}}{X_{61p}} \times 100\%$	Where X_{61a} is the actual number of workers, X_{61p} is the planned number of workers (excluding management personnel).
Personnel health and safety protection rate M_{62}	-	Estimate the value of personal health and safety protection rate based on the use of on-site protective measures, such as safety helmets, safety nets, wearing glasses during welding, dust prevention measures during shotcrete, as well as safety education and operation training before construction.

3.1.2. Grading Scale for Evaluation Indicators

Based on relevant standards, previous research, and expert experience [51–55], and comprehensively considering the characteristics of green construction for tunnels, a quantitative grading table for evaluation indicators of tunnels in frigid plateau regions is formulated, which is listed in Table 3.

Table 3. The grading scale for evaluation indicators.

First-Level Evaluation Indicator	Second-Level Evaluation Indicator	Grade				
		Very Poor (I)	Poor (II)	Moderate (III)	Good (IV)	Very Good (V)
Land resource	The utilization rate of temporary land/%	<60	60–70	70–80	80–90	>90
	Excavation rate of earth work/%	<5	5–10	10–15	15–20	>20
	The utilization rate of excavation/%	<30	30–50	50–70	70–80	>80
	Vegetation restoration rate/%	<60	60–75	75–85	85–95	>95
Energy	Construction electricity saving rate/%	<10	10–15	15–20	20–25	>25
	Domestic electricity saving rate/%	<50	50–60	60–70	70–80	>80
	Mechanical equipment saving rate/%	<10	10–15	15–20	20–25	>25
	The replacement rate of clean energy/%	<5	5–10	10–20	20–30	>30
Water resource	Construction water saving rate/%	<10	10–20	20–30	30–40	>40
	Domestic water saving rate/%	<60	60–70	70–80	80–90	>90
	The utilization rate of non-traditional water sources/%	<10	10–15	15–20	20–30	>30
Material	Physical material saving rate/%	<5	5–10	10–20	20–30	>30
	Turnover material utilization rate/%	<30	30–40	40–50	50–60	>60
	Material recovery and reuse rate/%	<5	5–10	10–15	15–20	>20
	Material localization rate/%	<30	30–40	40–50	50–60	>60
Environmental protection	PM value inside the tunnel/(mg·m ^{−3})	>12	3–12	1.4–3	1–1.4	<1
	Construction waste disposal amount/[t/(10 ⁴ m ²)]	>200	150–200	100–150	50–100	<50
	Waste collection rate after classification/%	<10	10–20	20–30	30–40	>40
	Wastewater treatment rate/%	<60	60–70	70–80	80–90	>90
	Ventilation and smoke exhaust rate/%	<60	60–70	70–80	80–90	>90
	Resource protection rate/%	<40	40–60	60–70	70–90	>90
Human resource, health, and safety	Human resource saving rate/%	<15	15–30	30–45	45–60	>60
	Personnel health and safety protection rate/%	<70	70–80	80–90	90–95	>95

3.2. Evaluation Model

3.2.1. Weight of Indicators

The reasonable weighting of evaluation indicators is essential to green construction evaluation. This research uses the analytic hierarchy process (AHP) to determine the weight of each indicator. Its basic idea is to systematically express the elements related to decision making, at the levels of goals, criteria, and plans, and then analyze them.

AHP usually includes three steps [56,57]:

- (1) Establish the judgment matrix of each layer. Establish a judgment matrix $M = (a_{ij})_{n \times m}$ for the evaluation indicators of the same layer under a certain criterion layer based on the importance of the factors. Decision makers compare each pairwise comparison to obtain a ratio scale of measurement where a_{ij} represents the relative importance value of factor a_i to a_j , with values ranging from one to nine.
- (2) Calculate the maximum eigenvalue and eigenvector of the judgment matrix. Based on the judgment matrix, calculate the eigenvector w' corresponding to the maximum eigenvalue of M using the formula $Mw = \lambda_{\max}w$. The normalized weight vector $w' = (w'_1, w'_2, \dots, w'_n)$ is the importance ranking of each indicator, that is, the weight of each indicator.
- (3) Perform consistency verification. Whether the weights obtained above are within the allowable range requires consistency testing using a testing equation.

$$CR = \frac{CI}{RI} \quad (2)$$

CR represents the examination coefficient, CI represents the consistency index, and RI represents the random consistency index.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (3)$$

When $CR < 0.1$, consistency requirements are met. Otherwise, the judgment matrix should be adjusted.

When the consistency verification meets the requirements, the weight vector is normalized to obtain the weight of each indicator. The normalized weight vector in step (2) is the weight of each indicator.

3.2.2. Fuzzy Matter-Element

The fuzzy matter-element theory applies the characteristics of fuzzy mathematics to the matter–element analysis method. It has the advantages of formalization of process, quantification of the fuzzy problem, and simplification of the solving process.

If its magnitude has fuzziness, an ordered triplet of “subject, feature, and fuzzy magnitude” is formed in the matter element. Such a matter element is called a fuzzy matter element [58], and the n -dimensional fuzzy matter element of m subjects is recorded as:

$$R_{mn} = \begin{bmatrix} & M_1 & M_2 & \cdots & M_m \\ C_1 & \mu_1(x_{11}) & \mu_2(x_{21}) & \cdots & \mu_m(x_{m1}) \\ C_2 & \mu_1(x_{12}) & \mu_2(x_{22}) & \cdots & \mu_m(x_{m2}) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ C_n & \mu_1(x_{1n}) & \mu_2(x_{2n}) & \cdots & \mu_m(x_{mn}) \end{bmatrix} \quad (4)$$

where R_{mn} is the n -dimensional fuzzy complex matter element of m subjects; M_j ($j = 1, 2, \dots, m$) is the j th subject; $\mu_j(x_{ji})$ is the membership degree of the i th feature corresponding value of the j th subject ($j = 1, 2, \dots, m$; $i = 1, 2, \dots, n$); j, i refers to the serial number of the subject and the serial number of the subject feature, namely, the dimension of the matter element.

The magnitude range of the evaluation grade M_j concerning the corresponding evaluation indicator C_i is defined as the classical domain matter element, namely:

$$R_j = \begin{bmatrix} C_1 & (a_{j1}, b_{j1}) \\ C_2 & (a_{j2}, b_{j2}) \\ \vdots & \vdots \\ C_n & (a_{jn}, b_{jn}) \end{bmatrix} \quad (5)$$

If R_p is the whole of the evaluation grade, $x_p = (a_{pi}, b_{pi})$ represents the corresponding magnitude range of R_p concerning C_i , then the nodal domain matter elements are:

$$R_p = \begin{bmatrix} C_1 & (a_{p1}, b_{p1}) \\ C_2 & (a_{p2}, b_{p2}) \\ \vdots & \vdots \\ C_n & (a_{pn}, b_{pn}) \end{bmatrix} \quad (6)$$

If the classical domain and the nodal domain are overlapped into one, it is closer to the actual situation, and the results obtained are also more reasonable.

In the practical operation of a green construction evaluation, the measured values of each indicator are often discrete. When the number of tests is high, it can be approximated

that the affiliation function of the data to the same category is satisfying the normal distribution, i.e.:

$$\mu(x) = \exp\left[-\left(\frac{x-p}{q}\right)^2\right] \quad (7)$$

where $p > 0$, $q > 0$, are the characteristic parameters of the function; x is the value of the evaluation indicator.

$$p = \frac{a+b}{2} \quad (8)$$

$$q = \frac{b-a}{2\sqrt{\ln 2}} \approx \frac{b-a}{1.665} \quad (9)$$

The affiliation degree of indicators can be calculated from the above affiliation function. In this research, the classical domain overlaps with the nodal domain, so the correlation coefficient $\zeta(x)$ equals the degree of affiliation.

Based on the above-obtained correlation coefficient, the composite fuzzy object element R_ζ of the correlation coefficient of n features of m subjects can be constructed, namely:

$$R_\zeta = \begin{bmatrix} & M_1 & M_2 & \cdots & M_m \\ C_1 & \zeta_{11} & \zeta_{21} & \cdots & \zeta_{m1} \\ C_2 & \zeta_{12} & \zeta_{22} & \cdots & \zeta_{m2} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C_n & \zeta_{1n} & \zeta_{2n} & \cdots & \zeta_{mn} \end{bmatrix} \quad (10)$$

The association analysis uses the correlation degree composite fuzzy element and lets R_K be the correlation degree composite fuzzy element composed of m correlations, calculated as follows:

$$R_K = R_w \times R_\zeta \quad (11)$$

where R_w is the weighted composite fuzzy matter element of each feature; $\times$ is an operation symbol denoting multiplication before addition using the $M(\cdot, +)$ algorithm. It can be obtained as follows:

$$R_K = \begin{bmatrix} & M_1 & M_2 & \cdots & M_m \\ K_j & K_1 = \sum_{i=1}^n w_i \zeta_{1i} & K_2 = \sum_{i=1}^n w_i \zeta_{2i} & \cdots & K_m = \sum_{i=1}^n w_i \zeta_{mi} \end{bmatrix} \quad (12)$$

where K_j represents the characteristic correlation degree value.

After calculating the value of K_j , the results are ranked in order, and the maximum value of K^* is selected, called the maximum correlation principle. The equation can be expressed as follows:

$$K^* = \max\{K_1, K_2, \cdots, K_m\} \quad (13)$$

The final evaluation results can be obtained according to the maximum correlation principle.

4. Case Calculation

This study selects the #11 tunnel of the first branch of the Yindajihuang project in Qinghai Province as the project case for analysis. According to the measured values in the field, the actual values of each evaluation indicator are shown in Table 4.

Table 4. The measured value of each evaluation indicator and the fuzzy matter element of green construction.

First-Level Evaluation Indicator	Second-Level Evaluation Indicator	Indicator Value	Fuzzy Matter Element of Green Construction				
			Very Poor (I)	POOR (II)	Moderate (III)	Good (IV)	Very Good (V)
Land resource	The utilization rate of temporary land/%	86	0.0894	0.0000	0.0349	0.9727	0.1059
	Excavation rate of earth work/%	14	0.0000	0.0092	0.7792	0.2571	0.3999
	The utilization rate of excavation/%	65	0.0005	0.0131	0.8409	0.0625	0.0131
	Vegetation restoration rate/%	96	0.0349	0.0000	0.0008	0.3686	0.7792
Energy	Construction electricity saving rate/%	18	0.0092	0.0349	0.9727	0.1059	0.3768
	Domestic electricity saving rate/%	85	0.0185	0.0000	0.0000	0.0625	0.8409
	Mechanical equipment saving rate/%	27	0.0000	0.0000	0.0000	0.1059	0.5374
	The replacement rate of clean energy/%	11	0.0003	0.2571	0.6418	0.0044	0.1921
Water resource	Construction water saving rate/%	38	0.0000	0.0000	0.0092	0.7792	0.4545
	Domestic water saving rate/%	88	0.0750	0.0000	0.0092	0.7792	0.2571
	The utilization rate of non-traditional water sources/%	16	0.0349	0.2571	0.7792	0.1059	0.2571
Material	Physical material saving rate/%	18	0.0000	0.0000	0.7792	0.2571	0.2866
	Turnover material utilization rate/%	38	0.1960	0.7792	0.2571	0.0003	0.0471
	Material recovery and reuse rate/%	13	0.0000	0.0349	0.9727	0.1059	0.3841
	Material localization rate/%	48	0.0349	0.0092	0.7792	0.2571	0.1696
Environmental protection	PM value inside the tunnel/(mg·m ⁻³)	1.2	0.2329	0.2571	0.3386	1.0000	0.2571
	Construction waste disposal amount/[t/(10 ⁴ m ²)]	66	0.0000	0.0000	0.0211	0.9141	0.1550
	Waste collection rate after classification/%	38	0.0000	0.0000	0.0092	0.7792	0.4545
	Wastewater treatment rate/%	88	0.0750	0.0000	0.0092	0.7792	0.2571
	Ventilation and smoke exhaust rate/%	91	0.0570	0.0000	0.0008	0.3686	0.6418
	Resource protection rate/%	80	0.0020	0.0020	0.0020	1.0000	0.0020
Human resource, health, and safety	Human resource saving rate/%	47	0.0000	0.0006	0.3289	0.6889	0.1515
	Personnel health and safety protection rate/%	97	0.1136	0.0000	0.0185	0.1059	0.9727

4.1. Results

According to the grading scale for evaluation indicators in Table 3, the evaluation level of green construction in frigid plateau tunnels, i.e., very poor, poor, moderate, good, and very good, is regarded as matter element M. The evaluation indicator is regarded as matter element feature C. By substituting the evaluation indicator values in Table 4 into the corresponding membership function Equations (7)–(9), the fuzzy matter element of green tunnel construction in the frigid plateau area can be constructed. The fuzzy matter element of the green construction of the #11 tunnel of the Yindajihuang project is shown in Table 4.

According to the AHP method, the weights of the first and second indicators are determined. The weight calculation results of the AHP method are shown in Table 5. Through calculation, the compound fuzzy matter element of the correlation degree of

the second-level evaluation indicator is obtained, which is used as the second-level fuzzy matter element evaluation set.

Table 5. Weights obtained from the AHP method.

First-Level Evaluation Indicator	Weight of First-Level Evaluation Indicator	Second-Level Evaluation Indicator	Weight of Second-Level Evaluation Indicator	Ultimate Weight
Land resource	0.3553	The utilization rate of temporary land	0.0481	0.0171
		Excavation rate of earthwork	0.2387	0.0848
		The utilization rate of excavation	0.1703	0.0605
		Vegetation restoration rate	0.5429	0.1929
Energy	0.0976	Construction electricity saving rate	0.4829	0.0471
		Domestic electricity saving rate	0.0882	0.0086
		Mechanical equipment saving rate	0.1570	0.0153
		The replacement rate of clean energy	0.2720	0.0265
Water resource	0.2119	Construction water saving rate	0.6483	0.1374
		Domestic water saving rate	0.1220	0.0259
		The utilization rate of non-traditional water sources	0.2297	0.0487
Material	0.1056	Physical material saving rate	0.4900	0.0517
		Turnover material utilization rate	0.1128	0.0119
		Material recovery and reuse rate	0.0897	0.0095
		Material localization rate	0.3075	0.0325
Environmental protection	0.0826	PM value inside the tunnel	0.3331	0.0275
		Construction waste disposal amount	0.1880	0.0155
		Waste collection rate after classification	0.0988	0.0082
		Wastewater treatment rate	0.2229	0.0184
		Ventilation and smoke exhaust rate	0.0730	0.0060
Human resource, health, and safety	0.1470	Resource protection rate	0.0842	0.0070
		Human resource saving rate	0.2500	0.0368
		Personnel health and safety protection rate	0.7500	0.1103

Then, the weight of each second-level evaluation indicator is substituted into Equations (11) and (12), and the compound fuzzy matter element of green construction correlation degree of the tunnel in the frigid plateau region is obtained through calculation. The results are as follows:

$$R_K = \{0.0367, 0.0396, 0.3220, 0.3842, 0.4659\}$$

According to Equation (13), $K_{\max} = K_5 = 0.4659$. Based on the maximum correlation principle, the green construction grade of this section is rated as Grade V, which means that the green construction level of the tunnel is very good.

4.2. Discussion

Green construction is the application of sustainable development ideas in engineering. Reasonable application of the green construction evaluation system and green construction technology will provide assistance for sustainable tunnel development and green strategies for socio-economic development in the frigid plateau regions.

- (1) Due to the harsh natural environment and fragile ecological environment in frigid plateau regions, the traditional indicator system of “Four savings and One protection” [59] is not sufficient to fully meet the green construction evaluation needs of tunnels. Considering the characteristics of the frigid plateau region, two indicators of human resource saving and personnel protection are proposed and added to form the “Five savings and Two protections” evaluation index system suitable for green construction of tunnels in the frigid plateau region. It contains six first-level evaluation indicators, including land saving, energy saving, material saving, water resource conservation, environmental protection, human resources and health and safety protection, and 23 corresponding second-level evaluation indicators.

- (2) The weight calculations used in this study were obtained by the AHP method. The AHP method was used to invite experts to provide scores, which determined the weights of indicators at all levels. This method has some invisible, subjective impact. However, by comparing the weights of evaluation indicators with other similar regions [55], it can be proven that the final weight values obtained are reasonable.
- (3) This paper adopts the established evaluation indicator system and uses the fuzzy matter-element method to evaluate the green construction grade of the Yindajihuang project. However, due to space limitations, this article did not conduct sensitivity analysis for the calculated weights and for all the grades. The impact of different factors will be further studied in the future.
- (4) Various green construction technologies have been adopted in the Yindajihuang project, such as adopting a non-excavated slope approach, developing and using a hydraulic tunnel secondary lining trolley, and adopting a standardized management system to ensure quality and improve production efficiency. Through scientific management and technological innovation, construction methods conducive to saving resources, protecting the environment, reducing emissions, improving efficiency, and guaranteeing quality have been adopted to realize the harmonious coexistence between humans and nature. Therefore, the green construction evaluation grade of the #11 tunnel is very good, basically consistent with the actual situation on site.

It should be noted that few intelligent technologies were used in this project's construction. Intelligent construction technologies should be the goal of green construction for tunnels. In the significant technical challenges faced by China's tunnel engineering, many innovative technologies have emerged, such as intelligent construction, digital management, and intelligent equipment [60–63]. The high cold and high altitude area has the apparent characteristics of low temperature, low pressure, and low oxygen, which will lead to regional problems such as the decrease of the physical ability of the construction crew, the decrease of production efficiency, the increase of the sewage discharge of machinery, and the slowing down of the construction progress and productivity of the tunnel project. Therefore, informatization and intellectualization are the inevitable trends for tunnel construction to achieve safety, efficiency, and quality controllability. Figure 7 shows the main components of intelligent tunnel construction, including design method, technological method, and collaborative management. In addition, with the increase in labor costs and the decrease of construction workers, the inevitable trend for tunnel construction in the frigid plateau region should be more and more mechanized and intelligent, with fewer people on site. Based on the deep integration of informatization and mechanization, the intelligent tunnel construction process is of great significance to improving construction efficiency and ensuring construction quality and the safety and health of workers.

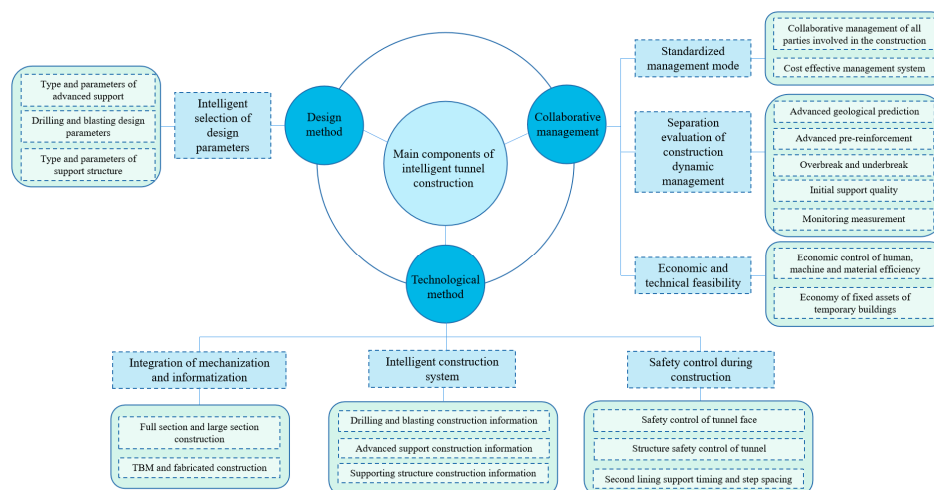


Figure 7. The architecture of hybrid intelligent systems (after: [64]).

5. Concluding Remarks

The fragile ecological environment in the frigid plateau region is under increasing pressure. Focusing on the concept of green construction, implementing green construction engineering technology for a tunnel is an important measure to ensure the effective conjunction of engineering construction and scientific research and to promote the integration of practical application and scientific research results. The main conclusions are summarized as follows:

- (1) As a particular underground tunnel structure project, the tunnel project is suitable for classification into the three stages of green planning, green design, and green construction operation based on the concept of green construction. It is necessary to clarify the implications of the green construction of tunnels and to promote practice and innovation in green construction technology, while focusing on quality assurance and environmental protection. This is an essential prerequisite for the promotion and implementation of green construction. The green construction of the tunnel project in a cold, arid, and frigid plateau area has important strategic significance in responding to green development.
- (2) Driven by China's policy of vigorously promoting the construction of ecological civilization, the new concept of green construction technology for tunnels is proposed and optimized. A green construction evaluation indicator system set suitable for tunnels in frigid plateau regions has been developed. It contains six first-level evaluation indicators, including land saving, energy saving, material saving, water resource conservation, environmental protection, human resources, and health and safety protection, and 23 corresponding second-level evaluation indicators, referred to as "Five savings and Two protections". Establishing this evaluation system is intended to make up for the shortcomings of most existing studies, which have carried out green evaluations from the aspects of soil and water conservation and environmental impact, so that tunnel construction can be coordinated with the ecological environment and achieve rapid development. It is also the inevitable result of implementing a green and sustainable development strategy for a tunnel in the frigid plateau region. Through the green construction evaluation of the tunnel of the Yindajihuang project, the evaluation grade was found to be "very good", which is basically consistent with the actual situation. The evaluation system can provide a reference for tunnel projects in other frigid plateau regions.
- (3) Considering the unique climatic characteristics, natural resource characteristics, environmental characteristics, and other regional conditions of frigid plateau regions, the following key points are put forward: (a) fine grading of surrounding rock and safety evaluation, (b) changes in seepage field caused by construction, and (c) the establishment of a standardized construction system. The green evaluation results of the tunnel in the Yindajihuang Project show that adopting these green construction technologies is beneficial for the evaluation results. In order to achieve "Five savings and Two protections", the development of intelligent construction technology should be the goal of green construction for tunnels.
- (4) Implementing green construction has a more profound connotation and significance. Considering the fragile and complex regional characteristics of the western frigid plateau region, the sustainable development of green construction of the tunnel in the frigid plateau region needs to advocate resource-saving, reduce energy consumption and pollution, and protect the health and safety of people and the environment as well.

Author Contributions: Conceptualization, Q.L. and J.L.; Data curation, C.Z. and X.X.; Investigation, H.L.; Methodology, J.L. and T.Z.; Writing—original draft, J.L. and T.Z.; Writing—review and editing, Q.L., J.L. and T.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Science and Technology Planning Project of Qinghai Province, China (2020-SF-138); Special Funds for Guiding Local Scientific and Technological Development by The Central Government (22ZY1QA005); the National Natural Science Foundation of China

(No. 51968041); the Foundation of a Hundred Youth Talents Training Program of Lanzhou Jiaotong University (2017150); the “Innovation Star” Project for Outstanding Graduate Students in Gansu Province, China; the Young Talent Fund of the University Association for Science and Technology in Shaanxi, China (No. 20190706); and the Middle-aged and Young Talent of Science and Technology Innovation for Shaanxi Railway Institute, China (No. KJRC201902).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors of this paper also appreciate the help of some of their colleagues in preparing this paper, especially Shang Wang, Kelin Chen, Baodong Shi, Wendi Zhou, Xiaowen Ma, and Shengjun Ai.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. National Energy Administration of China. Available online: http://www.nea.gov.cn/2022-07/01/c_1310636707.htm (accessed on 18 July 2023).
2. Hao, J.; Gao, F.; Fang, X.; Nong, X.; Zhang, Y.; Hong, F. Multi-factor decomposition and multi-scenario prediction decoupling analysis of China’s carbon emission under dual carbon goal. *Sci. Total Environ.* **2022**, *841*, 156788. [\[CrossRef\]](#)
3. Shi, Q.; Zuo, J.; Huang, R.; Huang, J.; Pullen, S. Identifying the Critical Factors for Green Construction—An Empirical Study in China. *Habitat Int.* **2013**, *40*, 1–8. [\[CrossRef\]](#)
4. Xiao, X.; Feng, D. Review and promoting suggestions of green construction for buildings. *Constr. Technol.* **2013**, *42*, 12–15.
5. Xiao, X.; Feng, D. Practical significance and implementation strategy of green construction in China. *Constr. Technol.* **2013**, *42*, 1–4.
6. Sun, Y.; Tang, J.; Wang, M.; Niu, F.; Qiu, Q. Connotation explore and research prospects for green railway engineering. *J. Railw. Sci. Eng.* **2021**, *18*, 1–11. [\[CrossRef\]](#)
7. You, X. State-of-art and prospectives of urban utility tunnels in China. *Tunn. Constr.* **2018**, *38*, 1603–1611.
8. You, X.; Hua, D.; Wang, H. Effective measures for green construction of utility tunnel. *Tunn. Constr.* **2018**, *38*, 1423–1427.
9. You, X.; Qu, L.; Luo, C. Urban Utility Tunnels in China: Experience, Problems and Suggestions. *Tunn. Constr.* **2020**, *40*, 621–628.
10. Rooshdi, R.R.R.M.; Rahman, N.A.; Baki, N.Z.U.; Majid, M.Z.A.; Ismail, F. An Evaluation of Sustainable Design and Construction Criteria for Green Highway. *Procedia Environ. Sci.* **2014**, *20*, 180–186. [\[CrossRef\]](#)
11. You, X. Green Construction Concept and Technology of Shield Engineering. *Archit. Technol.* **2019**, *50*, 644–646.
12. Zhang, Y. Research on Green Evaluation Index System and Evaluation Results of High-speed Railway. Master Thesis, Beijing Jiaotong University, Beijing, China, 2019.
13. Jiang, Z.; Xue, P.; Ma, X.; Xie, J.; Liu, J. Evaluation System of Green Highway Tunnels. *Tunn. Constr.* **2022**, *42*, 586–593.
14. Luo, W.; Sandanayake, M.; Hou, L.; Tan, Y.; Zhang, G. A systematic review of green construction research using scientometrics methods. *J. Clean. Prod.* **2022**, *366*, 132710. [\[CrossRef\]](#)
15. Qiu, W.; Liu, Y.; Lu, F.; Huang, G. Establishing a Sustainable Evaluation Indicator System for Railway Tunnel in China. *J. Clean. Prod.* **2020**, *268*, 122150. [\[CrossRef\]](#)
16. García-Trenas, T.; López, J.C.; Peña-García, A. Proposal to Forest Alpine Tunnels Surroundings to Enhance Energy Savings from the Lighting Installations. Towards a Standard Procedure. *Tunn. Undergr. Space Technol.* **2018**, *78*, 1–7. [\[CrossRef\]](#)
17. Lehner, P.; Hrabová, K. Evaluation of Degradation and Mechanical Parameters and Sustainability Indicators of Zeolite Concretes. *Constr. Build. Mater.* **2023**, *371*, 130791. [\[CrossRef\]](#)
18. Chi, B.; Lu, W.; Ye, M.; Bao, Z.; Zhang, X. Construction waste minimization in green building: A comparative analysis of LEED-NC 2009 certified projects in the US and China. *J. Clean. Prod.* **2020**, *256*, 120749. [\[CrossRef\]](#)
19. Li, H.; Huang, F.; Wang, Z.; Luo, X.; Yuan, Z.; Yi, Z.; Xie, Y. Review of Material Technology Used in Green Railway Tunnel Engineering. *Tunn. Constr.* **2021**, *41*, 1992–2000.
20. Barla, M.; Insana, A. Energy Tunnels as an Opportunity for Sustainable Development of Urban Areas. *Tunn. Undergr. Space Technol.* **2023**, *132*, 104902. [\[CrossRef\]](#)
21. Phillips, J. A Quantitative Evaluation of the Sustainability or Unsustainability of Three Tunnelling Projects. *Tunn. Undergr. Space Technol.* **2016**, *51*, 387–404. [\[CrossRef\]](#)
22. De La Fuente, A.; Blanco, A.; Armengou, J.; Aguado, A. Sustainability Based-Approach to Determine the Concrete Type and Reinforcement Configuration of TBM Tunnels Linings. Case Study: Extension Line to Barcelona Airport T1. *Tunn. Undergr. Space Technol.* **2017**, *61*, 179–188. [\[CrossRef\]](#)
23. Hrabova, K.; Vorechovska, D.; Teply, B. *Potential for the Inclusion of Sustainability Aspects in Limit States for Concrete*; STEF92 Technology: Sofia, Bulgaria, 2020; pp. 411–418. [\[CrossRef\]](#)

24. Li, W. Application Research on Green Construction in Metro Engineering. Master Thesis, South China University of Technology, Guangzhou, China, 2014.
25. Wan, Z. Study on Green Construction Technology and Cost Risk Management of Water Supply Project. Master Thesis, Southeast University, Nanjing, China, 2017.
26. Yin, Z. Metallurgical Industry Project Green Construction Techniques and Cost Risk Management. Ph.D. Thesis, Xi'an University of Architecture and Technology, Xi'an, China, 2014.
27. Guo, C.; Xu, J.; Yang, L.; Guo, X.; Liao, J.; Zheng, X.; Zhang, Z.; Chen, X.; Yang, K.; Wang, M. Life Cycle Evaluation of Greenhouse Gas Emissions of a Highway Tunnel: A Case Study in China. *J. Clean. Prod.* **2019**, *211*, 972–980. [\[CrossRef\]](#)
28. Lv, Y.; Jiang, Y.; Hu, W.; Cao, M.; Mao, Y. A review of the effects of tunnel excavation on the hydrology, ecology, and environment in karst areas: Current status, challenges, and perspectives. *J. Hydrol.* **2020**, *586*, 124891. [\[CrossRef\]](#)
29. Islam, M.S.; Iskander, M. Twin tunnelling induced ground settlements: A review. *Tunn. Undergr. Space Technol.* **2021**, *110*, 103614. [\[CrossRef\]](#)
30. Xiao, X. State and development strategy for green construction. *Constr. Technol.* **2018**, *47*, 1–4+40.
31. Department of Transport of Guangdong Province. Available online: http://td.gd.gov.cn/dtxw_n/gdjrxw/content/post_4118665.html (accessed on 18 July 2023).
32. GB 50487-2008; Code for Engineering Geological Investigation of Water Resources and Hydropower. Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2009.
33. GB/T 50218-2014; Standard for Engineering Classification of Rock Mass. Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2014.
34. Yin, H.; Zhang, Y.; Zhou, H.; Zhong, Z. Review on the Classification of Engineering Rock Mass. *J. Yangtze River Sci. Res. Inst.* **2011**, *28*, 59–66.
35. Cai, B. Discussion about several problems of the use of standard for engineering classification of rock masses. *Rock Soil Mech.* **2003**, *51*, 74–76. [\[CrossRef\]](#)
36. Hao, Z. Review and suggestions on China's current rock mass classification system. *Met. Mine* **2005**, *9*, 59–62+73.
37. TB 10003-2016; Code for Design of Railway Tunnel. National Railway Administration of People's Republic of China: Beijing, China, 2017.
38. Kim, T.H.; Chung, S.Y.; Senapathi, V.; Sekar, S.; Elzain, H.E. Groundwater Decrease and Contamination around Subway Tunnels in a Coastal Area of Busan City, Korea. *Environ. Earth Sci.* **2021**, *80*, 550. [\[CrossRef\]](#)
39. Chen, K.-L.; Wu, H.-N.; Cheng, W.-C.; Zhang, Z.; Chen, J. Geological Characteristics of Strata in Chongqing, China, and Mitigation of the Environmental Impacts of Tunneling-Induced Geo-Hazards. *Environ. Earth Sci.* **2017**, *76*, 10. [\[CrossRef\]](#)
40. Liu, J.; Liu, D.; Song, K. Evaluation of the Negative Effects on Groundwater Environment Resulted by Geleshan Tunnel Drainage. *Mod. Tunn. Technol.* **2012**, *49*, 178–183. [\[CrossRef\]](#)
41. Vincenzi, V.; Gargini, A.; Goldscheider, N. Using Tracer Tests and Hydrological Observations to Evaluate Effects of Tunnel Drainage on Groundwater and Surface Waters in the Northern Apennines (Italy). *Hydrogeol. J.* **2009**, *17*, 135–150. [\[CrossRef\]](#)
42. Liu, Z.; Wang, M. Research on Evaluation Technique of Interaction Between Shibanshan Tunnel and Groundwater Environment. *China Civ. Eng. J.* **2015**, *48* (Suppl. 1), 321–325.
43. Liu, Y.; Yu, C.; Cao, S.; Song, M.; Lin, J. Study on Comprehensive Assessment Method of Water Quality in Dong'e Groundwater Source. *J. Water Resour. Water Eng.* **2015**, *26*, 99–103.
44. Ferreira, A.; Pinheiro, M.D.; Brito, J.D.; Mateus, R. A Critical Analysis of LEED, BREEAM and DGNB as Sustainability Assessment Methods for Retail Buildings. *J. Build. Eng.* **2023**, *66*, 105825. [\[CrossRef\]](#)
45. Luo, K.; Scofield, J.H.; Qiu, Y. Water Savings of LEED-Certified Buildings. *Resour. Conserv. Recycl.* **2021**, *175*, 105856. [\[CrossRef\]](#)
46. Derek, J.P.; Bradford, F.T. Design for Sustainable and Economical Tunnels. In *North American Tunneling: 2010 Proceedings*; Society for Mining, Metallurgy, and Exploration, Inc.: Littleton, CO, USA, 2010; pp. 183–190.
47. Gangoellis, M.; Casals, M.; Gassó, S.; Forcada, N.; Roca, X.; Fuertes, A. A Methodology for Predicting the Severity of Environmental Impacts Related to the Construction Process of Residential Buildings. *Build. Environ.* **2009**, *44*, 558–571. [\[CrossRef\]](#)
48. Kim, Y.-D.; Cha, H.-S.; Kim, K.-R.; Shin, D.-W. Evaluation Method of Green Construction Technologies Using Integrated LCC and LCA Analysis. *Korean J. Constr. Eng. Manag.* **2011**, *12*, 91–100. [\[CrossRef\]](#)
49. Bao, X.; Yang, S.; Wang, Q. Research on the grade evaluation for railway green construction based on grey clustering methods. *J. Railw. Eng. Soc.* **2016**, *33*, 106–110.
50. Chen, J.; Jiskani, I.M.; Lin, A.; Zhao, C.; Jing, P.; Liu, F.; Lu, M. A Hybrid Decision Model and Case Study for Comprehensive Evaluation of Green Mine Construction Level. *Environ. Dev. Sustain.* **2022**, *25*, 3823–3842. [\[CrossRef\]](#)
51. GB/T 50378-2019; Assessment Standard for Green Building. Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2019.
52. GB/T 50434-2018; Standard of Soil Erosion Control for Production and Construction Projects. Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2019.
53. Li, X. Key Technology for Expressway Land Intensive Economical Use and Comprehensive Evaluation on Its Effect. Ph.D. Thesis, Chang'an University, Xi'an, China, 2013.
54. Wang, H.; Wu, F.; Gong, L. Evaluating the Green-grade of Railway Passenger Stations Based on Whole Life Cycle. *J. China Railw. Soc.* **2012**, *34*, 14–21.

55. Bao, X. Study on Application and Formation of Railway Green Construction Grade Evaluation Systems for Cold and Arid Areas in Northwest China. Ph.D. Thesis, Lanzhou Jiaotong University, Lanzhou, China, 2017.
56. Thungngern, J.; Wijitkosum, S.; Sriburi, T.; Sukhsri, C. A Review of the Analytical Hierarchy Process (AHP): An Approach to Water Resource Management in Thailand. *App. Envi. Res.* **2015**, *37*, 13–32. [[CrossRef](#)]
57. Wu, L.; Zhao, X.; Cheng, Y.; Jing, J.; Jia, S.; Sun, D. Evaluation of water resources carrying capacity and water resources security in Gansu section of Yellow River Basin. *J. Drain. Irrig. Mach. Eng.* **2021**, *39*, 897–903.
58. Wu, X.; Wang, H.; He, Y. Excavation stability evaluation of Karst tunnel based on fuzzy matter-element. *China Saf. Sci. J.* **2018**, *28*, 99–104. [[CrossRef](#)]
59. Bao, X.; Zhang, J.; Wang, Q. Study on Grade Evaluation of Green Construction in Northwest Cold and Arid Areas. *J. China Railw. Soc.* **2019**, *41*, 33–39.
60. Editorial Department of China Journal of Highway and Transport. Review on China's tunnel engineering research: 2015. *China J. Highw. Transp.* **2015**, *28*, 1–65.
61. Tian, S.; Wang, W.; Gong, J. Development and prospect of railway tunnels in China (Including statistics on China railway tunnels by the end of 2020) Tunnel Construction. *Tunn. Constr.* **2021**, *41*, 308–325.
62. Hong, K.; Feng, H. Development trends and views of highway tunnels in China over the past decade. *China J. Highw. Transp.* **2020**, *33*, 62–76. [[CrossRef](#)]
63. Yan, J. Achievements and challenges of tunneling technology in China over past 40 years. *Tunn. Constr.* **2019**, *39*, 537–544.
64. Wang, T. Development Status and Prospect of Intelligent Construction Technology for Railway Tunnel in China. *China Railw.* **2020**, *12*, 1–9. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.