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Review

Research on the Design and Construction of Inclined Shafts for Long Mountain Tunnels: A Review

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Abstract: In recent years, inclined shafts have been widely used in long mountain tunnels, but the corresponding design and construction technical specifications need to be improved. By means of literature statistics and actual cases, a comprehensive and systematic review is made on the tunnel profile, lining structure, construction and operation ventilation, construction methods, and machinery of inclined shafts for long mountain tunnels. The results show that: (1) The design of a gentle slope section of an inclined shaft with large longitudinal slope needs to be further improved; (2) When an inclined shaft is only used for ventilation in the operation stage, it is necessary to make full use of the natural wind and eliminate its adverse effects; (3) It is suggested to study the supporting parameters of an inclined shaft in order to realize the standardised design of the supporting parameters; (4) The space of an inclined shaft is narrow, and it has practical demand in improving the automation, intelligence, management, and dispatching level of transport vehicles. In the future, it is an inevitable trend for electric vehicles to replace fuel vehicles. It is necessary to carry out further research on inclined shaft longitudinal slope design, construction and operation ventilation design, and transportation mode.

Keywords: inclined shaft; slope design; rail transportation; trackless transportation; construction ventilation; operational ventilation

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1. Introduction

With the construction of transportation infrastructure for long and large railways or highway trunk lines in western mountainous areas, China's tunnel construction has entered a period of rapid development. One of the significant characteristics of tunnel engineering during this period is the increasing number of ultra deep and ultra long tunnels [1,2]. To shorten the construction period and solve the problems of tunnel construction and operational ventilation, inclined shafts are extensively used in long mountain tunnel engineering projects [3,4].

Before the 1970s, parallel pilot pits spanning distances > 3 km were mostly used for the excavation of mountain tunnels in China, but parallel pilot pits had to be constructed ahead of time with large sections, long transport distances, and high costs; thus, the early mountain tunnels were very limited in length. Japan pioneered the popularisation of inclined shaft auxiliary tunnels in the construction of long tunnels [5], thus accelerating the construction progress of main tunnels and providing the possibility for the construction of extra-long mountain tunnels. In the early stages, China took the lead in utilising inclined shaft auxiliary construction in the coal, metallurgy, and other mining industries. In 1972, construction progress was achieved in the construction of Hunan Province (364.5 m/month), and China ranked first in the world in inclined shaft construction [6]. However, in the 1980s, the original equipment and technology could not meet the continuous improvement of inclined shaft construction requirements, and the research and development of inclined shaft construction equipment stagnated [7]. After the middle of the 1990s, following the improvement of inclined shaft construction equipment and technology, mature construction technologies were gradually established with the Chinese characteristics of 'two lights and three buckets'; these efforts elevated the complexity and quality of inclined shaft construction in China. In recent years, following the progress of mechanised excavation technology and the improvement of management technology, the construction technology of inclined shaft auxiliary main tunnels has developed rapidly, and inclined shaft projects have become one of the main ways to guarantee the rapid and efficient construction of long mountain tunnels. However, disproportionately to the broad range of applications and important functions of inclined shafts, their design specifications are still incomplete at this stage. Systematic and unified regulations on the design theory in the railway and highway industries, construction methods, and support measures for inclined shafts are still lacking [8].

To clearly explain the development process of inclined shaft design and construction technology of mountain tunnels, the authors quantified the number of publications in CNKI, Web of Science, and other databases over the past 40 years that are highly correlated with the design and construction of inclined shafts in mountain tunnels, screened keywords and summaries, and gathered hundreds of relevant documents. The statistical results of documents were classified into two categories according to 'inclined shaft design' and 'inclined shaft construction', as shown in Figures 1 and 2.

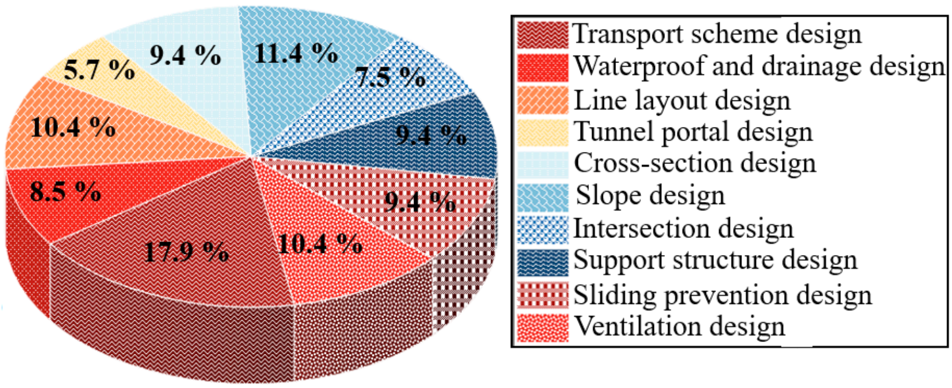

Figure 1. Proportions of Research Subject Classifications of Papers Related to Inclined Shaft Design.

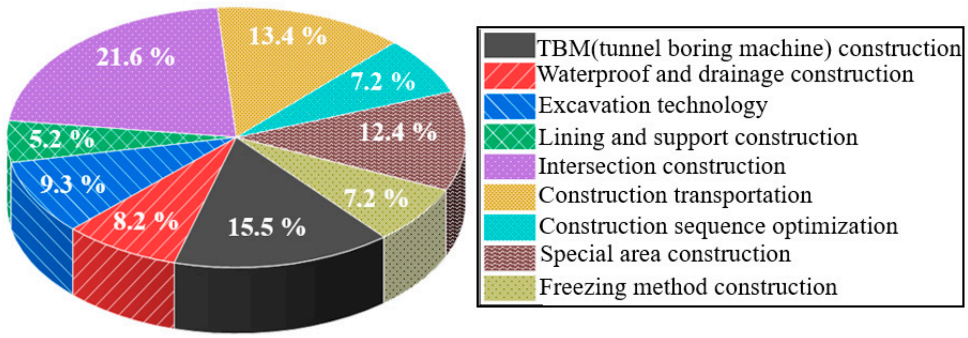

Figure 2. Proportions of Research Subject Publications Related to Inclined Shaft Construction.

Statistics show that the transportation scheme and longitudinal slope design account for the largest proportions of related studies on inclined shaft design at 17.9% and 11.4%, respectively. In studies on inclined shaft construction, the construction method of the intersection between the inclined shaft and the main tunnel and the construction technology of the TBM inclined shaft were mostly studied; these accounted for 21.6% and 15.5%, respectively. Comparatively, there is no obvious difference between the portal of the inclined shaft and the design and construction of the support scheme compared to those of a general tunnel; therefore, the research publications are also fewer and account for <10% of the total. Additionally, different research directions correspond to different time distribution rules. For example, the slag transportation research scheme on inclined shafts mainly focused on the period of 2011–2013, and the TBM construction technology research on inclined shafts was mainly conducted after 2016. Statistics on the application field of inclined shafts show that most of the early cases of inclined shaft analysis were based on coal mine roadways; however, with the construction needs of long mountain tunnels, research on related cases of inclined shafts in mountain tunnels has gradually increased.

Based on an analysis of the existing literature, engineering cases, and the relevant experience gained from the actual inclined shaft project in which the author participated, this study discusses and summarises the inclined shaft design and construction technology of mountain tunnels from the perspectives of section shape and dimension design of inclined shafts, reasonable selection of longitudinal slopes, design and construction methods of different parts, effective ventilation methods, inclined shaft support, and transportation schemes. The research results can provide a reference for engineering the construction of inclined shafts and for related research.

2. Design of an Inclined Shaft Section and Longitudinal Slope

The inclined shaft section and longitudinal slope are important components of inclined shaft design, and directly affect the key elements of inclined shafts, such as the tunnel length, transportation mode, ventilation effect, project cost, construction period, disaster prevention, and evacuation.

2.1. Longitudinal Slope Design of an Inclined Shaft

The code for the design of railway tunnels in China [9] mainly stipulates the inclined shaft's inclination from the perspective of transportation mode: when an inclined shaft adopts trackless transportation, the comprehensive slope should be less than 10%, and the maximum climbing angle of the vehicle can be calculated according to Formula (1) [10]; when rail transportation is adopted, the longitudinal slope is better than 25%, and the maximum climbing angle of the tramcar can be calculated according to Formula (2) [11].

$$\alpha_1 = \arcsin\frac{M i_g i_o u \eta}{r_d m g\sqrt{1+f^2}} - \arctan f \tag{1}$$

In Formula (1), α_1 is the maximum climbing angle of a trackless transport vehicle (rad), M is the output torque of the transport vehicle engine (N·m), i_g and i_o are the transmission ratio of transmission and transmission ratio of the main reducer at the gear I of the transport vehicle, respectively, u is the correction coefficient of external characteristics of the engine, η is the mechanical efficiency of transport vehicles, f is the wheel rolling resistance coefficient, m is the mass of the transport vehicle (kg), and g is the gravitational acceleration (N/kg).

$$\alpha_2 = \arcsin\frac{N}{G_0 + G_1} \tag{2}$$

In Formula (2), α_2 is the maximum climbing angle of the tramcar (rad), G_0 is the maximum loading mass of the tramcar (T), G_1 is the dead weight of the tramcar (T), and N is the maximum static tension of steel wire rope for tramcar lifting (T).

However, unlike the specifications, in most cases, the longitudinal slope of the inclined shaft is not determined simply by the mode of transportation. First, the principle of geological priority should be followed when selecting the inclined shaft's position and longitudinal slope to avoid unfavourable geological areas as far as possible. From the view point of the longitudinal section diagram of an inclined shaft, for a general topographic tunnel, if the longitudinal slope of the inclined shaft is set to values that are too large, such as the No. 3 inclined shaft or even the vertical shaft shown in Figure 3, topography at the head of the inclined shaft is considerably higher than that of the main tunnel, and the height difference between the head of the inclined shaft and the bottom part of the shaft increases accordingly; this is not conducive to mechanical transportation, increases the difficulty of drainage on the slope of the inclined shaft, and increases the risk of the evacuation of personnel in the case of sudden water inrush in a water-rich inclined shaft. If the longitudinal slope is extremely small, like the parallel pilot pits shown in Figure 3, the length of the shaft increases [12]. For mountain tunnels, due to the undulating terrain in mountainous areas, building a completely horizontal parallel pilot pit may not have good engineering conditions. Due to the lack of significant horizontal height difference, parallel pilot pits are not conducive to using natural pressure difference to assist tunnel ventilation, requiring the addition of fans, which increases ventilation costs. At this time, using inclined shafts can flexibly select the entrance and exit positions, reducing the length of auxiliary pilot pits, and is more conducive to utilising the auxiliary tunnel function.

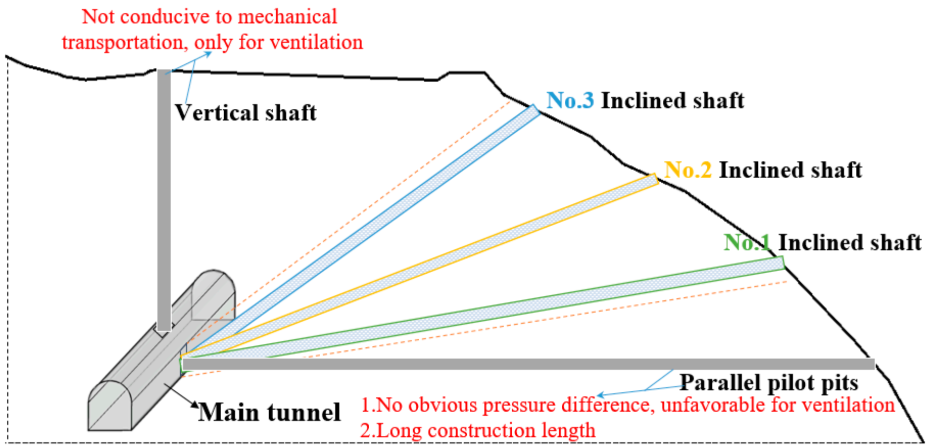

Figure 3. Schematic of Relationship Between Slope and Length of Inclined Shaft.

When the topography of the tunnel site is significantly undulating and each condition is suitable, an inclined shaft can be set along the slope according to the topography to give full play to the advantages of drainage along the slope; this saves energy and effectively deals with water inrush accidents. One project we participated in before had a similar situation and a three-dimensional numerical model combined with terrain was established as shown in Figure 4. Considering the pressure of the surrounding rock, some scholars have shown that when the longitudinal slope of the inclined shaft increases, the bearing capacity of the surrounding rock increases [13,14], and properly increasing the longitudinal slope of the inclined shaft can improve the stability of the surrounding rock. In highway tunnels, ensuring operational ventilation is one of the main functions of an inclined shaft, and the steep-slope inclined shaft is mostly used in design to control construction and operational ventilation costs. Constrained by domestic intelligent and mechanised construction levels, large longitudinal inclined shafts are associated with many difficult problems, such as slow construction progress, high risk, and great difficulty [15]. Therefore, the mechanical construction of an inclined shaft is an important future research direction. In contrast, the mechanised construction of inclined shafts abroad began earlier. For example, in the 1990s, Japan extensively used an ME632H inclined shaft-side unloading loader, which can achieve the construction of 30° inclined shafts. Additionally, a Clyde Gate rock grabber in North America also succeeded to excavate a 55° large longitudinally inclined shaft [16]. To compensate for the backward situation of large-scale construction equipment, China should also, in the future, begin to study the mechanical matching of large, longitudinal, slope-inclined shaft construction with the use of large-scale rock-loading equipment.

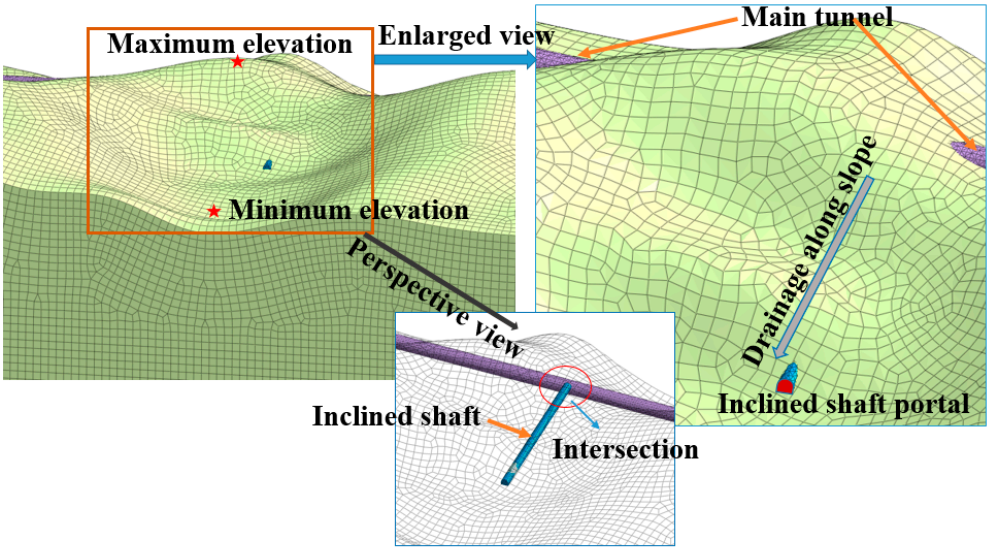

Figure 4. Schematic of Inclined Shaft with Downslope.

For a large-length inclined shaft, considering disaster prevention requirements, it is appropriate to set gentle, flat, or even reverse slopes along the longitudinal section of an inclined shaft. For example, it is stipulated in the specification that a ramp section with a longitudinal slope of not less than 3% should be set at the portal of the inclined shaft to avoid water flowing from the outer parts into the inclined shaft, and a transitional gentle slope section should be set at the bottom of the shaft. In addition, a vertical curve transition with a radius in the range of 12–20 m should be used at the change point of the wellhead and bottom of the shaft. A gentle slope section with a longitudinal slope <3% should also be set every ~200–300 m to provide space for the installation and construction of inclined shaft drainage protection facilities, staggered lanes, and crashproof car-sliding equipment. However, in actual engineering, the design of the gentle slope section of an inclined shaft should not be generalised, and the slope and length of the gentle slope section should be adjusted in time. A slope that is too gentle increases the overall slope and length of the inclined shaft. A slope that is too large or a gentle slope section that is too short will reduce the cushioning effect, as shown in Figure 5.

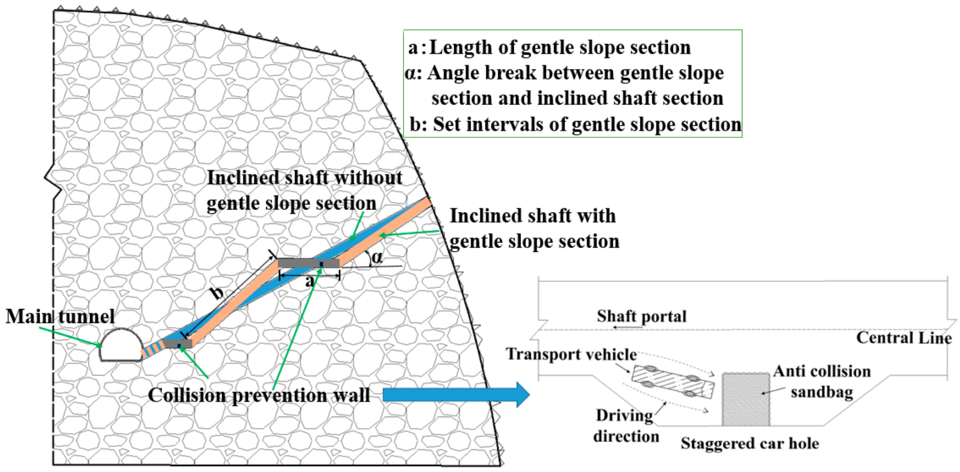

Figure 5. Schematic of Single Longitudinal Slope Comprising an Inclined Shaft with a Gentle Slope Section and an Inclined Shaft Without a Gentle Slope Section.

Some scholars have also found that an excessive fold angle of an inclined shaft and gentle slope sections also affect a tunnel's ventilation effect [17]. It is necessary to conduct additional research on the selection of intervals and longitudinal slopes of gentle slope sections of inclined shafts. It is better to comprehensively consider factors such as inclined shaft route design, slope design, type of transport machinery, ventilation requirement of the inclined shaft, and friction coefficient of the inclined shaft pavement so that the final route arrangement cannot only avoid unfavourable geological sections, but can also meet the requirements of transportation safety and ventilation functions.

2.2. Inclined Shaft Section Design

In a long mountain tunnel, some inclined shafts are specially used for operation ventilation, some of which are only used to increase the working face of the main tunnel; some are also used for disaster prevention and rescue or for quick construction and operation ventilation of the main tunnel, which determines the diversification of the inclined shaft sections. Therefore, the standardisation of inclined shaft sections is not feasible. However, because the inclined shaft section is related to many factors, it is easy for designers to ignore the actual problems encountered in construction when determining the inclined shaft section. This leads to a contradiction between the original design section and the space required for ventilation and mechanical transportation during the construction stage. For example, for some trackless transport inclined shafts, the clearance of the inclined shaft after lining cannot simultaneously meet the requirements for vehicle passage and ventilation duct layout (Figure 6). If a large section of the inclined shaft is added at this time, not only will the project cost increase, but the construction difficulty and duration will also increase [18]. Therefore, when designing an inclined shaft section, we should fully consider various factors, pay attention to the standardisation of the design process, and attempt to avoid the aforementioned problems.

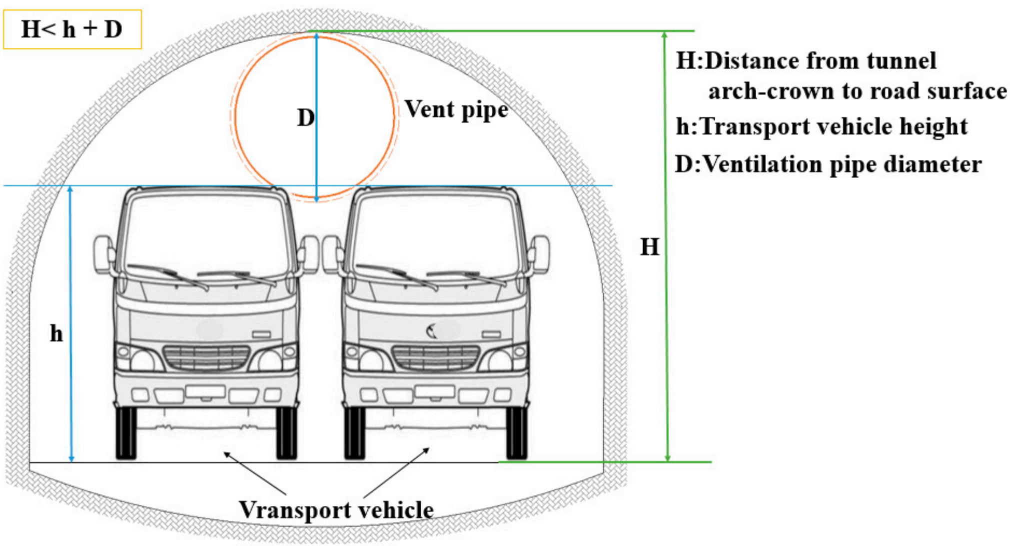

Figure 6. Trackless Transport Vehicle Intersects with Ventilation Duct.

In the design of an inclined shaft section, factors such as the geological conditions of the surrounding rocks, stress of the surrounding rocks, function of the inclined shaft, and construction method used need to be considered. The stress condition of the surrounding rocks is an important factor in the design of an inclined shaft section [19]. Dai and Li [20] analysed the variation rule of the pressure arch boundary and thickness with different section shapes of an inclined shaft based on the Porsche pressure arch theory of bulk mechanics. The results showed that the effect of the straight wall arch section on arching was stronger than that of the circular section, and the bearing capacity of the surrounding rock increased, which is more suitable for geological conditions with high geostress. Dong and Wu [21] suggested that when the pressure at the side wall of an inclined shaft is less than that at the vault, a straight wall arched section should be used. For certain special geological conditions, the horseshoe section can also be selected according to the stress characteristics.

For an inclined shaft only used for ventilation in the operation stage, the air demand is the main factor determining the section. If the required ventilation volume is constant, the section size increases, the wind speed is reduced, the power consumption of the fan decreases, and operational costs are lowered. However, a larger section size will increase the project cost; thus, comprehensive consideration should be taken in design. If the required wind speed is constant, the section area can be reduced appropriately, and the cost of project construction and the operational cost of ventilation can be reduced [22]. For an inclined shaft in auxiliary main tunnel construction, the section design should consider the aforementioned factors and meet the functional requirements of auxiliary main tunnel construction. The section height and width of the inclined shaft can be calculated according to Equations (3) and (4), respectively [23].

$$h = h_1 + h_2 + h_3 + d \tag{3}$$

In Formula (3), h is the inclined shaft section height (m), h_1 is the height of the slag-loading machine (m), h_2 is the height from the track bed to the car tray or rail bottom (m), h_3 is the safety control height of the transportation equipment (m), and d is the diameter of the ceiling ventilation pipe (m).

$$b = b_1 + b_2 + \sum b_i \tag{4}$$

In Formula (4), b is the inclined shaft section width (m), b_1 is the width of the slag loading machine (if it is a double transportation corridor, its value is multiplied by two) (m), b_2 is the width of sidewalks (m), and $\sum b_i$ is the sum of the safety gaps between equipment rooms, equipment, and the surrounding rock (m).

3. Inclined Shaft Ventilation Design

In the construction of long mountain tunnels, inclined shafts are typically required to assist ventilation [24]. The common ventilation methods for inclined shafts include single-head press ventilation, air-duct ventilation of the middle partition plate, and air-bin ventilation. Different ventilation methods have advantages, disadvantages, and adaptive conditions that need to be selected reasonably.

3.1. Construction Ventilation

3.1.1. Project Design

Single-head press-in ventilation is the most commonly used ventilation method for inclined-shaft construction. This ventilation method directly conveys air outside the tunnel to the excavation face of the inclined shaft. However, long-distance press-in ventilation may have adverse effects, such as air leakage. This can be alleviated by increasing the length of the single-throttle duct and by choosing high-quality, long-filament polyester fibres as the base cloth. With the rapid development of high-power and high-volume fans, the application of forced ventilation in auxiliary jet ventilation conditions in the construction of inclined shaft auxiliary main tunnels is increasing [25], as shown in Figure 7.

In some cases where the ventilation requirements of the twin-line main tunnel are met simultaneously, the cross-channel between the twin-line tunnels can be excavated to coordinate with the inclined shaft for ventilation, as shown in Figure 8 [26]. It was found that when the inclined shaft adopted forced ventilation, the main factors which influenced the ventilation efficiency were the angle between the inclined shaft and main tunnel, length of the tunnel, and the distance between the air duct opening and tunnel face. In addition, the longitudinal slope of the inclined shaft influences forced ventilation [27].

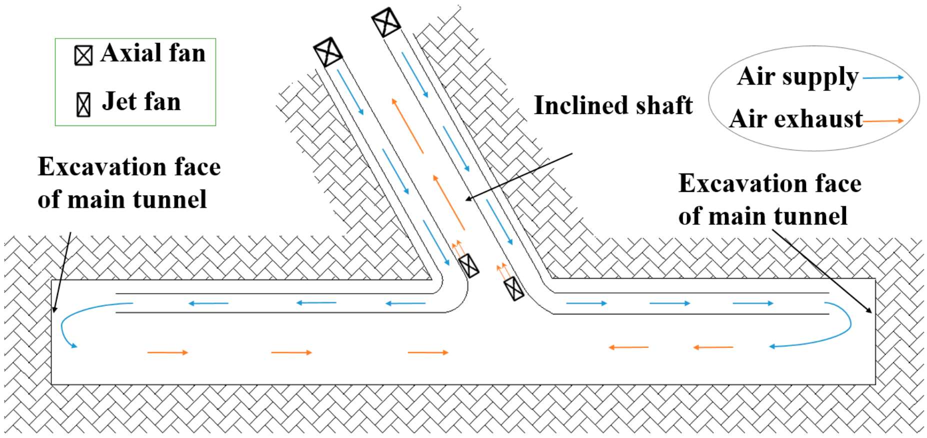

Figure 7. Schematic of an Outlet Pressure Ventilation System.

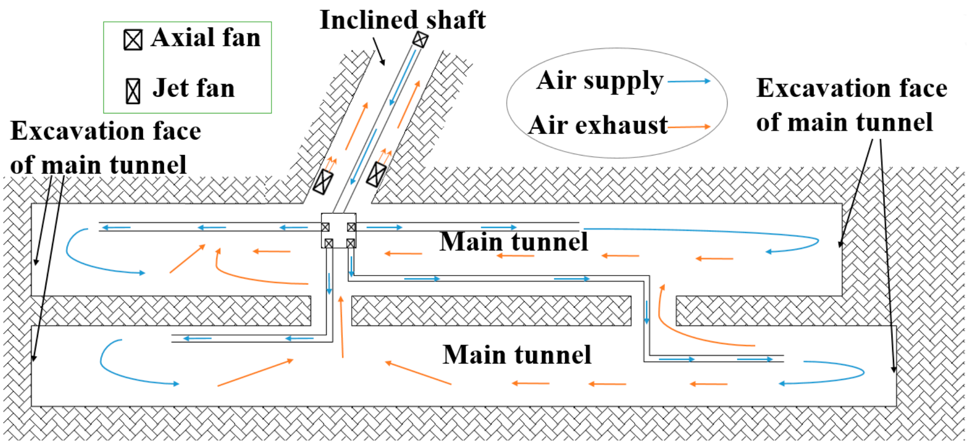

Figure 8. Single Outlet for Multi-face Pressure Ventilation System.

Air-duct ventilation with a middle bulkhead can be used when the construction section of the auxiliary main tunnel in a long inclined shaft is far away. This ventilation method divides the cross-section of the inclined shaft into upper and lower parts by means of a middle bulkhead, with an upper air-inlet duct and a lower air-outlet duct (see Figure 9). This method can increase the air-supply area of the air-inlet duct and reduce air leakage and drag loss along the way. When medium-partition ventilation is used, the ventilation resistance of the inclined shaft partition duct can be calculated using Formula (5) [28].

$$\begin{aligned} H_J &= R_J {Q_J}^2 + \sum \xi \cdot \tfrac{\rho}{2} {v_J}^2 \\ R_J &= \tfrac{\alpha L U}{S^3} \end{aligned} \quad (5)$$

where R_J is the wind's resistance coefficient along the air inlet duct at the upper part of the diaphragm, S is the sectional area of the air inlet duct (m^2), α is the wall friction resistance coefficient (N·s^2/m^8), L is the length of the inclined shaft (m), U is the wet perimeter length (m), H_J is the total resistance loss of the air inlet duct (Pa), Q_J is the ventilation volume of the air inlet duct (m^3/s), ξ is the local resistance coefficient, v_J is the wind speed of the air inlet duct (m/s), and ρ is the air density (kg/m^3).

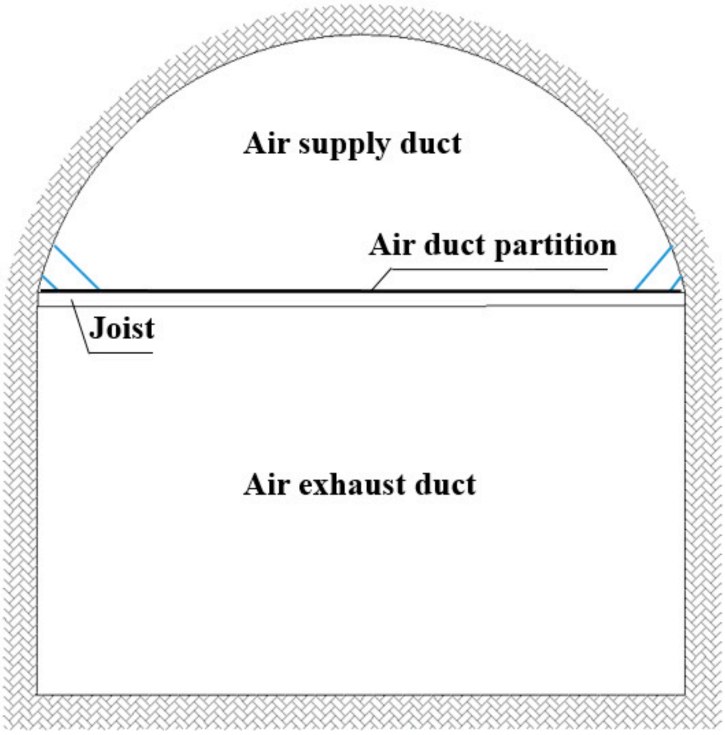

Figure 9. Diaphragm Structure in Inclined Shaft Tunnel.

The partitioned air-duct method has lower energy consumption and a relatively long ventilation distance. For example, because the Guanjiao Tunnel is located in a plateau area, the environmental conditions are adverse, air pressure is low, and the oxygen content in the air is low. After careful consideration, the ventilation scheme of the partition inclined shaft was finally adopted, which effectively solved the ventilation problem of the plateau tunnel [29]. When the partition ventilation scheme for an inclined shaft is designed, the distance between the middle partition and the outlet of the air duct and the face of the palm should be adequately controlled. The distance between the end of the middle partition and the excavation face should be less than 20 m, and the distance between the outlet of the air duct and the excavation face should be less than 30 m to meet the requirements of the Code for Construction of Railway Tunnels, which indicates that the wind speed at the excavation face should not be less than 0.15 m/s. Sun et al. [30] found that in an inclined shaft with a length > 300 m, the ventilation effect was better when the fan was arranged in series, whereas the ventilation volume was larger when a short inclined shaft was arranged in parallel. When a partition air duct is used for ventilation in an inclined shaft, if the adopted air-leakage prevention measures for the partition are inadequate, air leakage will be increased and dirty air will be circulated. Therefore, effective closure measures must be enforced when a partition air duct is constructed [31].

In recent years, to solve the problems of low efficiency of forced ventilation and small airflow in the working face, a silo ventilation scheme has been developed and applied. This ventilation scheme involves setting up an air silo at the intersection of the inclined shaft and main tunnel and the installation of axial fans in the air silo, which can effectively control the airflow from the air outlet to the excavation face and improve ventilation efficiency [32,33]. The silo-type ventilation of the inclined shaft auxiliary main tunnel mainly includes two types: duct-combined and bulkhead-combined air silos. In the duct-type ventilation scheme, fresh air is pressed into the silo at the bottom of the inclined shaft by axial flow fans, and the air is then supplied to the main tunnel in two directions by axial flow fans on both sides of the silo. After removing the harmful gas, it is discharged out of the tunnel by jet fans through the inclined shaft, as shown in Figure 10. Bulkhead-combined air silo-type ventilation has fewer applications than duct-type ventilation, but the large space section on the upper part of the bulkhead can significantly reduce the resistance along the way and improve ventilation efficiency. When the air demand for heading-face construction is large, several groups of relay jet fans can be set in the partition panel intake duct to ensure a fresh air supply in the air silo, while jet fans can also be installed in the exhaust duct to provide auxiliary power for the exhaust of dirty air. This set of ventilation systems can be used for the construction of long complex tunnels on multiple working surfaces, as shown in Figure 11. According to the study by Chen et al [34], the specifications of the air-storage silo and the arrangement position of the fan significantly influence the ventilation efficiency of the axial flow fan. When the fan is farther from the inclined shaft port (L1), the silo length (L3) is larger, the partition length (L2) has the same width as the silo, and the efficiency is higher. The efficiency was stable when the silo length was larger than 25 m (see Figure 12 for the optimal arrangement scheme).

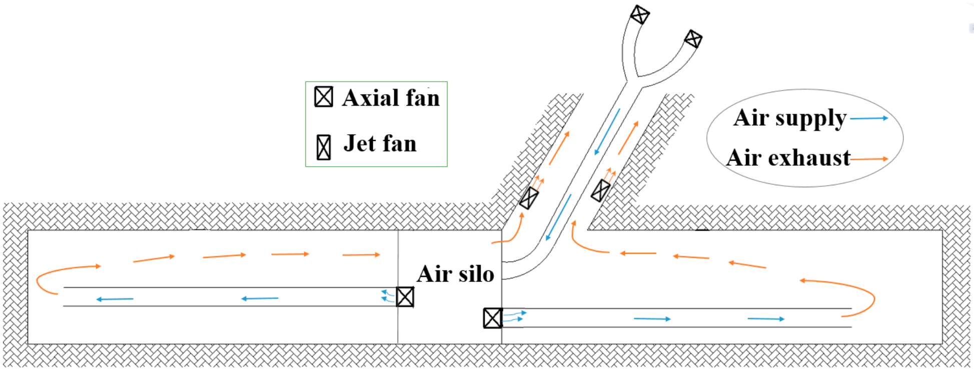

Figure 10. Ventilation Schematic with Air Duct and Wind Bin.

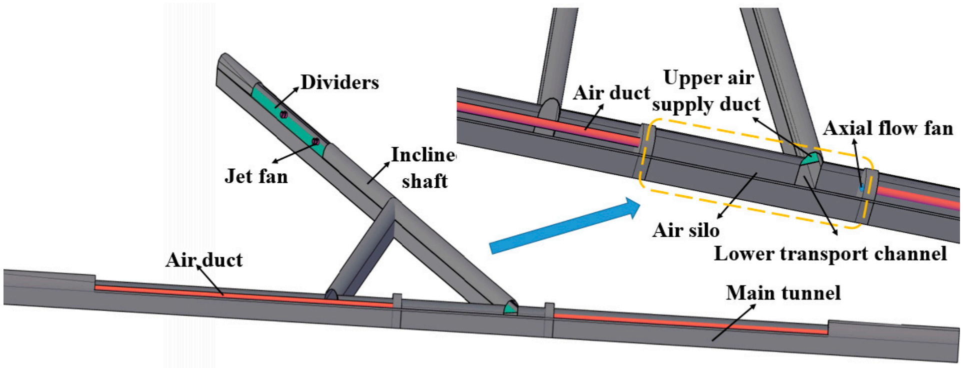

Figure 11. Ventilation Schematic of Partition Wind-Bin-Type Ventilation Space.

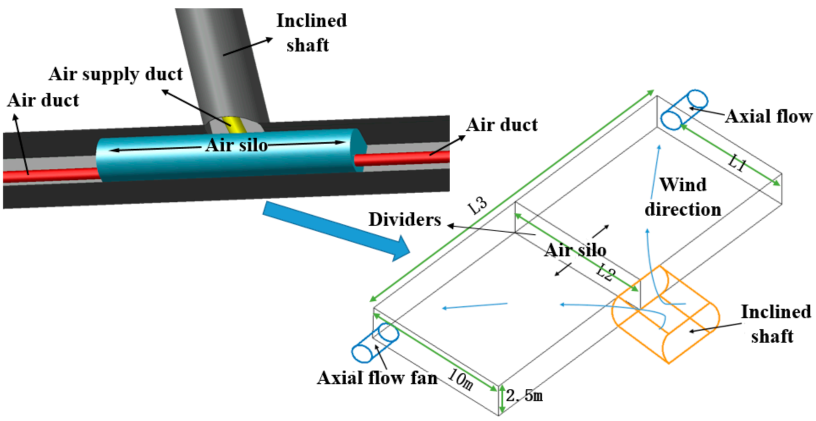

Figure 12. Schematic of Wind Bin and Fan Layout.

3.1.2. Calculation of Air Demand

In the design of inclined shaft ventilation, in addition to the reasonable selection of ventilation scheme, the calculation of ventilation volume required during the inclined shaft and main tunnel's construction is also important, and determines the ventilation scheme to a certain extent. When determining the air demand of an inclined shaft, the main factors to be considered are the number of workers, the minimum allowable wind speed, the dilution of exhaust gas from the internal combustion engines, and the elimination of blasting waste smoke. The air demand calculated according to the above factors is expressed by Q_1, Q_2, Q_3, and Q_4, respectively. The final air demand can be determined according to Formula (6) [35,36].

$$Q = \max(Q_1, Q_2, Q_3, Q_4) \tag{6}$$

Case statistics show that (Table 1) the air volume required for the dilution and emission of exhaust gas from internal combustion engines is often the largest; in most cases, this is the control value of the air volume required for inclined shaft construction.

Table 1. Statistics of Air Volume Required for Inclined Shaft Construction Ventilation Cases.

Project Name	Q_1	Q_2	Q_3	Q_4
No. 2 inclined shaft of Shiziping Tunnel of Wen-Ma Expressway	234	1080	621	1629
Yantai Wanhua Industrial Park Underground Tunnel	/	7110	3026	8327
No. 6 inclined shaft of Guanjiao Tunnel of Qinghai-Tibet Railway	85	1080	1012	1800
West Qinling Tunnel inclined shaft of Lanzhou-Chongqing Railway	210	938	1001	1069
Wushaoling Tunnel inclined shaft of Lanzhou Xinjiang Railway	/	525	546	786

In recent years, with the construction of tunnels in high-altitude areas, owing to the characteristics of 'low-air pressure, low-oxygen content, and high cold', the four air-demand calculations described above are all related to high-altitude factors, except the lowest allowable wind speed. In the ventilation design, it is necessary to modify the relevant parameters with altitude, and the correction coefficient typically increases linearly with elevation. In an actual project, it was also found that the fan efficiency of the high-altitude tunnel was significantly lower than that of the plain tunnel, and the efficiency loss reached 36.3% [37]. The transportation efficiency of construction machinery in a low-pressure environment was only 25–80% [38] of that in a plain environment, which further increases the difficulty of ventilation for traditional diesel locomotives.

In recent years, electric vehicles have developed rapidly. At present, China has more than 800,000 main domestic construction machinery products. One of the main goals of the construction of China's modern energy system during the 14th Five Year Plan period is to accelerate the low-carbon transformation of energy and increase the proportion of non-fossil energy. Under the joint promotion of policies and development trends, it provides opportunities and potential for the application of new energy engineering machinery, and improves the low-carbon and electrification level of terminal energy consumption. If electric vehicles can be used to replace diesel locomotives in inclined shaft construction, the demand for construction ventilation can be significantly reduced. In 2015, the world's first electric trackless rubber-tire transport vehicle was successfully used in the Daliuta Coal Mine of the China Coal Group, marking the beginning of the era of new energy transport vehicles in mine roadways, as shown in Figure 13 [39]. However, the use of new energy transport vehicles in mountain tunnel inclined shaft construction has not been reported yet.

Figure 13. Electric trackless rubber wheel transporter used for mining.

At present, the developed large-power electric transport vehicle has good transport performance. For example, the battery-powered tractor designed by CRRC Sifang Co., Ltd. (Qingdao, China) is driven by a rear axle rubber wheel, which includes two operation modes: tracked and trackless. The maximum operating speed is 22 km/h, and the maximum climbing angle can reach 20° during trackless transport, as shown in Figure 14 [40]. Following the development of electric vehicle technology, electric vehicles can undertake inclined shaft excavation, slag removal, and transportation, which has broad application prospects in the future.

Figure 14. Rear axle rubber-wheel drive electric traction transport vehicle.

At present, with respect to the design of inclined shaft ventilation schemes, many ventilation calculation parameters are still selected based on experience, and they mainly focus on ventilation design when the inclined shaft is used to assist the main tunnel construction, ignoring research on the ventilation characteristics of the inclined shaft itself. For example, the intersection of the inclined shaft and main tunnel and the intersection of bent ventilation pipes are prone to the phenomenon of waste air circulation; in-depth research on these problems has not been conducted yet. The inclined shaft has a large longitudinal slope, and the internal combustion machinery requires different air volumes when moving up and down the slope of the inclined shaft. When going up the slope, the exhaust gas increases as the size of the vehicle increases, and the required air volume is far greater than that when going down the slope. In this case, the design of a suitable ventilation scheme for an inclined shaft requires further research. In addition, existing tunnel ventilation and disaster prevention are primarily aimed at completed tunnels. However, for large-scale projects with multiple working faces, multiple equipment entrances and exits, and many workers, there is only one inclined shaft entrance and exit before the connection. If the fire hazard is high, the identification of ways to conduct effective disaster prevention and ventilation at this time is of great significance for saving the lives of construction personnel.

3.2. Ventilation Operation

The energy consumption of the operating ventilation equipment of a long mountain tunnel accounts for approximately 70% of the overall operating cost [41], which introduces great economic pressure to the management and operation of the tunnel. Therefore, the impact on the subsequent ventilation operation should also be considered in the construction ventilation design phase. However, current research on inclined shaft ventilation is mostly focused on the construction period. With the diversification of inclined shaft functions, the inclined shaft can also assist the main tunnel ventilation or can be used as an emergency exit during the operation period. At this time, the temperature of the natural wind in the inclined shaft varies greatly in different seasons; thus, it is necessary to master its influence law to reduce the operating ventilation cost [42].

When an inclined shaft is used to assist in the ventilation of the main tunnel, the wind speed and its direction are affected by natural wind pressure [43]. The natural wind pressure is composed of the thermal potential difference, overpressure difference, and air-wall pressure; among these, the thermal potential difference is the most significant [44]. The calculation method for the thermal potential difference of mountain tunnels with inclined shafts is shown in Figure 15 and is expressed by Formula (7) [45].

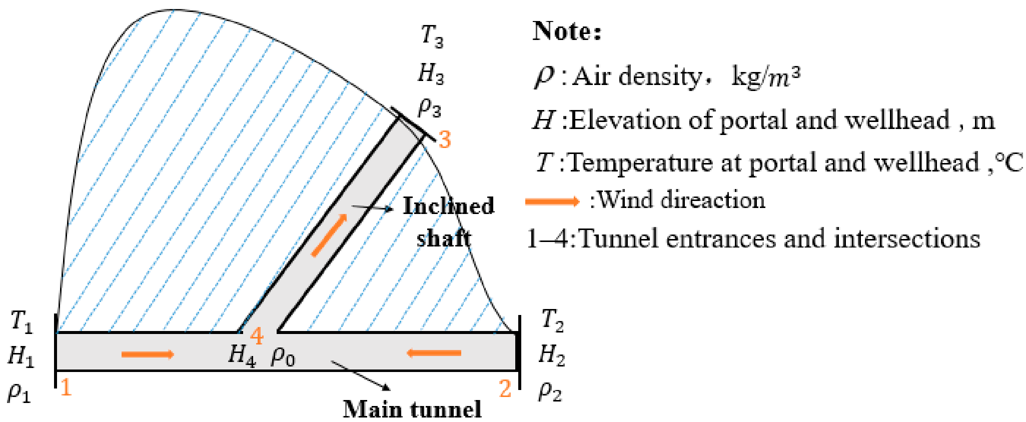

Figure 15. Schematic of Thermal Potential Difference Between Inclined Shaft and Main Tunnel.

The calculation formula of thermal potential difference is

$$\begin{aligned} \Delta P_{13} &= \rho_{13} g H_{13} - \rho_0 g H_{14} - \rho_0 g H_{43} \\ \Delta P_{23} &= \rho_{23} g H_{23} - \rho_0 g H_{24} - \rho_0 g H_{43} \end{aligned} \tag{7}$$

where ΔP_{13} and ΔP_{23} are the thermal potential differences from the tunnel portal 1 and 2 to the inclined wellhead (Pa), ρ_{13} is the average density of portal 1 and inclined wellhead 3, $\rho_{13} = \frac{(\rho_1+\rho_3)}{2}, kg/m^3$, ρ_{23} is the average density of portal 2 and inclined wellhead 3, $\rho_{23} = \frac{(\rho_2+\rho_3)}{2}, kg/m^3$, H_{ij} represents the relative height difference between I and j (m), and ρ_0 is the air density in the tunnel (kg/m^3).

Formula (7) shows that the greater the temperature difference inside and outside the tunnel and inclined shaft, the greater the air density difference, and the greater the corresponding thermal potential difference. Overall, the wind speed in the inclined shaft tunnel is positively correlated with the environment and the temperature difference between the main tunnels. Typically, the temperature in the main tunnel changes slightly. When the ambient temperature in the winter is less than the temperature in the tunnel, the inclined shaft wind direction is exhausted. When the ambient temperature in the summer is greater than the temperature in the tunnel, an inclined shaft wind direction is supplied. If the inclined shaft only plays the role of auxiliary main tunnel ventilation during operation, the number of fans can be controlled according to the wind direction of the inclined shaft during different seasons to achieve maximum energy conservation. In cases with inclined shafts for long and large railway tunnels, if it is used as an emergency rescue passage, the protective door at the intersection of the inclined shaft and the main tunnel should be opened for evacuation in the case of an accident (as shown in Figure 16). However, owing to the influences of seasonal temperature, wind speed, or wind direction at the protective door, the specification requirements may not be met.

Figure 16. Protective Door at the Intersection of the Inclined Shaft and Main Tunnel.

In 2021, one of the authors quantified the wind speed, wind pressures inside and outside the tunnel, and temperature at the protective door of the auxiliary tunnel in nine tunnels on a railway line, as shown in Figure 17. The results show that when the protective door was turned on and the jet fan was not turned on, some protective doors had wind blowing to the main tunnel (the wind direction did not meet the requirements), whereas the wind at the protective door between the cross-tunnel passage and the main tunnel blew from the main to the cross-tunnel (the wind direction met the requirements). When the jet fan installed in the auxiliary tunnel was turned on, only part of the inclined shaft protective door was associated with air flows in the opposite wind direction; in this case, the wind speed met the requirements. However, the wind direction or wind speed of the other inclined shaft protective door could not meet the specification requirements. The aforementioned results are only the measured results at a certain time during winter. If the test was conducted in the summer, opposite results may be obtained. Therefore, it is recommended to strengthen the monitoring of wind speed and the thermal potential difference at the tunnel's protective door subject to the conditions listed above; this can accumulate data, achieve linkage control, and accomplish the timely adjustment of the working state of the fan to achieve a balance between operational ventilation and tunnel energy conservation [46].

In the future, to design an inclined shaft ventilation scheme, more attention should be paid to the development of intelligent control and energy conservation. For example, the automatic opening, closing, and dynamic speed regulation-control technology of fans should be studied at different natural wind pressures, with and without vehicles in the tunnel [47,48]. Additionally, annual intelligent monitoring of the wind speed and direction of the inclined shaft should be conducted to obtain the seasonal change rule, which should be used in ventilation and energy conservation. This is also the focus of future research on the ventilation and energy conservation of inclined shaft tunnels.

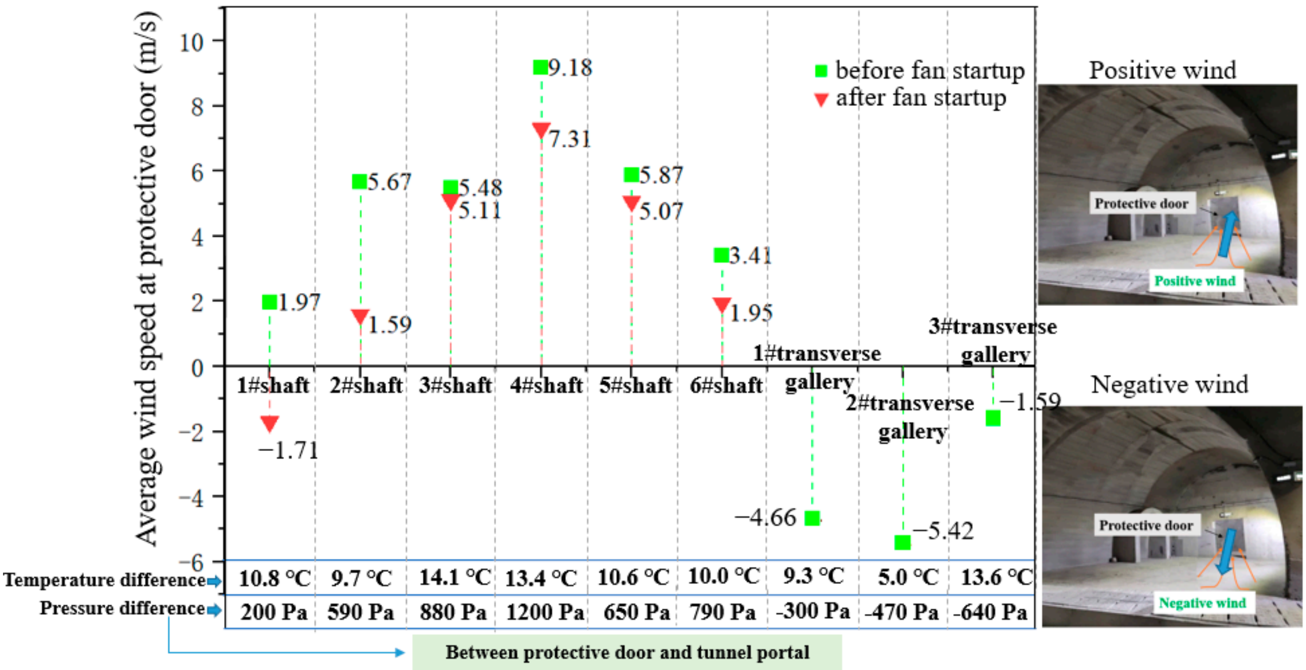

Figure 17. Wind Speed Results of Nine Auxiliary Passageway Protection Doors on a Railway Line.

4. Support Structure for an Inclined Shaft

At present, the design of inclined shaft supports in China mostly refers to the main tunnel; this is a stage that still relies on engineering experience. The lining and support parameters of inclined shafts for different surrounding rocks are briefly defined in the Highway Tunnel Design Specification [23]; only the recommended support parameters with an inclined shaft width < 5 m are provided, whereas in Highway Tunnel Design Details [9], only the support parameters of inclined shafts with a span of 5–8 m are provided. However, both of these two specifications are approximate. Considering the influences of various factors, such as the grade of the surrounding rock, formation parameters, groundwater, and in situ stress [49] on the surrounding-rock pressure of the inclined shaft lining, and the interactions of these factors that collectively affect the stability of the inclined-shaft-surrounding rock, it is inferred that research on the support parameters of the inclined shaft is insufficient.

4.1. Calculation of Surrounding-Rock Pressure

The calculation of the surrounding pressure of an inclined shaft refers to the main tunnel, including the collapse arch height, Porsche, and Tershaki theories.

For an inclined shaft with a gentle slope, the surrounding-rock pressure can be calculated according to the aforementioned general tunnel calculation method; however, for a steep-slope inclined shaft, the surrounding-rock pressure needs to consider the influence of the longitudinal slope. However, there is currently no uniform standard for the calculation of the surrounding-rock pressure of steep-slope inclined shafts in the industry, and only a few scholars have studied this. In the *Well Construction Engineering Manual* [50], it was indicated that when the longitudinal slope of an inclined shaft is less than 45°, the surrounding rock-pressure can be calculated according to its actual longitudinal slope. The calculation method is expressed by Formula (8). When the longitudinal slope of the inclined shaft is in the range of 45–80°, the surrounding-rock pressure can be calculated to be equal to 45°. When the longitudinal slope of the excavated shaft is greater than 80°, the surrounding-rock pressure can be calculated based on the shaft.

$$F_1 = \gamma h_0 B \cos\alpha \tag{8}$$

$$F_2 = \gamma h_0 B\sin\alpha$$

In Formula (8), F_1 and F_2 are the pressures (kN/m) acting in the direction of the inclined shaft support and the longitudinal direction of the inclined shaft, respectively; h_0 is the pressure arch height (m), and its value is related to the Prat coefficient of the inclined shaft surrounding the rock [51]. When the Prat's coefficient is >3, $h_0 = \frac{B}{2tg\varphi}$, where φ is the internal friction angle of the surrounding rock (°). When Prat's coefficient is <2, $h_0 = \frac{B_1}{tg\varphi}$, where $B_1 = \frac{B}{2} + \frac{H}{\cos\alpha}ctg(45° + \frac{\varphi}{2})$, H is the inclined shaft height (m), γ is the geotechnical capacity of surrounding rock at the vault (kN/m^3), B is the width of the inclined shaft section (m), and α is the longitudinal slope of the inclined shaft.

4.2. Selection of Support Scheme

Traditional support measures for inclined shaft sections are the concrete linings combined with anchor net shotcrete support. In recent years, with the complexity of engineering geological conditions and the expansion of inclined shaft scale, support measures have become more diversified, such as steel support, mortar anchor, resin anchor, shotcrete, and pipe shed advanced support.

In addition to the pressure of the surrounding rock, many factors influence the selection of support parameters for inclined shafts. Ji and Lv [52] indicated that for a water-rich sand layer, its structure is loose, its cohesion is small, and the surrounding rock of the inclined shaft in this formation is easily relaxed and deformed. As shown in Figure 18, reinforcement support measures, such as formation reinforcement and well-point precipitation, grouting in the tunnel, and the freezing method [53], are needed to enhance the stability of the surrounding rock of the inclined shaft in the water-bearing sand layer. The study also shows that when precipitating the surrounding rocks of deep-buried water-rich inclined shafts, the axial force and bending moment of the tunnel side wall significantly increase, while the axial force at the tunnel arch and inverted arch decreases; with the discharge of water, the compressive stress concentration will occur in the inclined shaft lining at the stratum junction. Therefore, the support measures need to be strengthened in the position where the internal force of the inclined shaft increases and stress concentration will likely occur. The joint-support scheme of a wooden board and small pipe shed (Figure 19) was designed for an inclined shaft in a water-rich sand layer, which can effectively alleviate extrusion and sand outcropping at the excavation face. Niu [54] found that for inclined wells in water-bearing strata, when conventional support measures are used to support them, the deformation increases significantly, and the difficulty of support is significantly higher than that in non-water-bearing strata. For a large inclined shaft section in non-water-bearing strata, temporary support with a steel arch and permanent support with a steel mix can play a very good role in surrounding rock reinforcement. Therefore, the necessary advance pre-support should be applied to water-bearing strata.

For an inclined shaft in a soft rock stratum, the pressure is high at the beginning of the excavation, and the deformation is significant. At this point, permanent support should be avoided. The surrounding rock can be actively reinforced first and shotcrete applied when the deformation of the surrounding rock is stable. When choosing support measures, in addition to considering the influence of groundwater, attention should also be paid to the combination of the pressure relief of the surrounding rocks, pressure relief, and support-bearing capacity improvement. Typically, combined support composed of anchor rods, anchor cables, metal nets, and shotcrete can form the structural effect of the rigid beam together with the surrounding rock, transfer pressure to the depth of the surrounding rock, and effectively improve the stability of the inclined shaft support. If the surrounding rocks of the inclined shaft are relatively fractured, grouting reinforcement measures [55] should be applied based on the aforementioned support measures. The integrity of the support structure and bearing capacity of the surrounding rocks can be greatly improved using bolt-mesh injection-coupled support technology.

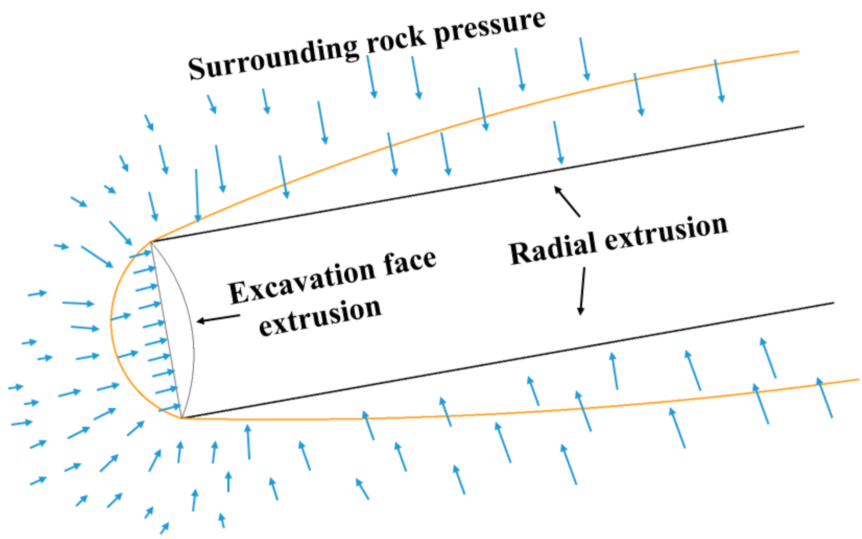

Figure 18. Deformation Characteristic Diagram of Surrounding Rock of Inclined Shaft in the Water-Bearing-sand Layer.

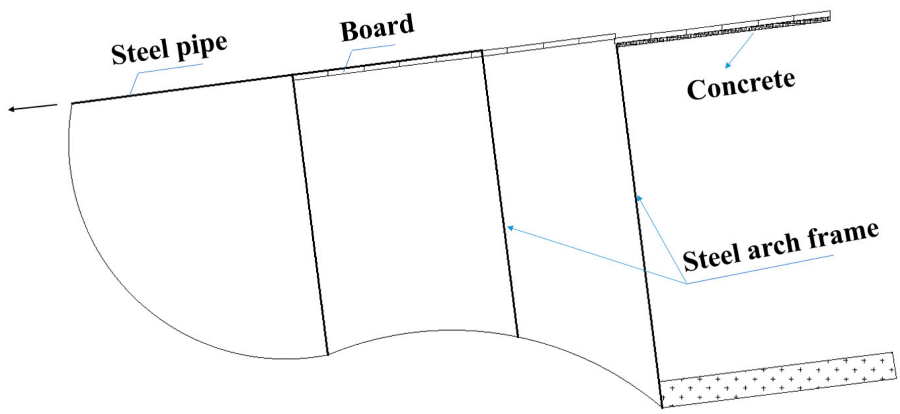

Figure 19. Advance Support of Small Pipe Shed Combined with a Wood Board in an Inclined Shaft in a Water-rich Sand Layer.

Research shows that support of safety awareness for auxiliary tunnels, such as inclined shafts, is currently very weak in the industry. Simple bolting and shotcrete support measures were only applied after the excavation of some inclined shaft tunnels. Compared with the main tunnel, the surrounding-rock classification of the inclined shaft by the design unit was also rough. Therefore, with the function of the inclined shaft in long mountain tunnels becoming increasingly important, both the designer and constructor should pay more attention to the support structure of the inclined shaft [56]. When designing support parameters, they should be linked to the function of the inclined shaft as far as possible. For example, for an operating ventilated inclined shaft, the ventilation function should be exerted for a long time and the support of the entire tunnel section of the inclined shaft should be strengthened appropriately. For inclined shafts only assisting with the main tunnel's construction, the inclined shaft was backfilled and closed after the completion of construction. If the surrounding rock has a better grade, anchor shotcrete support can be used to reduce expenditure, but support measures at the weak section and bottom of the shaft cannot be blindly reduced to save investment. During the support design, the standardised support scheme can be adopted.

5. Inclined Shaft Transport System

To satisfy the requirements of slag discharge and feeding, the inclined shaft should be designed in the corresponding transportation mode; this can be divided into two types: rail and trackless transport.

5.1. Rail Transport

The traditional transportation mode of inclined shafts in mine tunnels is rail transportation. The interference of its transportation machinery with tunnel construction is minor and transportation vehicles do not emit tail gas, which is conducive to ventilation. In steeply inclined shafts, rail transportation is used extensively.

The rail transportation system is mainly composed of lifting containers (tramcar, skip), concrete tankers, drum hoists, head sheaves, tracks, and steel wire ropes, as shown in Figure 20 [57].

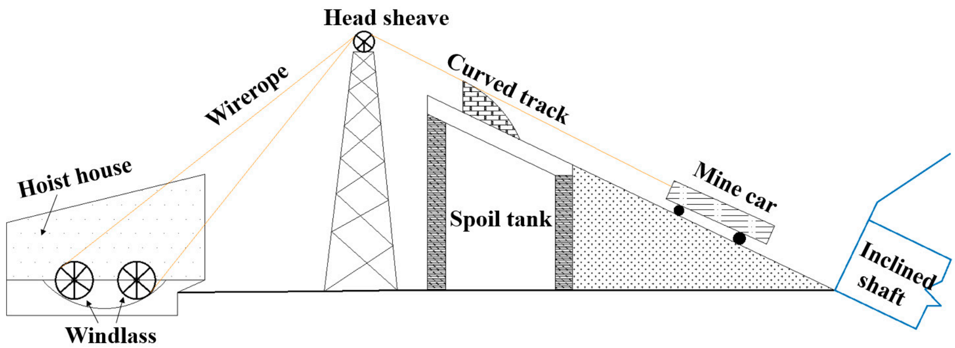

Figure 20. Schematic of a Rail Transportation System in an Inclined Shaft.

Mine car volume can be calculated according to Formula (9) [58],

$$V = \frac{1.25AK}{\varphi nt} \tag{9}$$

where A is the blasting slag volume of each cycle footage of the tunnel (m^3), K is the loose coefficient of slag soil (with values in the range of 1.8–2.0), φ is the utilisation coefficient of the mine car volume (value set to 0.9), n is the number of transportation cycles per unit time, and t is the time consumption of one lift (h).

The amount of wire rope lifted can be calculated according to (10) [59],

$$P = \frac{Q(\sin\alpha + f_1\cos\alpha)}{\frac{110\sigma}{m} - L(\sin\alpha + f_2\cos\alpha)} \tag{10}$$

where P is the dosage of the steel wire rope (kg/m); Q is the lifting load, which is the sum of the dead weight (Q_1) and load (Q_2) of the mine car (kg); α is the longitudinal slope of the inclined shaft (°); f_1 is the tramcar running resistance coefficient (with values in the range of 0.01–0.015); σ is the tensile strength of the steel wire rope (values in the range of 1519–1666 MPa); m is the safety factor (set to the values of 6.5 and 9 when lifting muck and lifting people, respectively); L is the lifting length of the steel wire rope (m); and f_2 is the resistance coefficient of the steel wire rope (with values in the range of 0.35–0.4).

To avoid excessive bending stress when the steel wire rope is wound, the ratio of drum diameter to steel wire rope diameter should be greater than 60, as indicated in The Coal Mine Safety Code (China 2016), and the ratio of the diameter of the lifting head sheave to the diameter of the steel wire rope should be greater than 40. When selecting the windlass type, it is necessary to comprehensively consider the dead weight, load, lifting capacity, longitudinal slope of the inclined shaft, and other factors of the mine car. The stress of the windlass is shown in Figure 21, and its maximum static tension (F_1) and maximum static tension difference (F_2) can be calculated according to Formula (11) [60]:

$$\begin{aligned} F_1 &= nQ(\sin\alpha + f_1\cos\alpha) + PL(\sin\alpha + f_2\cos\alpha) \\ F_2 &= F_1 - nQ_2(\sin\alpha + f_1\cos\alpha) \end{aligned} \quad (11)$$

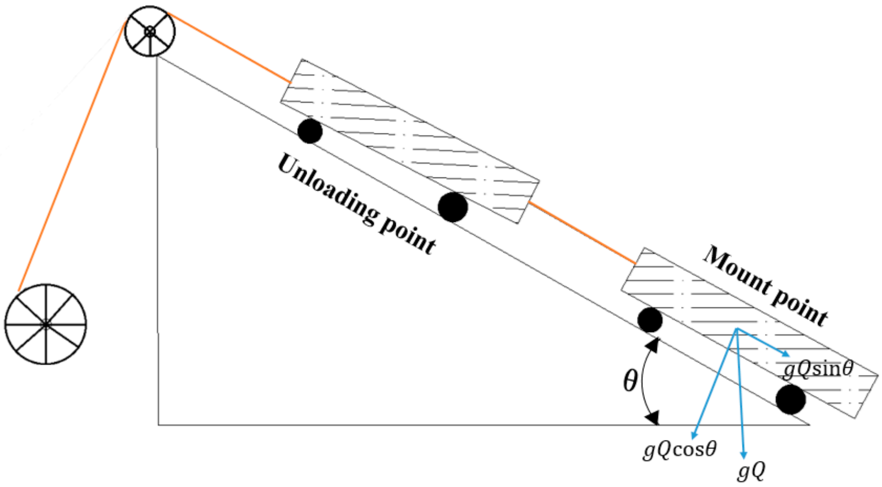

Figure 21. Hoist Diagram.

When the inclined rail transport shaft conducts double-barrel lifting, it can be arranged as a combination of four rails and two lanes, and single-barrel lifting can be arranged in the form of two rails and one lane [61]. To facilitate slag discharge and feeding material, during track layout, the slag discharge transportation track at the shaft bottom can be shrunk and merged to both sides of the inclined shaft, and the concrete transportation tanker is set in the middle of the track to provide the driving space of the transportation vehicle for Trestle type's slag unloading and material loading. The concrete can be directly poured into the transportation vehicle by the feeding tanker, and the slag truck continues to drive to the bottom of the shaft, gradually reducing its track height to values below the road surface at the shaft bottom to facilitate the slag truck to dump the slag, as shown in Figure 22. This smart, shaft-bottom transfer design and the management of slag discharge or material feeding greatly improve transportation efficiency.

Typically, the longitudinal slope of the inclined shaft for rail transportation is large, and if a car-sliding accident occurs that would cause great harm, certain safety protection measures need to be set. For example, attempts have been expended to reduce the number of hook removals on the mine car during transportation, and regularly assess the connection between the steel wire rope and the latch of the tramcar to prevent the pin from decoupling; to reduce the running resistance of the steel wire rope, the installation quantity of the ground roll needs to be increased, oil lubrication can be applied regularly, and an anti-decoupling safety device can be installed on the mine car frame to hook the sliding mine car when the steel wire rope is accidentally broken. In addition, if car slipping occurs, some buffer and anti-collision devices should be set in the middle and bottom of the inclined shaft. Examples include reinforced concrete anti-collision walls, reinforced car stoppers, and electric car stoppers (Figure 23) [58]. The electric car stopper is normally closed; when the electric box assumes that the mine car will pass normally, it will send a signal to lift the car stopper, and then lower it to its place after it passes; if a car-sliding accident happens, the car barrier will not be raised to block the mine car.

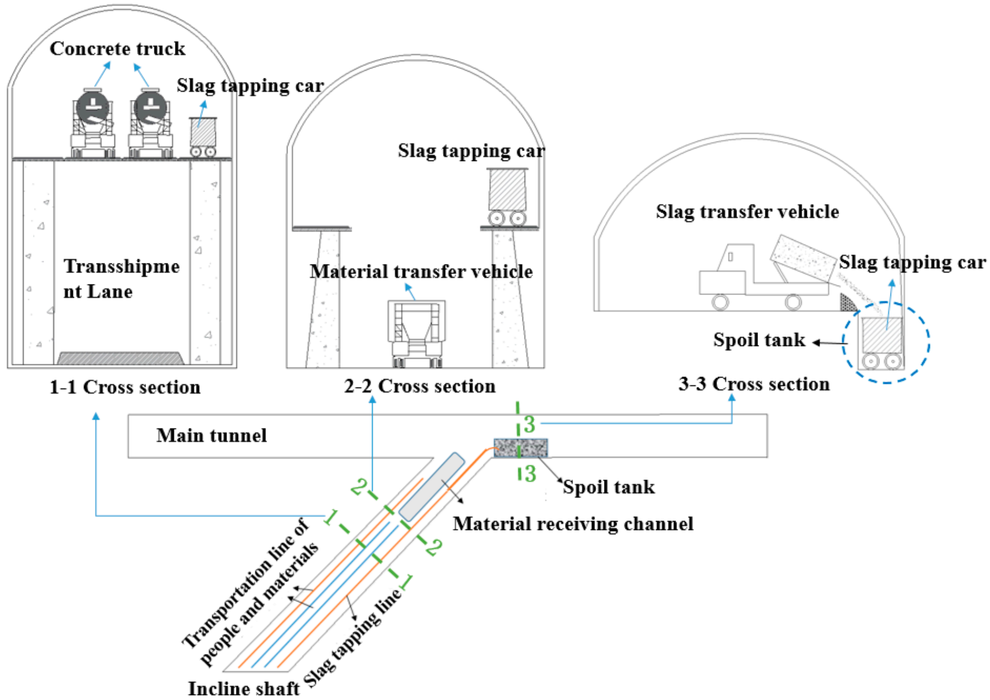

Figure 22. Schematic of Slag Transfer in the Well in Rail Transportation.

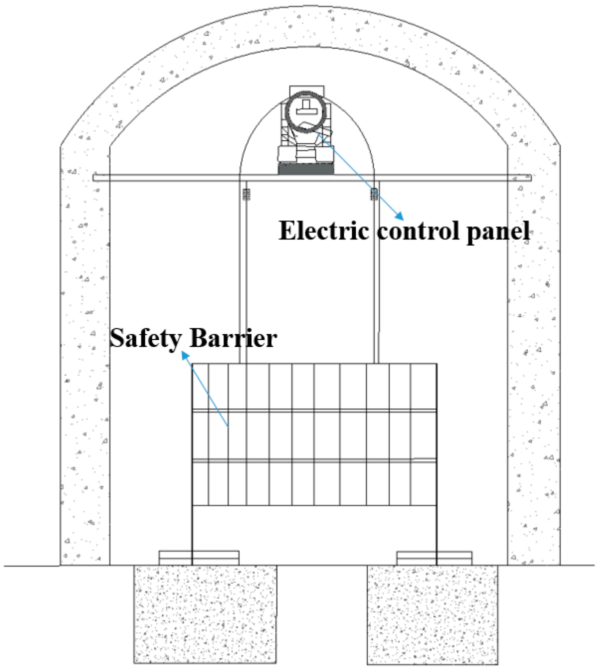

Figure 23. Schematic of the Electric Control Bar.

5.2. Trackless Transport

In recent years, trackless transportation inclined shafts have been extensively used in the construction of mountain tunnels because of their speed and efficiency, simple process, low investment, and strong flexibility and adaptability. There was some trackless transportation in small longitudinal slope inclined shafts (<10°). The Code for Design of Railway Tunnels [9] stipulates that the longitudinal slope of an inclined shaft using trackless transportation should be compatible with the climbing capacity of transportation vehicles and the comprehensive longitudinal slope should be less than 10°. The Code for

Design of Highway Tunnels [23] also recommends that the longitudinal slope of trackless transportation should not be greater than 7°, and there are many cases of trackless transportation in steeply inclined shafts in engineering practice. For example, the maximum longitudinal slope inclined shaft of the Mayazi tunnel of the Lan-Hai Expressway reached 18.6%, and the maximum longitudinal slope inclined shaft of the Taining tunnel of the Jian-Tai Expressway was nearly 20%.

In addition to the considerations of the influence of the longitudinal slope, construction efficiency is a major advantage of trackless transportation over rail transportation. As the transportation time of drilling and blasting slag accounts for 40–60% of the overall tunnel construction period [62], improving the transfer efficiency of the bottom shaft can effectively shorten the construction period. During the transportation of slag from the inclined rail transit shaft, the slag and soil should be transferred at the bottom part of the shaft; it also needs to be transported many times during material feeding. In particular, it is sometimes necessary to use feeding holes for the transportation of concrete materials. The numerous transfer processes in rail transportation often cause problems, such as downtime, during the peak construction period, which prolongs the construction period. Trackless transportation has fewer transfer steps; thus, the transportation efficiency is higher [63]. In practice, the inclined shaft No. 10 of the Wushaoling tunnel adopted an ITC312 excavator and loader combined with a 15 t dump truck to form a trackless transportation system, thus creating a construction record of 437.5 m per month, whereas the inclined shaft No. 11 of the same tunnel adopted a PC78US-6 Komatsu excavator and an ZJK-2/20X double barrel windlass to form a rail transportation system, wherein the maximum construction progress was 221.8 m per month. It can be observed that the auxiliary construction efficiency of the rail transportation inclined shaft is lower than that of the trackless inclined shaft.

Although the transportation efficiency of the rail transportation inclined shaft is high, the frequent entry and exit of slag trucks will interfere with the lining and ventilation of the tunnel, particularly when high-power transportation vehicles produce more tail gas; this increases the difficulty and cost of construction ventilation. In addition, trackless transport vehicles may slip because of braking failures in long-distance downhill sections. Therefore, in addition to the regular maintenance of transport vehicles and the replacement of brake pads, anti-collision sandbags should be set at intervals in the inclined shaft. If the inclined shaft section is small, the section where the anti-collision sandbags are located should also be increased to avoid vehicles (as shown in Figure 24), and emergency refuge holes should be set on the sidewalls at the bottom of the inclined shaft to reduce the harm of car-sliding accidents [64].

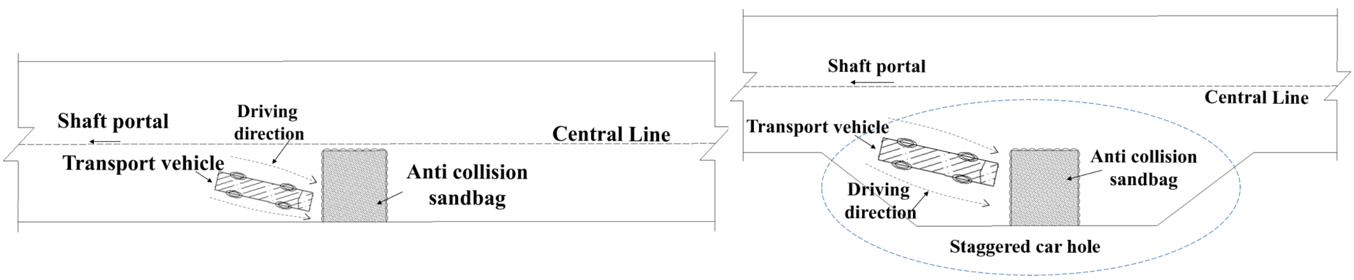

Figure 24. Layout of Two Lanes when Using Trackless Transportation.

However, the settings of these blocking devices have not been specified yet. The size and setting interval of impact-proof sandbags or piers are often determined by experience and often fail to play an effective blocking role. In addition, the section of the inclined shaft installed with an anti-impact pier needs to be widened locally, which increases construction difficulty. In addition, the materials of the anti-impact pier and anti-impact sand bag are rather hard, and the construction and transportation machinery generally have a higher quality. When a car is blocked from impact, it cannot be buffered effectively. Instantaneous impact forces may cause harm to tools and operators. Therefore, the aforementioned disadvantages of existing blocking devices for trackless transportation need to be optimised in the future to improve the convenience, reliability, safety, and scientific nature of blocking devices.

Regardless of whether rail or trackless transport is used, the effect of shortening the construction period of a tunnel with an inclined shaft is remarkable. In the future, more investment should be made in the R&D of transportation equipment, especially in the design and development of vehicular automation, intelligence, and cleanliness, to reduce tail gas pollution, improve operator safety, and enhance the degree of automation and informatization of transportation vehicles. In addition to the improvement of hardware facilities, such as transportation equipment, it is necessary to improve the level of management and dispatching to achieve efficient production and reduce the incidence of accidents caused by humans.

From the above discussion, we can infer that there are many elements to be considered in the design of an inclined shaft section, longitudinal slope, ventilation, inclined shaft support, and inclined shaft transportation system. The corresponding design principles should be formulated based on the function of the inclined shaft, as shown in Figure 25.

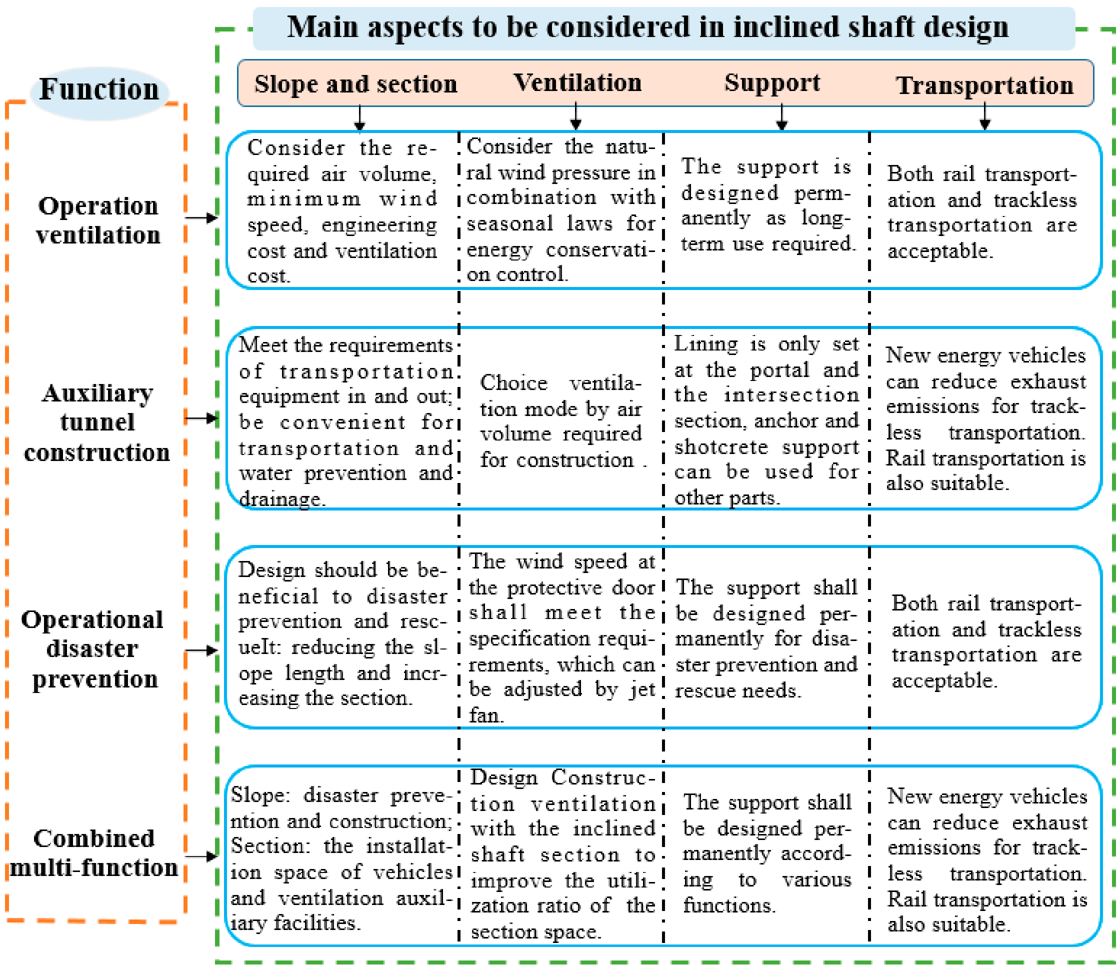

Figure 25. Inclined Shaft Design Principles Based on Function.

6. Construction Method for Inclined Shafts

Construction technology for inclined shafts in mountain tunnels originated from mine construction at the earliest time. The selection of construction tools and methods is usually between the shaft and lane, and construction technology and equipment are gradually developed with their own inclined-shaft characteristics.

6.1. Construction of the Inclined Shaft

The construction of the inclined shaft can be achieved using two methods according to the slag discharge and excavation direction: the forward shaft method for excavation from the shaft head to the main tunnel and the reverse shaft method for excavation from the main tunnel to the shaft head.

The forward-well method is the most commonly used method for inclined shaft construction. The inclined shaft plays a role in increasing the excavation face of the main tunnel and shortening the construction period as a channel used to assist main tunnel construction. However, the forward-well method requires the transportation of construction equipment and raw materials from the inclined shaft wellhead, and all excavated muck is also transported from the inclined shaft wellhead. Therefore, the inclined shaft's location must have certain transportation conditions to build construction access roads and provide a site for the layout of large elevators. In the excavation of the forward-well method, the rock is broken using a rock drill or blasting. A small longitudinal slope inclined shaft (<12°) rock is loaded by a side dump loader and transported out of the hole by a trackless transportation diesel truck, which is similar to the construction method of an ordinary mountain tunnel. When the longitudinal slope of the inclined shaft is large (>12°), the rock is loaded with a scraper and transported out of the hole by a railcar, which is similar to the construction method of an inclined shaft, as shown in Figure 26.

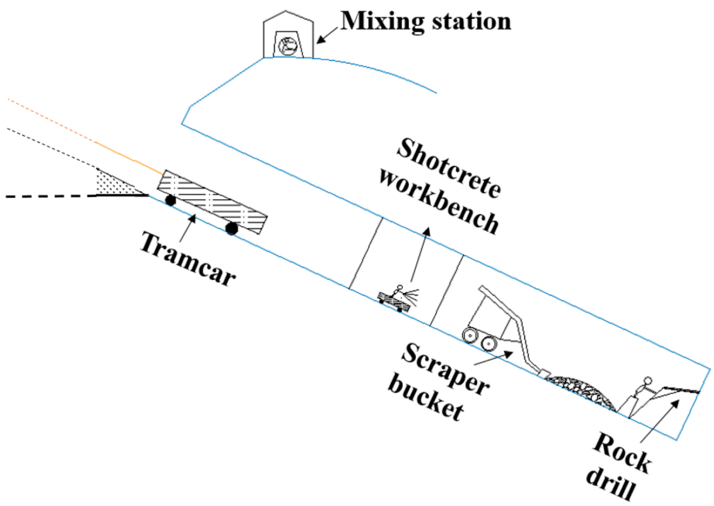

Figure 26. Schematic of Positive-well Construction Method.

The reverse-well method is used in the case of an inclined shaft that only has operational ventilation or disaster prevention functionalities. During construction, excavation is conducted from the bottom to the top at the intersection of the inclined shaft and main tunnel. If the longitudinal slope of the inclined shaft is less than 12°, construction using the reverse-shaft method is similar to that of an ordinary mountain tunnel in which rock is broken by drilling or blasting; loading is applied by a side-dump loader, and slag discharging is achieved by trackless transportation, as shown in Figure 27. However, when the longitudinal slope and cross-section of the inclined shaft are large, it is generally necessary to excavate the construction pilot tunnel from bottom to top, expand the excavation (top-down approach), or expand the excavation from the bottom to the top in combination with the site conditions. When the slag is discharged, gravity can be used to slide the chute, or a rail car can be used to discharge the slag. As the slag discharged and transported by the reverse shaft method is transported through the main tunnel, the construction access and safety amplification equipment need not be occupied by the outer space of the well head; therefore, the terrain conditions of the inclined well head are low and the environmental interference is small. In recent years, TBM machines have been gradually applied in inclined shaft constructions. At this time, owing to the longitudinal slope of an inclined shaft, the sludge is easier to cut and load under the action of gravity when driving against the slope. Compared with a flat tunnel, the instantaneous cutting rate can be increased by 2–5 times, but when the longitudinal slope of the inclined shaft is too large, the daily service time of TBM machines and tools is reduced [65].

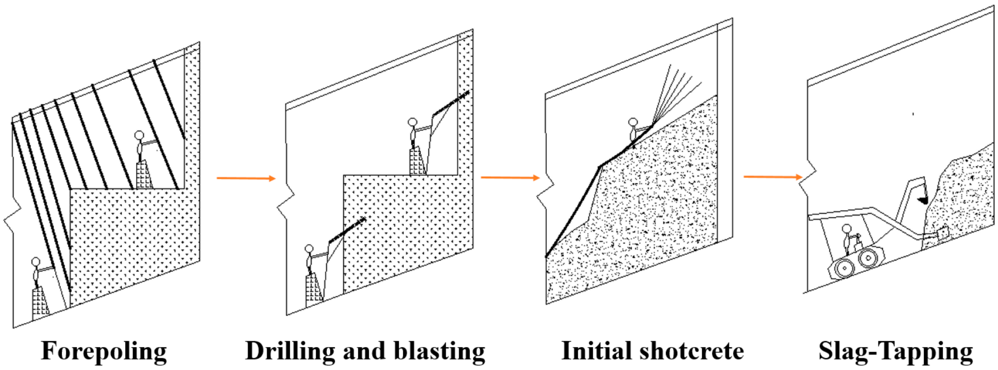

Figure 27. Schematic of Reverse-well Construction Method.

Considering giving full play to the role of the inclined shaft in assisting the construction of the main tunnel and improving the efficiency of the project, it is suggested to adopt a more mature and safer forward-well method when conditions permit. However, the construction using the reverse-well method is beneficial for environmental protection, and it is more suitable for inclined shafts with complex portal environments or TBM construction.

6.2. Construction at the Intersection of the Inclined Shaft and Main Tunnel

The transition of the inclined shaft to the main tunnel is the key part and weak link of construction [66]. The stress of the surrounding rock in this section of the tunnel space is complex, and the design unit often only provides a design scheme or framework description. If not handled properly during construction, a large deformation or collapse will occur. Therefore, it is necessary to refine the construction technology for the intersection of inclined shafts and main tunnels. At present, the transition of the inclined shaft to the construction of the main tunnel in a mountain tunnel is mostly achieved via a roof-picking method, which can be divided into direct roof-picking, transitional roof-picking (small pilot tunnel), and full-envelope construction methods.

The direct roof-picking method continues to be excavated to the centre line of the main tunnel along the inclined shaft entering the main tunnel, which is then expanded up to the design section of the main tunnel; it is gradually excavated to the entire section along the contour of the design section on both sides. The size and direction of the excavation can be adjusted according to the geological conditions of the surrounding rocks. As shown in Figure 28a, when the surrounding rock conditions are good, the tunnel can be excavated step-by-step upwards over the full span of the tunnel. If there are developed joints or groundwater in the surrounding rocks, only the width of the middle part of the section (3–5 m) is picked up when the excavation is expanded upwards and then the wall is expanded after reinforcement, as shown in Figure 28b. In addition, it is also possible to support the vehicular yard at the shaft's bottom part when constructing the intersection of the inclined shaft and main tunnel; the roof of the main tunnel to the vault of the main tunnel is then excavated diagonally upwards directly along the vehicular yard, stabilising and expanding the excavation to both sides, as shown in Figure 28c [67]. For tunnels with large sections and poor stability of the surrounding rocks, a multi-step excavation method with reserved core soil can also be used, and reinforcement measures such as supporting steel frames and grouting bolts are applied for every excavation step. After repeating this step to the vault, a steel frame with the middle bulkhead is set up from top to bottom and then constructed using the CRD (cross diaphragm) method [68], as shown in Figure 29.

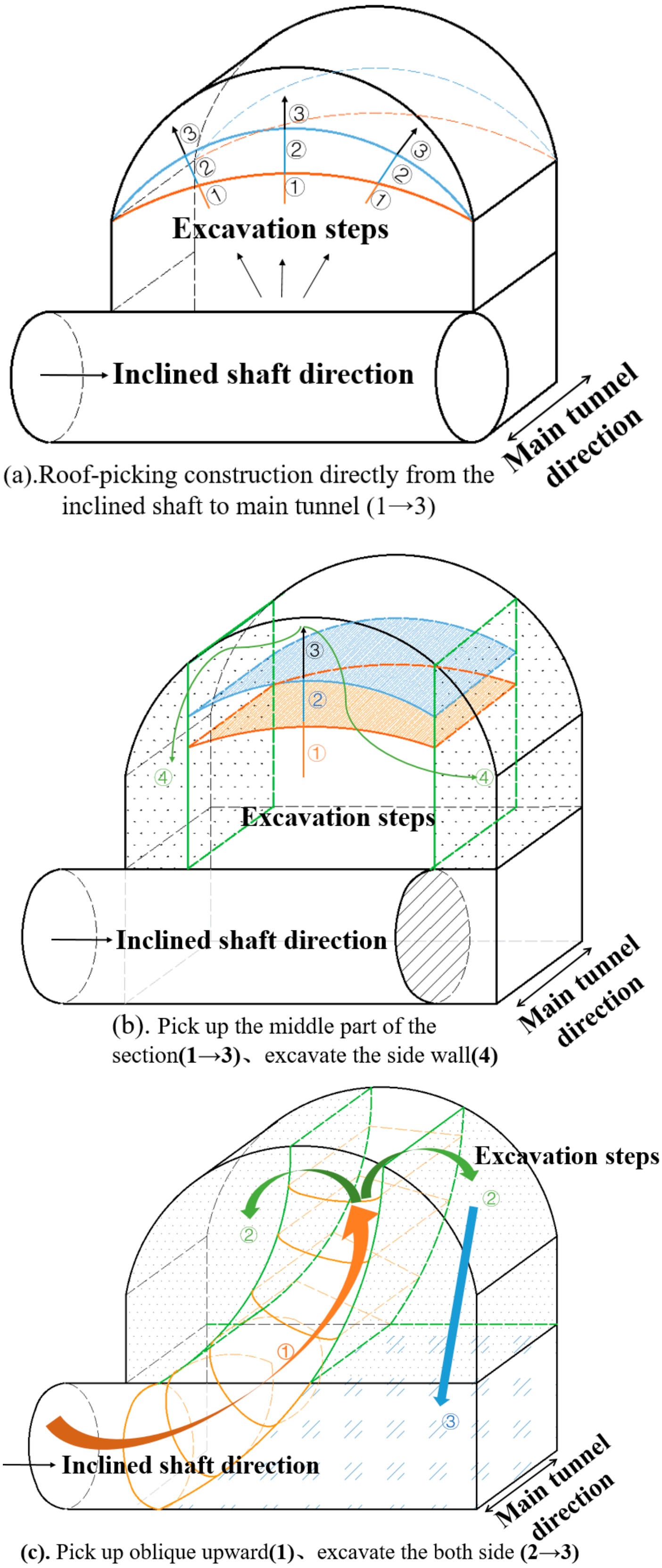

Figure 28. Schematic of Direct Expansion Excavation Method from Inclined Shaft to the Main Hole.

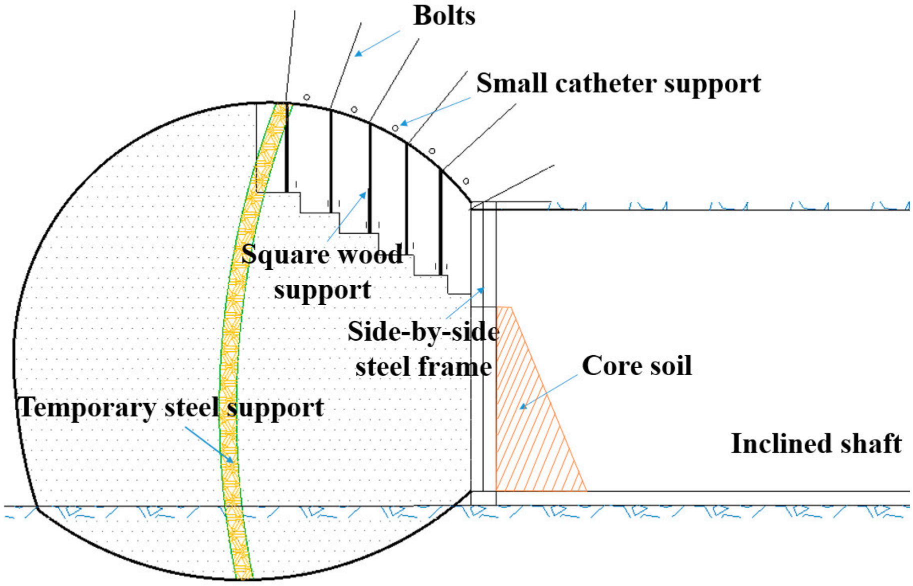

Figure 29. Schematic of Upward Expansion Excavation of a Large Section and Weak Surrounding Rock.

After the inclined shaft enters the main tunnel, the transitional roof-picking method involves the excavation of a section of a parallel pilot pit with an initial length 1.5–2 times the tunnel width and a width of 2.5–4.5 m along the axis of the main tunnel, and the subsequent upward excavation of the side wall. In recent years, a small pilot tunnel construction method has been developed based on the transitional roof-picking method. When an inclined shaft is constructed close to the main tunnel, the excavation direction is gradually deflected to the axis direction of the main tunnel by adjusting the layout of the arch, and then advancing along this direction to expand the excavation to the design section boundary [69], as shown in Figure 30. In essence, both methods avoid the weak rock mass at the intersection of the main tunnel of the inclined shaft, excavate and support the tunnel section outside a certain distance to form a relatively stable support, and then turn back and excavate the intersection section to ensure the safety of construction.

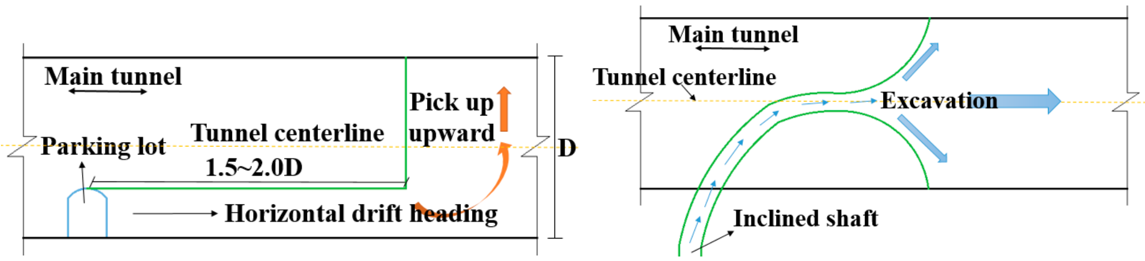

Figure 30. Schematic of Indirect Expansion Method (**left**) and Small Pilot Method (**right**).

The full-envelope method originated from the construction of an urban subway and, compared with the previous two construction methods, the steps are more complex. When the inclined shaft was excavated to a distance in the range of 18–20 m from the main tunnel, the inclined shaft was continuously lifted upward at a height of 1 m above the arch crown of the main tunnel according to the sectional outline of the inclined shaft, and the bench method was used to excavate the pilot tunnel to the main tunnel. The excavation outline of the pilot tunnel was larger than that of the main tunnel, thus indicating a state of wrapping the main tunnel. The formed upper steps were used to carry out the temporary arch construction of this section in time, and the temporary scaffolding was used to support the top arch. The scaffolding was welded with steel bars as a whole to form a temporary support system. When the pilot tunnel was excavated to the opposite end of the main tunnel, it was excavated along the sidewall to the excavation contour of the main tunnel, and the lower steps were gradually excavated. After all the steps were excavated and the advance support was completed, the main tunnel excavation step can be entered [70], as shown in Figure 31.

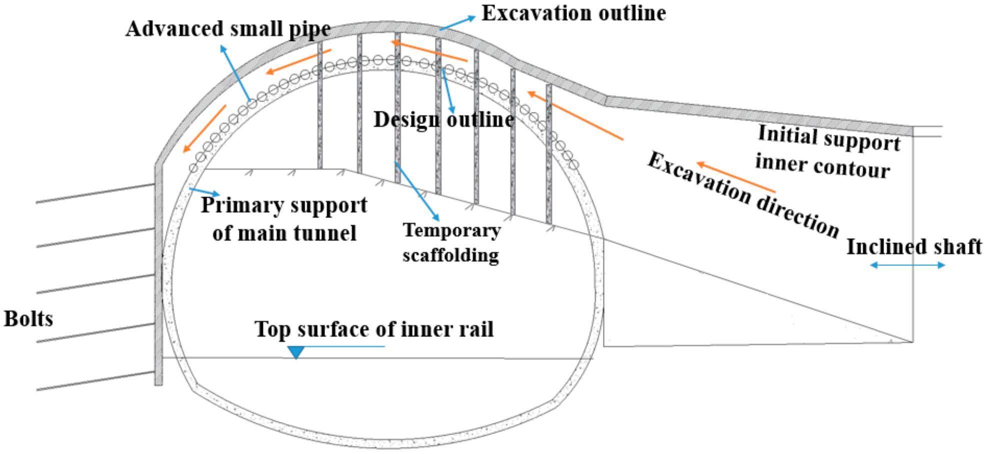

Figure 31. Schematic of Circumferentially Expanding Excavation Method from Inclined Shaft to Main Tunnel.

Regardless of the construction method adopted, as the included angle between the inclined shaft and main tunnel increases, the difficulty of roof-picking construction diminishes. In addition, the straight-wall type used in the lower half section of the main tunnel in the bell mouth section was more conducive to controlling the deformation and giving play to the restraint effect of the early support structure on the lining compared with the curved wall type. In practice, the inclined shaft No. 7 of the Wushaoling tunnel adjusted the half section of the main tunnel in the bell mouth section from the curved wall to the straight wall and adjusted the intersection angle between the inclined shaft and the main tunnel from 35° to 60°. Finally, the cumulative deformation convergence value was less than 15 cm, which was the expected effect [71]. For practical engineering applications, it is necessary to select the most suitable construction method by comprehensively considering the surrounding rock conditions, longitudinal slope of the inclined shaft, intersection angle of the inclined shaft, and the main tunnel.

7. Conclusions and Outlook

This study reviewed the development history of inclined shafts in mountain tunnels, systematically summarised the research status of inclined shafts in design and construction, and outlined the prospects for future research focuses on inclined shafts. Based on these, the following conclusions are drawn:

(1) Based on the diversity of functions of inclined shafts, the feasibility of standardising the form of inclined shaft sections is not high; however, considering both the ventilation function after operation and rapid construction, the design process of inclined shaft sections should be standardised. A long inclined shaft must comprehensively consider construction safety, construction, and operation ventilation. For inclined shafts in water-rich strata, a longitudinal slope design of drainage along a slope can be adopted when the surface topographic conditions of the main tunnel permit, which can save a great deal of expense and speed up construction progress. Despite the provisions for the gentle slope design of an inclined shaft section proposed in the current specifications, the basis for value determination is not yet clear, and additional research is still necessary.

(2) The ventilation in the construction stage of the inclined shaft did not differ from that in the main tunnel. When an inclined shaft assists the ventilation in the main

tunnel, one-head indentation, mid-bulkhead air-duct, and silo ventilation can be used. However, there are a few cases of the application of silo and bulkhead ventilation, and their application conditions need to be clarified further. When an inclined shaft is used for operational ventilation, it is necessary to conduct research to fully utilise the thermal pressure difference between the main tunnel and the outer environment to realise energy-saving ventilation. When the inclined shaft is used for the emergency exit of a railway tunnel, the wind speed and direction at the intersection of the inclined shaft and main tunnel are significantly affected by the thermal pressure difference between the main tunnel and the outer environment, which may lead to situations that do not meet the specifications.

(3) The surrounding-rock pressure of an inclined shaft primarily refers to the calculation method for the surrounding rock of the main tunnel. For a steeply inclined shaft, the effect of the longitudinal slope of the inclined shaft should be considered in combination with the installation method of the support structure. The support of the inclined shaft is generally weaker than that of the main tunnel, and research on the support parameters of inclined shafts has not received sufficient attention in the industry. Therefore, it is recommended to conduct additional research studies on the support parameters of the inclined shaft to achieve a standardised design of the support parameters.

(4) The inclined shaft transportation system can be divided into two categories: rail and trackless transportation. Rail transportation is suitable for steeply inclined shafts with strong lifting capacity, but the time required for bottom-hole reloading is quite considerable; therefore, it is necessary to improve management and dispatching levels to achieve efficient construction. Trackless transportation is suitable for a gently sloped inclined shaft, and the efficiencies of slag discharge and feeding are higher. However, discharging or diluting the exhaust gas discharged from the internal combustion engine of an engineering vehicle leads to a large air demand in construction and is mostly the control factor of construction ventilation. With the development of electric vehicle technology, purely electric engineering vehicles may replace traditional internal combustion engine vehicles in the future; these will influence tunnel construction ventilation and construction efficiency.

(5) There is no essential difference between the excavation method for an inclined shaft section and a main tunnel. It can be divided into the forward-well and reverse-well methods from the construction direction. The inclined shaft can be used as the auxiliary construction passage when the forward-well method is used, while the inclined shaft can only play the role of operation ventilation when the reverse-well method is used. The cross-section of the inclined shaft and main tunnel is the key and difficult point in construction. Direct top-lifting, transitional top-lifting (small guide tunnel method), and large package methods can be used in the construction of the inclined shaft to turn into the main tunnel. At this stage, the research studies on the cross-section of the inclined shaft and main tunnel mainly focus on construction technology. Accordingly, additional studies on different applicable conditions of construction methods and spatial stress characteristics of support ought to be conducted.

(6) Due to the limitations of research conditions, there are still some drawbacks and parts that need to be improved in the research process of this paper. For example, in 2021, one of the authors quantified the wind speed, wind pressures inside and outside the tunnel, and temperature at the protective door of the auxiliary tunnel in nine tunnels on a railway line, but it was winter at that time, and the pressure difference and temperature difference inside and outside the tunnel were quite different from those in summer. Later, we will collect data in different seasons in the same tunnel to form a seasonal distribution law of the year to achieve intelligent ventilation regulation. At present, the application of new energy vehicles in inclined shaft construction has not formed a system, but with the proposal of low-carbon construction strategies and the rapid development of new energy industry, the relevant research and applications are

also gradually increasing. However, at present, one of the biggest shortcomings of new energy vehicles is their lack of climbing ability. For special tunnels such as inclined shafts, the reliability of climbing power is more important, and the consequences of car-sliding accidents caused by insufficient power are serious. Therefore, in the future, the development and testing of new energy engineering machinery with high power and climbing ability should be strengthened to meet a variety of engineering construction needs.

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