

Article

Comparative Analysis of Carbon Emissions from Filled Embankment and Excavated Graben Schemes of Railway Subgrade Engineering

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Abstract: To quantitatively compare the carbon emissions between the filled embankment scheme and the excavated graben scheme of railway subgrade engineering, first, according to the life cycle assessment theory, the two schemes were separated into four stages: building materials production, building materials transportation, construction, and operation and maintenance. The carbon emission factor method was then used to compute the carbon emissions of the filled embankment scheme and the excavated graben scheme. The results indicate that the carbon emissions of the filled embankment scheme are 8783.76 t, 801.71 t, 627.78 t, and 1021.33 t at each stage, and 11,234.58 t over its total life cycle. The carbon emissions at each stage of the excavated graben scheme are 954.96 t, 52.62 t, 772.69 t, and 178.03 t, respectively, and 1958.30 t over its total life cycle. Finally, the carbon abatement potential of the excavated graben scheme with less carbon emissions was investigated by changing the soil nail wall slope to an ecological slope. The results show that after changing the soil nail wall slope of the excavated graben scheme to an ecological slope, the excavated graben scheme's carbon sequestration of the total life cycle is 3274.38 t.

Keywords: railway subgrade engineering filled embankment; railway subgrade engineering excavated graben; carbon emission factor method; LCA theory; carbon emission calculation model; carbon reduction measures



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1. Introduction

Since the beginning of the twenty-first century, global climate change has seriously threatened the sustainable and healthy development of human society, and the destructive impact of greenhouse gases on the environment has prompted a number of countries to make commitments and set targets for carbon reduction [1]. Against the backdrop of global climate change, the Chinese government has formulated the strategic goal of reaching peak carbon emissions by 2030 and carbon neutrality by 2060 to achieve the expected goals of the Paris Agreement signed in 2015 [2]. Based on data from the International Energy Agency (IEA), China produces 33.7% of the global carbon emissions as of 2023, reaching 12.6 billion tons of carbon emissions. As the second-highest carbon-emitting industry in China, transportation is a major contributor to China's GHG emissions, which exceeded 1.25 billion tons in 2023, accounting for about 10% of China's overall carbon emissions. Railroad, as a mode of transportation [3], has lower carbon emissions per unit of transport performance (passenger/kilometer or ton/kilometer) than other modes of transportation from an operational point of view, hence railroad is considered a sustainable mode of transportation [4]. However, the large scale of railroad infrastructure projects, the long construction periods, and the high energy consumption lead to a rise in carbon emissions [5]. Relevant research data show that greenhouse gas emissions from the construction of 1 km

of railroad are equivalent to greenhouse gas emissions from the construction of 45.59 km of highway, and the carbon emissions from railroad infrastructure construction may weaken the carbon reduction effect produced by railroad operation [6]. Railroad engineering is of strategic significance, and the continuous expansion and steady growth of China's railroad industry will inevitably lead to an increase in carbon emissions from the construction of railroad engineering infrastructure for a certain period [7]. Energy saving and carbon reduction in railway construction projects have become an urgent problem.

Relevant scholars have researched the measurement of carbon emissions during railroad engineering infrastructure construction. Hu et al. verified the railroad engineering carbon emission measurement model and factors by combining it with examples [7]. Lee et al. presented a method for reducing carbon emissions from railway infrastructure according to the current condition of carbon emissions in the railway infrastructure construction stage [8]. Standardization and consistency of data collection are the basis for accurate measurement of carbon emissions from railroad engineering infrastructure construction. To ensure the accuracy of carbon emission measurement during the construction stage of railroad engineering, Navaei et al. designed a form to achieve standardization and consistency in data collection [9]. Wang et al. established a whole life cycle analysis model of carbon emission and energy consumed by China's railway on the basis of the LCA theory and took the Beijing–Shanghai railway as an example for empirical analysis [10]. Lin et al. adopted the LCA method and the mixed economic input–output method to compute the carbon emissions from the Beijing–Shanghai railway [11]. Wang et al. used the Tsinghua combined with the Life Cycle Analysis Model (TLCAM) to construct a new life cycle model of GHG emissions from China's high-speed railways, which covers both the infrastructure construction and operation stages, and finally validated the model using the example of the Beijing–Shanghai railway [10]. Kaewunruen et al. used the life cycle cost assessment method and the LCA method to recognize the costs, energy consumed, and carbon emitted by the Beijing–Shanghai railway [12]. Cheng et al. utilized the mixed input–output life cycle methodology to compute the carbon, land, material, and water footprints of the Beijing–Tianjin railway [13]. Lin et al. calculated the carbon emissions from the Beijing–Tianjin railway by adopting a mixed input–output life cycle assessment methodology to quantify the environmental impact of the railway over the entire construction stage [14]. Chang et al. calculated the environmental and energy footprints of railway transportation using the Beijing–Shijiazhuang railroad as an example, using a bottom-up modeling approach. The results indicate that the greenhouse gas emissions and energy emissions from the high-speed rail infrastructure are 9.2 million tons and 104 PJ, respectively, which are largely on account of steel manufacturing [15]. Chang et al. evaluated the carbon emissions of railway infrastructure construction and used the example of the San Francisco to Anaheim high-speed railroad to conduct an empirical analysis [16]. Lee et al. estimated the carbon emissions during the infrastructure construction stage of the high-speed railroad from Daesong to Gwangju (South Korea) [17]. Liu et al. used an artificial neural network model on the basis of in-service lines to forecast the carbon emissions from the construction of metro infrastructure in Fuzhou [18]. Andrade et al. valued the carbon emissions and energy consumed from the construction of the Rio de Janeiro metro infrastructure, maintenance of the infrastructure, manufacturing of the trains, and operation of the trains [1]. Li et al. measured the carbon emissions per unit length from the Shanghai metro by utilizing the life cycle assessment method [19].

Liu et al. put forward a quota-based metro station construction carbon emission quantification model [20]. Liu et al.'s study explored the carbon emissions abatement potential of prefabricated structures for subway stations and indicated that the carbon emissions per unit length of prefabricated structure construction were 12.59% lower than those of cast-in-place sections [21]. Jia et al. used actual inventory data to quantify the embodied GHG emissions from HSR stations. On the basis of the results, a forecasting model was constructed to determine the correlation between the embodied carbon emissions of HSR stations with the design parameters [22]. To resolve the problem of existing

time-consuming carbon assessment methods, Wu et al. separated the assembled section of a subway station into several ring segments to quickly calculate the carbon emissions of the subway station [23]. Wang et al. combined BIM with life cycle assessment (LCA) to propose and estimate the carbon emission abatement strategy for railway stations in areas of China with a cold climate [24]. Kaewunruen et al. measured the carbon emissions of the railroad tunnels during the construction as well as the operation and maintenance stages using the theory of the full life cycle [25]. Wu et al. analyzed and quantified the level and intensity of carbon emissions during the construction phase of metro shield tunnels, and assessed the potential for carbon emission reduction in metro shield tunnels [26]. Chen et al., in order to solve the environmental problems generated by the metro shield slag, take a tunnel on Shenzhen Line 13 as an example and analyze the tunnel using a new type of shield slag integration and recycling technology to deal with shield slag carbon reduction; the results of the study can be used to provide experience for the utilization of shield slag resources in other metro projects [27]. Pritchard et al. investigated the impact of railroad tunnels on the overall carbon emissions of railroads in terms of implied emissions and energy and operational emissions and energy [28]. Ortega et al. used two conventional railroad lines to investigate the impact of the installation of sleeper pads (USPs) on carbon emissions during the renewal of railroad track lines [29].

In summary, many researchers have examined the entire life cycle of carbon emissions of railway engineering. Railway subgrade is an important component of railway engineering. The filled embankment scheme and the excavated graben scheme are two important structural forms of railway subgrade engineering; the two have significant differences, but there is little research on the comparative analysis of their carbon emissions. The life cycle assessment theory is a methodology used to assess the environmental impact of a product throughout its life cycle [30]. The method is known for its detailed and accurate procedures and is recognized by the International Organization for Standardization. When the carbon emission factor method is used to measure the carbon emissions of railway subgrade engineering, the required data mainly include activity data (such as the number of building materials, the distance over which building materials are transported, and energy consumption, etc.) and the corresponding carbon emission factor, which makes it more convenient to obtain the data compared with other carbon emission accounting methods. For this reason, this paper relies on actual engineering, according to the LCA theory, using the carbon emission factor method to compute the carbon emissions of the filled embankment scheme and the excavated graben scheme of railway subgrade engineering over its whole life cycle. On the basis of the carbon emission calculation results, the corresponding carbon reduction measures for the scheme with less carbon emission are adopted and then the potential of the carbon abatement measures is studied to guide the selection of a carbon reduction scheme and carbon abatement design for railway subgrade engineering.

2. Materials and Methods

2.1. Life Cycle Assessment Theory

Life cycle assessment (LCA) is applied to evaluate the potential environmental effects of a product (including a service or activity) throughout its life cycle, from the extraction of raw materials to its final disposal (cradle to grave) [31]. The life cycle assessment theory is considered the main methodology for conducting environmental assessment studies, and it is applied through four key steps, as illustrated in Figure 1: defining the objectives and scope, analyzing the full life cycle inventory, assessing the full life cycle impact, and interpreting the entire life cycle [30,32].

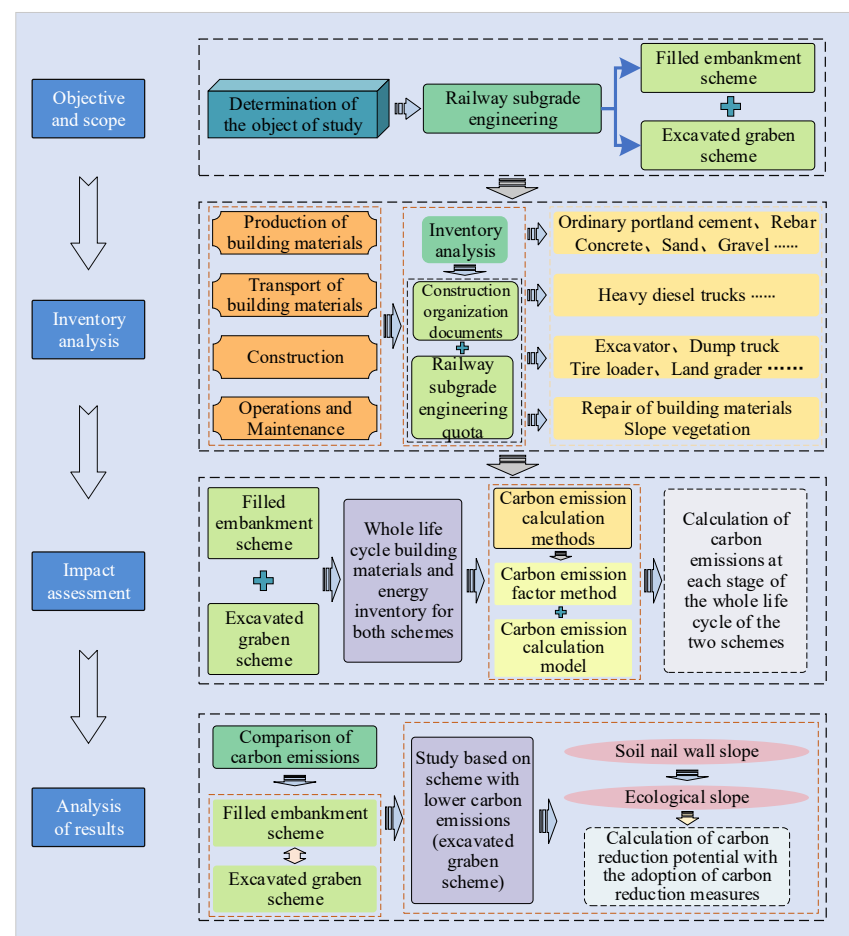


Figure 1. Carbon emission analysis of railway subgrade engineering over its whole life cycle.

2.2. Boundary for Carbon Emissions from Railway Subgrade Engineering

Filled embankment scheme and excavated graben scheme of railway subgrade engineering generate carbon emissions within the stages of building material production, building material transportation, construction, operation and maintenance, and scrapping and dismantling [33]. The filled embankment scheme and the excavated graben scheme do not have demolition cases and lack relevant data to support them, and thus carbon emissions from the scrapping and dismantling stages are not considered. Therefore, this paper only takes the four stages—building material production, building material transportation, construction, as well as operation and maintenance—of the filled embankment scheme and the excavated graben scheme of railway subgrade engineering as the boundaries of their full life cycle carbon emissions. It takes 1 km length as the functional unit of the railway subgrade engineering to measure the carbon emissions of the filled embankment scheme and the excavated graben scheme; the detailed measurement procedure is illustrated in Figure 1.

2.3. Methods for Calculating Carbon Emissions from Railway Subgrade Engineering

2.3.1. Carbon Emission Factor Method

The carbon emission factor method is a widely used carbon emission accounting method, and its basic principle is to calculate greenhouse gas emissions by multiplying the activity data (such as building material usage and energy consumption, etc.) with the carbon emission factor, as shown in Equation (1). The carbon emission factor method can decompose and study the specific carbon emissions in the building material production, building material transportation, construction, operation, and maintenance stages of the railway subgrade filled embankment scheme and excavated graben scheme [34]. The

carbon emission factor method provides a scientific and systematic accounting framework for the measurement of carbon emissions during the whole life cycle of the two schemes of railway subgrade engineering.

$$E = \sum AD_i \times EF_i \quad (1)$$

where AD_i denotes activity level data and EF_i denotes the carbon emission factor, i.e., carbon emissions per unit activity level.

The steps for applying the carbon emission factor method to the measurement of carbon emissions during the whole life cycle of the railway subgrade filled embankment scheme and excavated graben scheme are roughly as follows, and the measurement process of the carbon emission factor method is shown in Figure 2:

1. Determine the accounting boundary: define the scope for carbon emission accounting for the railway subgrade filled embankment scheme and excavated graben scheme, including the production of building materials, transportation of building materials, construction, and operation and maintenance stages.
2. Collect activity data: at the building material production and building material transportation stages, it is necessary to collect data on building material consumption and building material transportation distance according to the documents of the railway subgrade engineering organization; at the construction stage, it is necessary to collect data on energy consumption by construction machinery; at the operation and maintenance stage, it is necessary to collect data on building material consumption and energy consumption by maintenance machinery.
3. Determine the carbon emission factor: According to the type and characteristics of activity data, determine the corresponding carbon emission factor. This paper synthesizes the relevant literature and the “Building construction carbon emission calculation standard” and sorts out the main building materials and energy carbon emission factors involved in the full life cycle of the railway subgrade filled embankment scheme and excavated graben scheme, as indicated in Table 1.
4. Calculate the carbon emissions: Multiply the activity data with the carbon emission factor to calculate the carbon emissions of each stage of the railway subgrade engineering scheme. Then, summarize the carbon emissions of each stage to get the total carbon emissions for the whole life cycle of the railway subgrade engineering scheme.

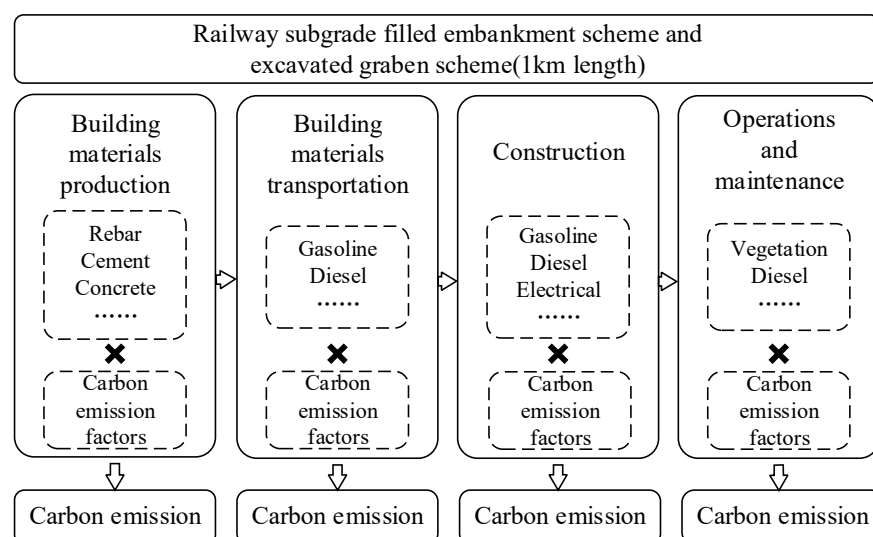


Figure 2. Carbon emission factor method measurement process.

Table 1. Carbon emission factors for railway subgrade engineering.

Stage	Type	Carbon Emission Factors	Unit
Building material production	Ordinary portland cement [35]	0.735	tCO ₂ e/t
	Ordinary cement, Grade 32.5 [7]	0.802	tCO ₂ e/t
	M30 cement mortar [36]	0.792	tCO ₂ e/t
	C20 concrete [37]	0.235	tCO ₂ e/m ³
	Rebar [38]	2.15	tCO ₂ e/t
	Galvanized iron wire [39]	2.35	kgCO ₂ e/kg
	Sand [40]	2.51	kgCO ₂ e/t
	Gravel [41]	2.00	kgCO ₂ e/t
	Geogrid [15]	3.00	kgCO ₂ e/kg
	Nonwoven geotextile [42]	0.06	kgCO ₂ e/kg
Construction	Polyvinyl chloride (PVC) pipe [17]	1.34	kgCO ₂ e/kg
	Diesel [43]	3.67	kgCO ₂ e/kg
	Gasoline [44]	2.91	kgCO ₂ e/kg
	Electricity [14]	0.9397	kgCO ₂ e/(Kw·h)

2.3.2. Carbon Emission Calculation Model

Formulas for calculating carbon emissions at the building material production, building material transportation, construction, and operation and maintenance stages of the filled embankment scheme and the excavated graben scheme of railway subgrade engineering are provided below [45]:

(1) Building materials production stage:

$$E_{js} = \sum_{i=1}^n D_i K_i \quad (2)$$

where E_{js} represents carbon emissions from building material production; n represents the type of building materials; D_i represents the amount of i building materials; K_i represents the carbon emission factor for i building materials.

(2) Building material transportation stage:

$$E_{jy} = \sum_{i=1}^n D_i A L_i \quad (3)$$

where E_{jy} represents the carbon emissions generated during the transportation of building materials; A represents the carbon emission factor for transportation means; L_i represents the transportation distance for i building materials.

(3) Construction stage:

$$E_{sg} = \sum_{j=1}^l F_j H_j P_j \quad (4)$$

where E_{sg} represents carbon emissions due to construction; F_j represents the energy consumed per shift by j construction machinery; H_j represents the number of construction machinery shifts; P_j represents the carbon emission factor for the energy consumed by the construction machinery; l represents construction machinery type.

(4) Operation and maintenance stage:

$$E_{yw} = \left(\sum_{x=1}^u D_x K_x + \sum_{x=1}^u D_x L_x K + \sum_{v=1}^z F_v H_v P_v \right) \left(\frac{T}{T_x} - 1 \right) - C \cdot S \cdot Y \quad (5)$$

where E_{yw} represents the carbon emission from operation and maintenance; D_x represents the amount of x repair building materials; K_x represents the carbon emission factor for x repair building materials; L_x represents the transportation distance for x repair building materials; K represents the carbon emission factor for transportation means for repair building materials; F_v represents the energy consumption of repair machinery per shift; H_v represents the number of repair equipment shifts; P_v represents the carbon emission factor for the energy consumed by repair machinery; T_x represents the useful life of x repair building materials; $(\frac{T}{T_x} - 1)$ represents the number of times x building materials are replaced, and the result is taken as an integer; $(\sum_{x=1}^u D_x K_x + \sum_{x=1}^u D_x L_x K + \sum_{v=1}^z F_v H_v P_v)(\frac{T}{T_x} - 1)$ represents the carbon emissions from repair building materials and machines in the operation and maintenance stage; C represents the annual carbon sequestration of plants, unit is $\text{kg}/(\text{m}^2 \cdot \text{y})$; S is the vegetation area of the railway subgrade engineering slope, unit is m^2 ; Y represents the design service life of railway subgrade engineering; $C \cdot S \cdot Y$ represents carbon sequestration by vegetation in the operation and maintenance stage.

The full life cycle carbon emission computation for the filled embankment scheme and the excavated graben scheme of the railway subgrade engineering is presented in Equation (6):

$$E_{LC} = E_{js} + E_{jy} + E_{sg} + E_{yw} \quad (6)$$

where E_{LC} represents the carbon emissions of the full life cycle of railway subgrade engineering.

3. Case Study

3.1. Project Overview

The railway subgrade filled embankment scheme and the excavated graben scheme are both located in the mountainous area of Southwest China on the line of the X railway project, which is located in Sichuan Province and Tibet Autonomous Region, starting from Chengdu in the east, passing through Ya'an and Linzhi in the west, and finally arriving at Lhasa, which is one of the major railways in Southwest China. Both the filled embankment scheme and the excavated graben scheme are located in an area with complicated terrain and big differences in height, which leads to the filled embankment scheme being in the form of a high embankment and the excavated graben scheme being in the form of a deep graben, making construction very difficult. At the same time, the filled embankment scheme and the excavated graben scheme are located in an area prone to soil erosion; thus, the task of designing railway subgrade engineering slope protection is arduous. The environmental protection requirements for this railway subgrade engineering project are high, so it is of great significance to measure the carbon emissions of the whole life cycle of the filled embankment scheme and the excavated graben scheme of the railway line in order to assess the environmental impacts of the railway subgrade engineering, formulate a green construction plan, and promote the sustainable development of railway construction. Below is the basic engineering information for the railway subgrade filled embankment scheme and excavated graben scheme.

Railway subgrade engineering filled embankment scheme: X railway project; a section of the starting and ending mileage of DK201+000~DK206+000; a total length of 6.0 mainline kilometers; the railway subgrade engineering project consists of 1.6 mainline kilometers, of which the main project includes earth and stone filling and soft soil ground treatment. This section needs 247,800 m^3 of earth and stone for railway subgrade engineering. All of them are borrowed earth fillings, and the sources of the earth are two soil extraction sites, A and B, with an average transportation distance of 25 km. The length of soft soil ground treatment in this section is 1.571 km, with large quantities, and the main treatment programs are powder spraying piles, sand bedding, geogrids, etc.

Railway subgrade engineering excavated graben scheme: Y railway project; a section of the starting and finishing mileage of DK6+000~DK10+140; the whole length is 4.14 km. The main construction processes in this section include excavation, rock excavation, laying of composite geomembrane, and filling of Group A fill. The excavation depth in this section ranges from 0 to 13.5 m, among which the D6+800~DK7+200 section has a maximum excavation depth of 13.5 m, the DK7+200~DK7+600 section has a maximum excavation depth of 11.6 m, the DK7+600~DK7+900 section has a maximum excavation depth of 11.0 m, and the DK7+900~DK9+100 section has a maximum excavation depth of 7.9 m.

3.2. Measurement of Carbon Emissions

(1) Carbon emission in the building material production stage

Based on the construction organization's documents and other relevant information about the filled embankment scheme and the excavated graben scheme, the main building materials for the filled embankment scheme include ordinary silicate cement, sand, graded gravel, and geogrid. The main building materials for the excavated graben scheme include C20 concrete and M30 cement mortar. Based on the functional unit (1 km) of the railway subgrade engineering project, Equation (2) is used to compute the carbon emission generated by the main building material production stage of the filled embankment scheme and the excavated graben scheme. The results of the computation are given in Tables 2 and 3.

Table 2. Carbon emissions of major building materials for the filled embankment scheme.

Types of Building Materials	Unit	Quantity of Building Materials	Carbon Emissions/kg	Transportation Distance for Building Materials/km	Carbon Emissions/kg
Ordinary silicate cement	t	6626	7,791,919	36	38,641
Sand	m ³	20,909	73,476	14	66,391
Gravel	m ³	13,220	39,660	14	29,983
Geogrid	m ²	60,966	67,670	36	18,961
Earthwork	m ³	120,746	—	14	629,857
Galvanized iron wire	kg	48,830	114,750	24	190
Rebar	kg	37,900	81,485	24	147
M30 cement mortar	kg	250,680	198,539	24	975
C20 concrete	m ³	1774	416,251	24	16,554
Polyvinyl chloride (PVC)	t	9.54	13	4.7	7.3

Table 3. Carbon emissions of major building materials for excavated graben scheme.

Types of Building Materials	Unit	Quantity of Building Materials	Carbon Emissions/kg	Transportation Distance for Building Materials/km	Carbon Emissions/kg
Group A fill	m ³	4021	23,666	20	35,174
Composite geomembrane	m ²	6701	2902	20	7
Galvanized iron wire	kg	55,350	130,073	22	197
Rebar	kg	67,961	146,116	22	242
M30 cement mortar	kg	268,576	212,712	22	957
C20 concrete	m ³	1873	439,481	22	16,021
Polyvinyl chloride (PVC)	t	9.65	13	16	25

(2) Carbon emissions in the building material transportation stage

The silicate cement and geogrid used in the railway subgrade engineering filled embankment scheme are delivered to the construction location from the production site using heavy diesel trucks, and the earth and stones are delivered to the construction site from soil extraction sites A and B. The C20 concrete used in the excavated graben scheme is delivered to the construction site from the production site using the same heavy diesel trucks. On the basis of the functional unit of the railway subgrade engineering project (1 km), the carbon emissions from the transportation stage of the main building materials

for the filled embankment scheme and the excavated graben scheme are calculated using Equation (3). The results of the computation are given in Tables 2 and 3.

(3) Carbon emissions in the construction stage

To more accurately as well as conveniently quantify carbon emissions from the construction stage of railway subgrade engineering projects, the construction processes of railway subgrade engineering projects are split. Through analysis of the construction organization's documents for the filled embankment scheme and the excavated graben scheme, the main construction processes and types of construction machinery for the two schemes are extracted. Relying on the standards and normative documents such as "Railway Engineering Budget Quota—Railway Subgrade Engineering" (TZJ 2000-2017) [46] and "Railway Engineering Construction Machinery Bench Cost Quota" (TZJ 3004-2017) [47], the energy consumed by each type of equipment per shift is clarified and the carbon emission of the corresponding machinery in each shift is calculated using Equation (4), and then, on the basis of the functional unit of the railway subgrade engineering project (1 km), the carbon emission of each type of equipment in the filled embankment scheme and the excavated graben scheme is calculated. The results of the computation are given in Tables 4 and 5. In this section, carbon emission bar charts are drawn to clearly illustrate the carbon emissions of each construction process in the filled embankment scheme and the excavated graben scheme, as shown in Figures 3 and 4.

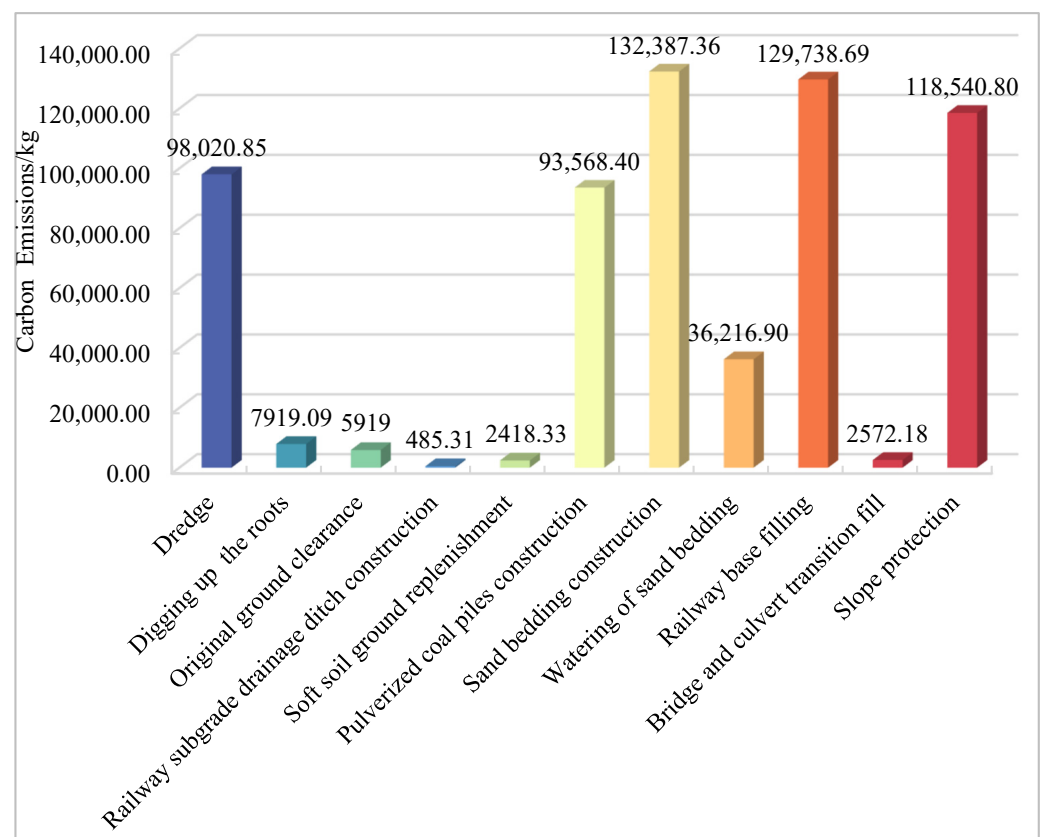


Figure 3. Filled embankment scheme construction process carbon emissions.

Table 4. Carbon emissions of construction equipment for the filled embankment scheme.

Construction Process	Machinery	Specification	Energy Consumption per Unit Shift/kg			kg/CO ₂ Taiwanese Troupe	Taiwanese Troupe	Total Carbon Emissions /kg
			Gasoline	Diesel	Electrical			
Dredge	Crawler hydraulic single bucket excavator	1 m ³		132.8		487.38	27	13,159.26
	Dump truck with cover	12 t		61.29		224.93	377.28	84,861.59
Digging up the roots	Crawler hydraulic single bucket excavator	1 m ³		132.8		487.38	13.33	6496.78
	Tire loader	3 m ³		87.09		319.62	4.45	1422.31
Original ground clearance	Crawler bulldozers	135 kw		107.52		394.60	15	5919
Railway subgrade drainage ditch construction	Crawler hydraulic single bucket excavator	0.6 m ³		44.08		161.77	3	485.31
Soft soil ground replenishment	Crawler bulldozers	135 kw		107.52		394.60	2	789.20
	Self-propelled vibratory rollers	25 t		118.54		435.04	2.52	1096.30
	Land grader	120 kw		63.44		232.82	2.28	530.83
Pulverized coal Piles construction	Powder jet mixing pile forming machine	d ≤ 0.5 m			271.68	294.12	318.13	93,568.4
Sand bedding construction	Crawler bulldozers	75 kw		49.73		182.51	91.02	16,612.06
	Self-propelled vibratory rollers	15 t		88.70		325.53	176.69	57,517.90
	Frog tamper	250 Nm			7.48	8.10	5925.63	47,997.60
	Impact rollers	25 t		290.30		1065.4	9.63	10,259.80
Watering of sand bedding	Sprinkler truck	9600 L	40.78			118.67	305.19	36,216.90
Railway base filling	Crawler bulldozers	105 kw		65.18		239.21	163.84	39,192.17
	Self-propelled vibratory rollers	15 t		88.70		325.53	250.58	81,571.31
	Land grader	120 kw		63.44		232.82	38.55	8975.21
Bridge and culvert transition fill	Self-propelled vibratory rollers	25 t		118.54		435.04	3.47	1509.59
	Land grader	120 kw		63.44		232.82	3.47	807.89
	Internal combustion tamping machine	7 kw		10		36.70	6.94	254.70
Slope protection	Electric air compressor	20 m ³ /min			691.60	649.90	181.60	118,021.84
	Mortar mixer	400 L			20.16	18.94	13.76	260.61
	Steel bar cutting machine	d ≤ 40			33.32	31.31	8.25	258.31

Table 5. Carbon emissions of construction equipment for the excavated graben scheme.

Construction Process	Machinery	Specification	Energy Consumption per Unit Shift/kg			kg/CO ₂ Taiwanese Troupe	Taiwanese Troupe	Total Carbon Emissions /kg
			Gasoline	Diesel	Electrical			
Excavated graben cut-off ditch construction	Crawler hydraulic single bucket excavator	1 m ³		132.8	(466.64)	487.38 (438.50)	1.64	799.30 (719.14)
Earth excavation	Crawler hydraulic single bucket excavator	1 m ³		132.8	(466.64)	487.38 (438.50)	324.64	158,223.04 (142,354.64)
Earthmoving	Self-discharging truck	25 t		106.24	(350)	389.90 (328.90)	1096.37	427,474.66 (360,596.09)
Disposal site preparation	Crawler bulldozers	135 kw		107.52	(240)	394.60 (225.53)	194.42	76,718.13 (43,847.54)

Table 5. Cont.

Construction Process	Machinery	Specification	Energy Consumption per Unit Shift/kg			kg/CO ₂ Taiwanese Troupe	Taiwanese Troupe	Total Carbon Emissions /kg
			Gasoline	Diesel	Electrical			
Stone blasting	Crawler type hydraulic breaking hammer	200 kW		137.09		503.12	0.73	367.28
	Crawler type hydraulic surface drilling rig	d ≤ 152		77.95		286.08	4.65	1330.27
Stone excavation	Crawler hydraulic single bucket excavator	1 m ³		107.52		394.6	15.72	6203.11
Stone moving	Self-discharging truck	25 t		106.24	(350)	389.90 (328.90)	46.65	18,188.84 (15,343.19)
Stone disposal site preparation	Crawler bulldozers	135 kw		107.52	(240)	394.60 (225.53)	7	2762.20 (1578.71)
Ground level	Crawler bulldozers	135 kw		88.7		325.53	1.89	615.25
	Impact rollers	25 t		290.3		1065.4	7.28	7756.11
	Land grader	120 kW		63.44		232.82	0.31	72.17
Fill compaction	Crawler bulldozers	135 kw		107.52	(240)	394.60 (225.53)	5.41	2134.79 (1220.12)
	Self-propelled vibratory rollers	15 t		88.7	(114.8)	325.53 (107.88)	10.72	3489.68 (1156.47)
	Land grader	120 kw		63.44		232.82	0.8	186.26
	Tire loader	3.5 m ³		132.8	(480)	487.38 (451.06)	0.34	165.71 (153.36)
	Sprinkler truck	9600 L	40.78			118.67	0.8	94.94
Slope protection	Electric air compressor	20 m ³ /min			691.6	649.90	101.27	65,815.37
	Mortar mixer	400 L			20.16	18.94	7.67	145.27
	Steel bar cutting machine	d ≤ 40			33.32	31.31	4.6	144.03

Note: data in parentheses are energy consumption parameters and carbon emissions data for electric construction machinery [48].

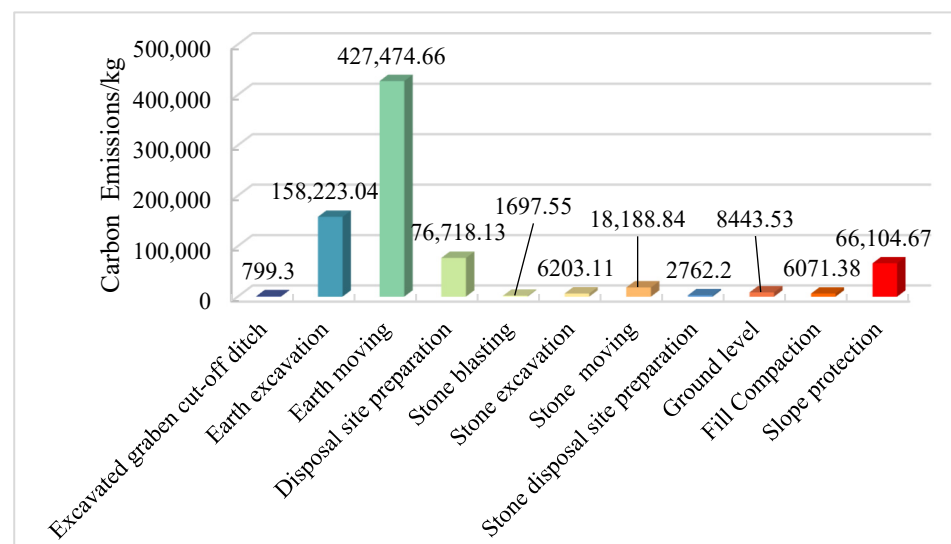


Figure 4. Excavated graben scheme construction process carbon emissions.

(4) Carbon emissions in the operation and maintenance stage

Carbon emissions from railway subgrade engineering repair are mainly considered in the operation and maintenance stage. By referring to Rungskunroch et al.'s way of dealing with the assumptions of the amount of maintenance building materials and the energy consumption of maintenance machinery during the operation and maintenance stage of railway infrastructure [49], this paper makes reasonable assumptions of the amount of maintenance building materials and the energy consumption of construction machinery during the oper-

ation and maintenance stage of railway subgrade engineering according to the construction organization's documents for the railway subgrade filled embankment scheme and excavated graben scheme. According to the construction organization's documents for the filled embankment scheme, the carbon emission of maintenance building materials required for the filled embankment scheme is 958,546.93 kg and that of maintenance machinery and equipment is 62,778.49 kg; according to the construction organization's documents for the excavated graben scheme, the carbon emission of maintenance building materials required for the excavated graben scheme is 100,758.60 kg and that of maintenance machinery and equipment is 77,268.64 kg.

(5) Whole life cycle carbon emissions

Calculation of the carbon emissions of the full life cycles of the filled embankment scheme and the excavated graben scheme shows that: For the filled embankment scheme, ordinary silicate cement has the highest carbon emission during the building material production stage, with the next highest being C20 concrete. Earthwork transportation has the highest carbon emission during the building material transportation stage, accounting for about 78.56%, followed by sand transportation; in the construction stage, the carbon emissions of different construction processes vary greatly, with slope protection, sand bedding construction, and railway base filling accounting for a higher proportion; in the operation and maintenance stage, the carbon emission generated by the maintenance building materials and machinery for the filled embankment scheme is 1,021,325.42 kg. The carbon emission of the full life cycle of this scheme is 11,234.58 t. For the excavated graben scheme, C20 concrete has the highest carbon emission during the building material production stage; Group A fill transportation has the highest carbon emission during the building materials transportation stage, with the next highest being C20 concrete transportation. The carbon emissions of different construction processes vary greatly in the construction stage, with moving earth accounting for a higher proportion; in the operation and maintenance stage, the carbon emission generated by maintenance building materials and machinery for the excavated graben scheme is 178,027.24 kg. The carbon emission of the full life cycle of this scheme is 1958.29 t.

3.3. Sensitivity Analysis

Sensitivity analysis can be used to study the impact of various design parameters of railway subgrade engineering on the carbon emissions of the whole life cycle. The larger the sensitivity coefficient, the greater the impact of the design parameters on the carbon emissions of the whole life cycle of railway subgrade engineering. The specific formula for calculating the sensitivity coefficient is as follows [50]:

$$Z = \frac{\Delta C/C}{\Delta x/x} \quad (7)$$

where Z denotes the sensitivity coefficient; ΔC denotes the value of carbon emission change during railway subgrade engineering, C denotes the baseline value of carbon emission of railway subgrade engineering, $\Delta C/C$ denotes the rate of change of carbon emission of railway subgrade engineering; Δx denotes the value of design parameter change; x denotes the baseline value of design parameter; and $\Delta x/x$ denotes the rate of change of design parameter.

In this paper, the carbon emissions of the whole life cycles of the railway subgrade filled embankment scheme and the excavated graben scheme are taken as the output parameters, and the carbon emission factor and the transportation distance for building materials are taken as the input parameters for the sensitivity analysis.

3.3.1. Sensitivity Analysis of Carbon Emission Factors

The whole life cycle carbon emission calculation for the railway subgrade filled embankment scheme and excavated graben scheme involves parameters such as the carbon

emission factor for building materials and energy; temporal and spatial changes lead to certain differences in the values of carbon emission factors. For the carbon emission factors for building materials, the production process for building materials will be improved based on the progress in science and technology, and the carbon emission of building materials per unit of quality will decrease year by year. Due to the improvement of the electric power structure and the increase in power plant efficiency, the carbon emission factors for electric power will also decrease. Meanwhile, considering the differences in carbon emission factors for building materials and energy in different regions, this paper assumes that the carbon emission factors for building materials and energy for railway subgrade engineering are increased by 10% and 20%, and the carbon emission factors are decreased by 10% and 20% and the impacts of changes in the carbon emission factors on the carbon emissions of the whole life cycle of railway subgrade engineering are calculated and analyzed. The results of the calculations are shown in Table 6.

Table 6. Sensitivity analysis of building material and energy carbon emission factors.

Scheme	Type of Building Materials/Energy	Carbon Emissions/kg					Sensitivity Factor/%
		20%	10%	Reference	−10%	−20%	
Filled embankment scheme	Ordinary silicate cement	12,792,964	12,013,772	11,234,580	10,455,388	9,676,196	69.357
	Sand	11,249,275	11,241,928	11,234,580	11,227,232	11,219,885	0.654
	Gravel	11,242,512	11,238,546	11,234,580	11,230,614	11,226,648	0.353
	Geogrid	11,248,114	11,241,347	11,234,580	11,227,813	11,221,046	0.602
	Galvanized iron wire	11,257,530	11,246,055	11,234,580	11,223,105	11,211,630	1.021
	Rebar	11,250,877	11,242,729	11,234,580	11,226,432	11,218,283	0.725
	M30 cement mortar	11,274,288	11,254,434	11,234,580	11,214,726	11,194,872	1.767
	C20 concrete	11,317,830	11,276,205	11,234,580	11,192,955	11,151,330	3.705
	PVC pipe	11,234,583	11,234,581	11,234,580	11,234,579	11,234,577	0.001
	Diesel	11,300,872	11,267,726	11,234,580	11,201,434	11,168,288	2.95
	Gasoline	11,241,823	11,238,202	11,234,580	11,230,958	11,227,337	0.322
	Electronic	11,286,601	11,260,591	11,234,580	11,208,569	11,182,559	2.315
Excavated graben scheme	Gravel	1,974,643	1,972,277	1,969,910	1,967,543	1,965,177	1.201
	Nonwoven geotextile	1,970,490	1,970,200	1,969,910	1,969,620	1,969,330	0.147
	Galvanized iron wire	1,995,925	1,982,917	1,969,910	1,956,903	1,943,895	6.603
	Rebar	1,999,133	1,984,522	1,969,910	1,955,298	1,940,687	7.417
	M30 cement mortar	2,012,452	1,991,181	1,969,910	1,948,639	1,927,368	10.798
	C20 concrete	2,057,806	2,013,858	1,969,910	1,925,962	1,882,014	22.31
	PVC pipe	1,969,913	1,969,911	1,969,910	1,969,909	1,969,907	0.001
	Diesel	2,111,309	2,040,609	1,969,910	1,899,211	1,828,511	35.89
	Gasoline	1,969,929	1,969,919	1,969,910	1,969,901	1,969,891	0.005
	Electronic	1,985,141	1,977,526	1,969,910	1,962,294	1,954,679	3.866

3.3.2. Sensitivity Analysis of the Transportation Distance of Building Materials

The large amount of building materials required by the railway subgrade filled embankment scheme and the excavated graben scheme has led to a greater impact of the transportation distance of building materials on the carbon emissions of the whole life cycle of railway subgrade engineering. Meanwhile, due to the uncertainty of the transportation distance of building materials, this paper carried out a sensitivity analysis of the transportation distance of building materials for the filled embankment scheme and the excavated graben scheme. It assumed that the transportation distance of building materials for railway subgrade engineering is extended by 10% and 20% and shortened by 10% and 20%, and the impact of the change in the transportation distance of building materials on the carbon emission of the whole life cycle of railway subgrade engineering was calculated and analyzed. The results of the calculations are shown in Table 7.

Table 7. Sensitivity analysis of the distance of transportation of building materials.

Scheme	Type of Building Material	Carbon Emission/kg					Sensitivity Factor/%
		20%	10%	Reference	−10%	−20%	
Filled embankment scheme	Ordinary silicate cement	11,242,308	11,238,444	11,234,580	11,230,716	11,226,852	0.3439
	Sand	11,247,858	11,241,219	11,234,580	11,227,941	11,221,302	0.591
	Gravel	11,240,577	11,237,578	11,234,580	11,231,582	11,228,583	0.2669
	Geogrid	11,238,372	11,236,476	11,234,580	11,232,684	11,230,788	0.1688
	Earthwork	11,360,551	11,297,566	11,234,580	11,171,594	11,108,609	5.6064
	Galvanized iron wire	11,234,618	11,234,599	11,234,580	11,234,561	11,234,542	0.0017
	Rebar	11,234,609	11,234,595	11,234,580	11,234,565	11,234,551	0.0013
	M30 cement mortar	11,234,775	11,234,678	11,234,580	11,234,483	11,234,385	0.0087
	C20 concrete	11,237,891	11,236,235	11,234,580	11,232,925	11,231,269	0.1473
	PVC pipe	11,234,581	11,234,581	11,234,580	11,234,579	11,234,579	0.0001
Excavated graben scheme	Gravel	1,976,945	1,973,427	1,969,910	1,966,393	1,962,875	1.7856
	Nonwoven geotextile	1,969,911	1,969,911	1,969,910	1,969,909	1,969,909	0.0004
	Galvanized iron wire	1,969,949	1,969,930	1,969,910	1,969,890	1,969,871	0.01
	Rebar	1,969,958	1,969,934	1,969,910	1,969,886	1,969,862	0.0123
	M30 cement mortar	1,970,101	1,970,006	1,969,910	1,969,814	1,969,719	0.0486
	C20 concrete	1,973,114	1,971,512	1,969,910	1,968,308	1,966,706	0.8133
	PVC pipe	1,969,915	1,969,913	1,969,910	1,969,908	1,969,905	0.0013

3.3.3. Analysis of Results

For the railway subgrade filled embankment scheme, the sensitivity coefficients of carbon emission factors are, in descending order, ordinary silicate cement, C20 concrete, diesel fuel, electricity, M30 cement mortar, galvanized iron wire mesh, rebar, sand, geogrid, gravel, gasoline, and PVC pipe. The higher sensitivity coefficients for ordinary silicate cement and C20 concrete are mainly due to the larger amount of ordinary silicate cement and C20 concrete used in the construction of the filled embankment scheme and the higher carbon emission factor for building materials. The sensitivity coefficients of gasoline and PVC pipe are lower, mainly because less gasoline machinery is used in the construction of the filled embankment scheme, resulting in less gasoline consumption, and the carbon emission factor for PVC pipe is high but the amount of PVC pipe used in the construction process is small. For the railway subgrade excavated graben scheme, the sensitivity coefficients of carbon emission factors are, in descending order, diesel fuel, C20 concrete, M30 cement mortar, rebar, galvanized iron wire, electric power, crushed stone, geotextile fabric, gasoline, and PVC pipeline. The diesel and C20 concrete sensitivity coefficients are higher, mainly because the excavated graben scheme construction process uses more diesel machinery, thus diesel energy consumption is higher, and the diesel carbon emission factor is higher. At the same time, the excavated graben scheme uses a larger amount of C20 concrete, and the carbon emission factor for C20 concrete is higher. The sensitivity coefficients of gasoline and PVC pipeline are lower, mainly because less gasoline machinery is used in the construction of the excavated graben scheme, and although the carbon emission factor for PVC pipelines is high, the quantity used in the construction process is small.

For the railway subgrade filled embankment scheme, the transportation sensitivity coefficients for building materials, are, in descending order, earth, sand, ordinary silicate cement, gravel, geogrid, C20 concrete, M30 cement mortar, galvanized iron wire, rebar, and PVC pipes. The transportation sensitivity coefficients for earth and sand are higher, mainly because earth and sand are the main building materials used in the construction of the filled embankment scheme, and the quantities are larger. Rebar and PVC pipes have lower transportation sensitivity coefficients, mainly because the quantities of rebar and PVC pipes used in the construction of the filled embankment scheme are small compared to other types of building materials. For the railway subgrade excavated graben scheme, the transportation sensitivity coefficients for building materials are, in descending order, gravel, C20 concrete, M30 cement mortar, rebar, galvanized iron wire, PVC pipe, and geotextile. The transportation sensitivity coefficients for gravel and C20 concrete are higher, mainly because gravel and C20 concrete are the main building materials used in the construction of the excavated graben scheme, and the quantities are larger. PVC pipes and geotextile

have lower transportation sensitivities, mainly because PVC piping and geotextile are used in smaller quantities than the other building materials in the construction of the excavated graben scheme.

4. Research on Carbon Reduction Measures

A comparison of the railway subgrade engineering filled embankment scheme and excavated graben scheme shows that the excavated graben scheme uses fewer building materials, resulting in its carbon reduction being significantly better than the filled embankment scheme; thus, this paper uses the excavated graben scheme as the optimal program for carbon reduction and as the object of the study to analyze the degree of carbon reduction measures on carbon emissions. The slope of the excavated graben scheme is supported by the soil nail wall, based on which an ecological slope can be constructed. At the same time, the vegetation on the ecological slope has the role of a carbon sink, which can reduce carbon emissions, to some degree. Based on the structural safety of the excavated graben scheme, changing the soil nail wall slope to an ecological slope will lead to changes in the quantity of construction materials and construction work in the excavated graben scheme, while the vegetation in the operation and maintenance stage will act as a carbon sink, ultimately changing carbon emissions during the stages of production of building materials, transportation of building materials, construction, and operation and maintenance of the excavated graben scheme. This section analyzes the carbon abatement potential of the excavated graben scheme after changing the soil nail wall slope to an ecological slope.

The change in the ecological slope gradient of the railway subgrade engineering excavated graben scheme leads to different construction volumes of the ecological slope, which affects the quantity of ecological slope building materials, building material transportation, energy consumption by construction machinery, and the slope area. In the case of a certain excavation depth in the excavated graben scheme, the slower the slope of the ecological side slope, the larger the amount of excavation work, and at the same time, the slower the slope, the larger the area of the slope; this affects the amount of carbon sequestered by the slope vegetation during the operation and maintenance stage. Therefore, this paper takes the ecological slope of the railway subgrade engineering excavated graben scheme as the research object and analyzes the change in the carbon emission of the ecological slope after the change in the slope gradient.

4.1. Carbon Reduction in the Ecological Slope

4.1.1. Computation of Changes in Carbon Emissions

(1) Change in carbon emissions in the building material production stage

After the excavated graben scheme is changed from a soil nail wall slope to an ecological slope, the production of building materials requires consideration of additional geotextile and planting bags. Based on the functional unit of railway subgrade engineering (1 km), Equation (2) is used to calculate the carbon emissions generated by the production of building materials, for instance, geotextile and planting bags, which need to be additionally considered after the slope of the excavated graben scheme is changed to the ecological slope. The results of the calculation are given in Table 8.

Table 8. Carbon emissions from building materials.

Building Material Types	Unit	Quantity of Building Materials	Carbon Emissions/kg	Transportation Distance for Building Materials/km	Carbon Emissions/kg
Geotextile	m ²	13,420	362.34	500	489.16
Planting bag	m ²	45,981	1241.46	500	1675.97

(2) Change in carbon emissions during the building material transportation stage

The soil nail wall slope of the excavated graben scheme is changed to an ecological slope. Because the transportation distance of the geotextile and planting bag used in the ecological slope cannot be obtained directly from the construction organization's documents, in this paper, the assumptions of the transportation distance for building materials in the "Construction Carbon Emission Calculation Standard" are made for the transportation distances of the geotextile and planting bag used in the ecological slope. Based on the functional unit (1 km) of railway subgrade engineering, Equation (3) is used to measure the carbon emissions from the transportation of the geotextile and planting bag that needs to be additionally considered after the slope of the excavated graben scheme is changed into an ecological slope. The results of the computation are given in Table 8.

(3) Changes in carbon emissions in the construction stage

After changing the soil nail wall slope of the excavated graben scheme to the ecological slope, additional considerations need to be given to the carbon emissions from equipment such as Hydraulic grass sprayers. The "Railway Engineering Budget Quota—Railway Subgrade Engineering" (TZJ 2000-2017), the "Railway Engineering Construction Machinery Bench Cost Quota" (TZJ 3004-2017), and other standards and normative documents are relied on to clarify the energy consumed by each type of construction machinery during ecological slope construction, and Equation (4) is used to compute the carbon emissions per shift. The railway subgrade engineering functional unit (1 km) is then used as the basis for computing the total carbon emissions of various types of construction equipment during ecological slope construction, and the results are given in Table 9. Because the ecological slope is built based on the soil nail wall slope, the carbon emissions from equipment used in the original excavated graben scheme can be combined with the carbon emissions generated by the equipment in Table 9 to arrive at the carbon emissions of the construction stage of the excavated graben scheme after adopting the carbon reduction strategy (using the ecological slope).

Table 9. Energy consumption and carbon emissions of ecological slope construction equipment.

Construction Process	Machinery	Specification	Energy Consumption per Unit Shift/kg			kg/CO ₂ Taiwanese Troupe	Taiwanese Troupe	Total Carbon Emissions /kg
			Gasoline	Diesel	Electrical			
Ecological slope	Hydraulic grass sprayer	4000 L		29.03		106.54	2.42	257.36
	Heavy-duty vehicle	6 t	34.56			100.57	28.18	2834.26
	Single-stage centrifugal freshwater pumps	12.5 m ³ /h–50 m			22.44	17.50	14.49	253.65

(4) Changes in carbon emissions during the operation and maintenance stage

This study considers the use of knotweed as the ecological slope vegetation. The operation and maintenance stage considers both carbon sequestration by the slope vegetation and carbon emissions from repair and maintenance. Carbon sequestered by the slope vegetation: based on the functional unit of railway subgrade engineering (1 km), the carbon sequestered by vegetation in the operation and maintenance stage is computed using Equation (5): $E_g = 7.81 \times 13,420 \times 50 = 5,240,510$ (kg). Carbon emissions from maintenance: The carbon emission of building materials for the excavated graben scheme during the operation and maintenance stage is calculated to be 376.89 kg, and the carbon emission of the maintenance of machinery is 334.53 kg. Finally, the carbon sequestered by slope vegetation is combined with carbon emissions from maintenance ($-5,240,510$ kg + 376.89 kg + 334.53 kg = $-5,239,798.58$ kg), resulting in a final carbon

sequestration of 5,239,798.58 kg by the excavated graben scheme (ecological slope) during the operation and maintenance stage.

4.1.2. Carbon Emissions from the Ecological Slope of the Excavated Graben Scheme

After changing the soil nail wall slope to an ecological slope in the excavated graben scheme, the carbon emissions of the production of building materials, transportation of building materials, construction, and operation and maintenance stages all changed. By sorting out the carbon emissions in each stage before measuring the abatement of the excavated graben scheme and the changes in carbon emissions of each stage of the carbon reduction measure, the carbon emissions of the excavated graben scheme after adopting the carbon reduction measure are calculated. The related data are given in Table 10. A bar chart of carbon emissions at different stages before and after the adoption of the carbon abatement measure of the excavated graben scheme is presented in Figure 5. It can be seen from the figure that although changing the soil nail wall slope of the excavated graben scheme to an ecological slope increases the carbon emissions of production of building materials, transportation of building materials, and construction to a certain degree, the vegetation of the ecological slope in the operation and maintenance stage can be used as carbon sinks, which could reduce the carbon emissions of the excavated graben scheme to a large degree. This ultimately results in a whole life cycle carbon sequestration of 3274.38 t for the excavated graben scheme.

Table 10. Carbon emissions from various stages of the excavated graben scheme.

	Building Material Production/kg	Building Material Transportation/kg	Construction /kg	Operation and Maintenance /kg	Whole Life Cycle/kg
Excavated graben scheme (soil nail wall slope)	954,963	52,623	772,686.41	178,027.24	1,958,299.65
Change in carbon emissions	+1603.80	+2165.13	+3345.27	−5,239,798.58	
Excavated graben scheme (ecological slope)	956,566.80	54,788.13	776,031.68	−5,061,771.34	−3,274,384.73

Note: “+” in the table represents an increase in carbon emissions and “−” represents a carbon sink.

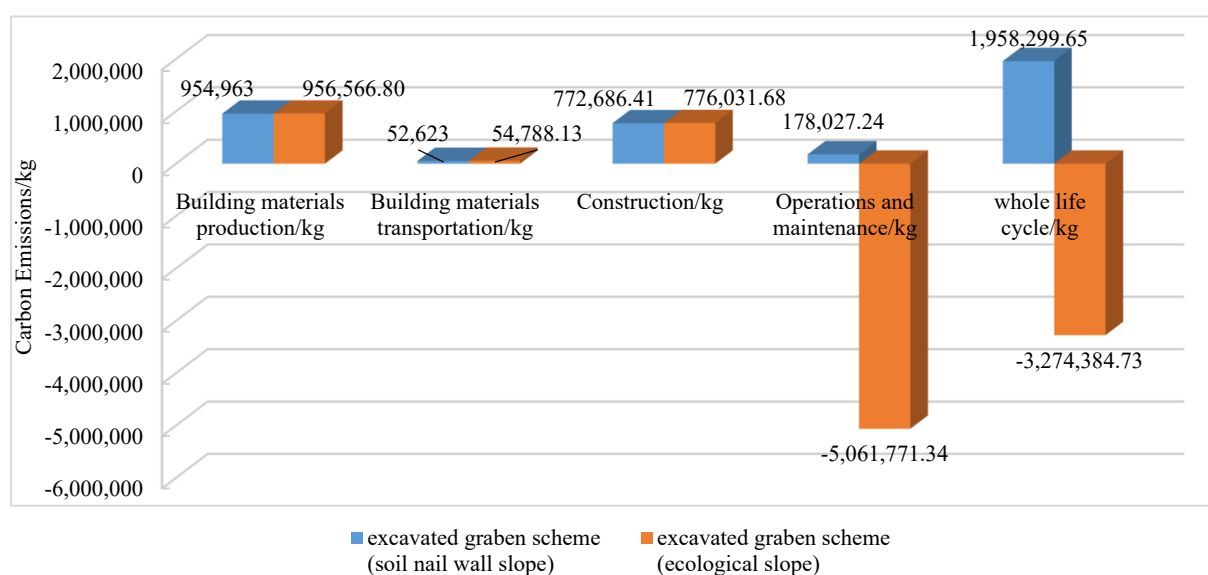


Figure 5. Comparison of carbon emissions before and after the adoption of carbon abatement measures for the excavated graben scheme.

4.1.3. “Carbon Reduction—Economic” Benefit Analysis

On the basis of ensuring the structural safety of the excavated graben scheme, the effect of carbon reduction after changing the soil nail wall slope to an ecological slope is remarkable. However, changing the soil nail wall slope to an ecological slope in the excavated graben scheme causes an increase in construction materials and construction volume, which ultimately leads to an increase in construction costs. Based on standard specifications such as “Railway engineering material base period price” and “Railway engineering construction machinery bench cost quotas”, this paper calculates the incremental construction costs due to the additional construction materials and construction machinery after changing the soil nail wall slope to an ecological slope; the results are shown in Table 11.

Table 11. Incremental costs of ecological slope construction in the excavated graben scheme.

Categorization	Quantity of Building Materials/ Machinery Shift	Unit Price	Construction Cost /yuan
Geotextile	14,760 m ²	2.87 yuan/m ²	42,361.2
Planting bag	50,579.1 m ²	2.87 yuan/m ²	145,162.02
Grass seed mix	335.5 kg	31.02 yuan/kg	10,407.21
Heavy-duty diesel trucks	23.55 shift	476.7 yuan/shift	11,226.29
Spray planter	2.662 shift	321.16 yuan/shift	854.93
Heavy-duty	30.99 shift	369.31 yuan/shift	11,444.92
Single-stage centrifugal Freshwater pumps	15.94 shift	83.77 yuan/shift	1335.29

Through the above calculations, it can be seen that changing the soil nail wall slope to an ecological slope in the railway subgrade excavated graben scheme results in an additional increase in building materials and construction machinery, increasing the construction costs by CNY 222,791.85. In order to ensure that the comparison of the construction costs of the soil nail wall slope and the ecological slope of the excavated graben scheme is scientific and reasonable, this paper calculates and analyzes the construction costs of the ecological slope and soil nail wall slope of the excavated graben scheme and then conducts a comparative analysis; the results of the calculations are shown in Table 12. As can be seen from the table, for the railway subgrade excavated graben scheme, the construction cost of the soil nail wall slope is CNY 196,688.10. If the ecological slope is preferred for this excavated graben scheme, the construction cost is CNY 223,671.10. In terms of construction costs, the soil nail wall slope of the railway subgrade excavation graben scheme has some advantages over the ecological slope.

Table 12. Construction costs for the soil nail wall slope and the ecological slope.

Slope Type	Categorization	Quantity of Building Materials/ Machinery Shift	Unit Price	Construction Cost /yuan
Soil nail wall slope	Ordinary silicate cement	46,467.62 kg	0.33 yuan/kg	15,334.31
	Medium coarse sand	58.77 m ³	34.25 yuan/m ³	2012.87
	Reinforcing Steel	47,290.97 kg	2.64 yuan/kg	124,848.16
	Heavy-duty Diesel Trucks	6.08 shift	476.7 yuan/shift	2898.34
	Electric Air Compressor	101.27 shift	501.09 yuan/shift	50,745.38
	Mortar Mixer	7.67 shift	97.19 yuan/shift	745.45
	Reinforcing Steel	4.6 shift	22.51 yuan/shift	103.55
	Cutting Machine			

Table 12. Cont.

Slope Type	Categorization	Quantity of Building Materials/ Machinery Shift	Unit Price	Construction Cost /yuan
Ecological slope	Geotextile	14,760 m ²	2.87 yuan/m ²	42,361.2
	Geobags	50,579.1 m ²	2.87 yuan/m ²	145,162.02
	Grass Seed Mixer	335.5 kg	31.02 yuan/kg	10,407.21
	Galvanized Low Carbon Steel Wire	241.56 kg	3.64 yuan/kg	879.28
	Heavy-duty Diesel Trucks	23.55 shift	476.7 yuan/shift	11,226.29
	Spray Grass Planter	2.662 shift	321.16 yuan/shift	854.93
	Heavy-duty Vehicle	30.99 shift	369.31 yuan/shift	11,444.92
	Single-stage centrifugal Freshwater pumps	15.94 shift	83.77 yuan/shift	1335.29

4.2. Combined Effects of “Slope Gradient–Vegetation Selection” on Carbon Emissions of Ecological Slope

Through the calculation and analysis in Section 4.1, it can be seen that the carbon sequestration effect of ecological slope vegetation during the operation and maintenance stage causes the ecological slope to have a significant impact on the carbon emission reduction of the railway subgrade engineering excavated graben scheme. The slope gradient is an important factor that influences the ecological slope. Gradient changes in the railway subgrade engineering excavated graben scheme’s ecological slope lead to different ecological slope constructions, affecting the building materials, building material transportation, energy consumption of construction machinery, and slope area of the ecological slope. In the case of a certain excavation depth in the excavated graben scheme, the slower the slope of the ecological side slope, the larger the amount of excavation work, and the slower the slope, the larger the area of the slope, which affects the amount of carbon sequestered by the slope vegetation during the operation and maintenance stage, as shown in Figure 6. At the same time, different slope vegetation types have different carbon sequestration factors that affect carbon sequestration in the operation and maintenance stage. The slope gradient of the excavated graben scheme project case is 1:0.5 and the vegetation in the slope is knotweed; this paper also selected two slopes, 1:0.4 and 1:0.6, and two vegetation types, bermudagrass and ryegrass, which are common on ecological slopes and have large differences in carbon sequestration factors. The study takes ecological slopes of the excavated graben scheme of the railway subgrade engineering as the object of research to analyze the comprehensive effects of different slope gradients and vegetation types on the carbon emissions of the whole life cycle of the ecological slope. The calculation results are shown in Table 13.

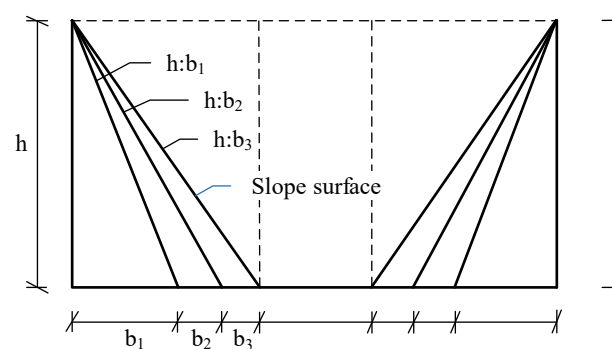
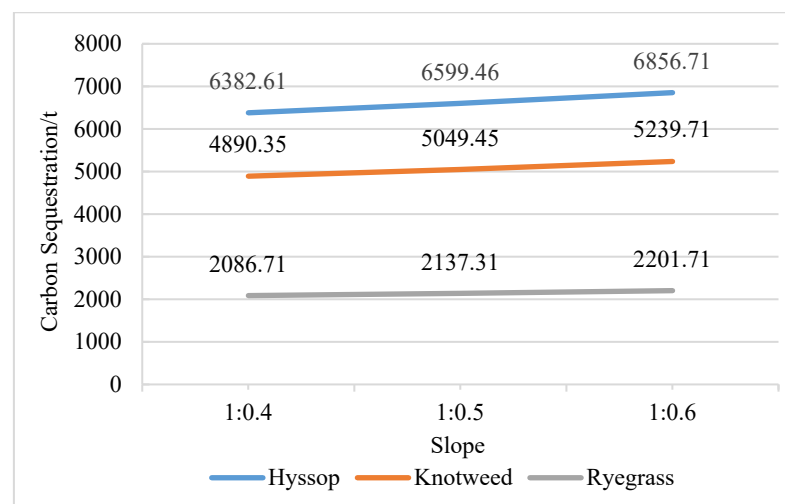


Figure 6. Influence of gradient change on the volume of ecological slope works.

Table 13. Effects of gradient and vegetation type on the whole life cycle carbon emissions of ecological slopes.

Slope	Building Material Production/t	Building Material Transportation/t	Construction /t	Operation and Maintenance/t			Whole Life Cycle/t		
				Hyssop	Knotweed	Ryegrass	Hyssop	Knotweed	Ryegrass
1:0.4	7.26	0.017	133.55	−6523.44	−5031.18	−2227.54	−6382.61	−4890.35	−2086.71
1:0.5	7.54	0.018	166.13	−6773.15	−5223.14	−2311	−6599.46	−5049.45	−2137.31
1:0.6	7.87	0.018	198.74	−7063.34	−5446.34	−2408.34	−6856.71	−5239.71	−2201.71

It can be seen from the above calculations that for different gradients and different vegetation types, ecological slopes show carbon sequestration capacity in the whole life cycle. As can be seen in Figure 7, although the vegetation types of ecological slopes are different, the carbon sequestration capacity of the ecological slope in the whole life cycle shows a trend of gradual increase with the decline in the slope. The main reason is that in the case of a certain ecological slope height, the slope decline leads to an increase in the ecological slope area, which leads directly to an increase in the area of vegetation carbon sequestration and an increase in the amount of vegetation carbon sequestration. Slope relaxation also increases the number of building materials and excavation works, but the increase in carbon sequestered by vegetation in the whole life cycle is higher than the carbon emission from the production of building materials, transportation of building materials, and construction caused by the increase in the amount of work. Therefore, for vegetation with different carbon sink capacities, reducing the gradient of the ecological slope should be considered to increase carbon sequestration in the whole life cycle under the perspective of carbon reduction. However, reducing the slope will lead to an increase in the amount of ecological slope work, resulting in an increase in the number of building materials and energy consumption of construction machinery; thus, it is necessary to determine a reasonable gradient for ecological slopes from a comprehensive perspective of “carbon reduction—economy”.

**Figure 7.** Effect of gradient and vegetation type on the whole life cycle carbon emission of ecological slopes.

5. Discussion

The railway is an environmentally friendly and efficient mode of transportation, but its long construction period and large energy consumption have led to a rise in carbon emissions, thus energy saving and carbon reduction in railway construction projects have become urgent problems. Railway subgrade is an important component of railway engineering. A filled embankment scheme and an excavated graben scheme are two important structural forms of railway subgrade engineering; the two have significant differences, but there is little research on the comparative analysis of their carbon emissions. For this

reason, this paper relies on the actual engineering, according to the LCA theory, using the carbon emission factor method to compute the carbon emissions of the filled embankment scheme and the excavated graben scheme of railway subgrade engineering. On the basis of the carbon emission calculation results, corresponding carbon abatement measures for the scheme with less carbon emission are adopted; then, the carbon abatement potential of the carbon abatement measures is studied.

Computation of the carbon emissions of the full life cycle of the filled embankment scheme and the excavated graben scheme shows that for the filled embankment scheme, ordinary silicate cement has the highest carbon emission during the building material production stage, with the next highest being C20 concrete, mainly because of the higher carbon emission factors of the ordinary silicate cement and C20 concrete and the larger quantity of cement and C20 concrete. Earthwork transportation has the highest carbon emission during the building material transportation stage, accounting for about 78.56%, mainly due to the large quantity of earthwork required for the filled embankment scheme. This is followed by sand transportation. In the construction stage, the carbon emissions of different construction processes vary greatly, with slope protection, sand bedding construction, and railway base filling accounting for a higher proportion, mainly because the above three construction processes require a large amount of work and the machinery used for construction consumes a large amount of energy. In the operation and maintenance stage, the carbon emitted by the maintenance of building materials and machinery for the filled embankment scheme is 1,021,325.40 kg. The carbon emissions from each stage of the filled embankment scheme are presented in the form of a bar chart, as can be seen in Figure 8; the carbon emission of the full life cycle of this scheme is 11,234.58 t, and the carbon emission of each stage is 8783.76 t, 801.71 t, 627.78 t, and 1021.33 t, respectively, with the carbon emission of the building material production stage accounting for the highest proportion (78.19%). Although the research object in the literature [1,8,12,13,15–17,20,23,25] is the carbon emission of railroad engineering and railroad bridge and tunnel engineering, the research conclusions have similarities; that is, the production stage of building materials is the stage with the highest proportion of carbon emissions. For the excavated graben scheme, C20 concrete has the highest carbon emission during the building materials production stage; Group A fill transportation has the highest carbon emission during the building materials transportation stage, with the next highest being C20 concrete transportation. The carbon emissions of different construction processes vary greatly in the construction stage, with earth moving accounting for a higher proportion. In the operation and maintenance stage, the carbon emission caused by the maintenance building materials and machinery for the excavated graben scheme is 178,027.24 kg. The carbon emission of the full life cycle of this scheme is 1958.30 t, and the carbon emission of each stage is 954.96 t, 52.62 t, 772.69 t, and 178.03 t. The production stage of building materials is still the stage with the highest proportion of carbon emissions.

Because the excavated graben scheme uses fewer building materials, resulting in its carbon reduction being significantly better than that of the filled embankment scheme, this paper discussed the excavated graben scheme as the optimal option for carbon reduction; thus the excavated graben scheme was chosen as the object of the study to analyze the degree of carbon reduction measures and their effect on carbon emissions. Because of the change in the construction volume occurring after changing the soil nail wall slope to an ecological slope, the results show that the carbon emissions of the building material production, building material transportation, and construction stages changed from the original 954.96 t, 52.62 t, and 772.69 t to 956.57 t, 54.79 t, and 776.03 t. The carbon sequestration occurred in the operation and maintenance stage of the ecological slope, which led to the sequestration of 5061.77 t of carbon in the operation and maintenance stage of the excavated graben scheme. Because the carbon capture by the vegetation carbon sink in the operation and maintenance stage is significantly higher than the carbon emission during the production of building materials, the transportation of building materials, and

the construction stage, there is carbon sequestration in the whole life cycle of the excavated graben scheme that is equivalent to 3274.38 t.

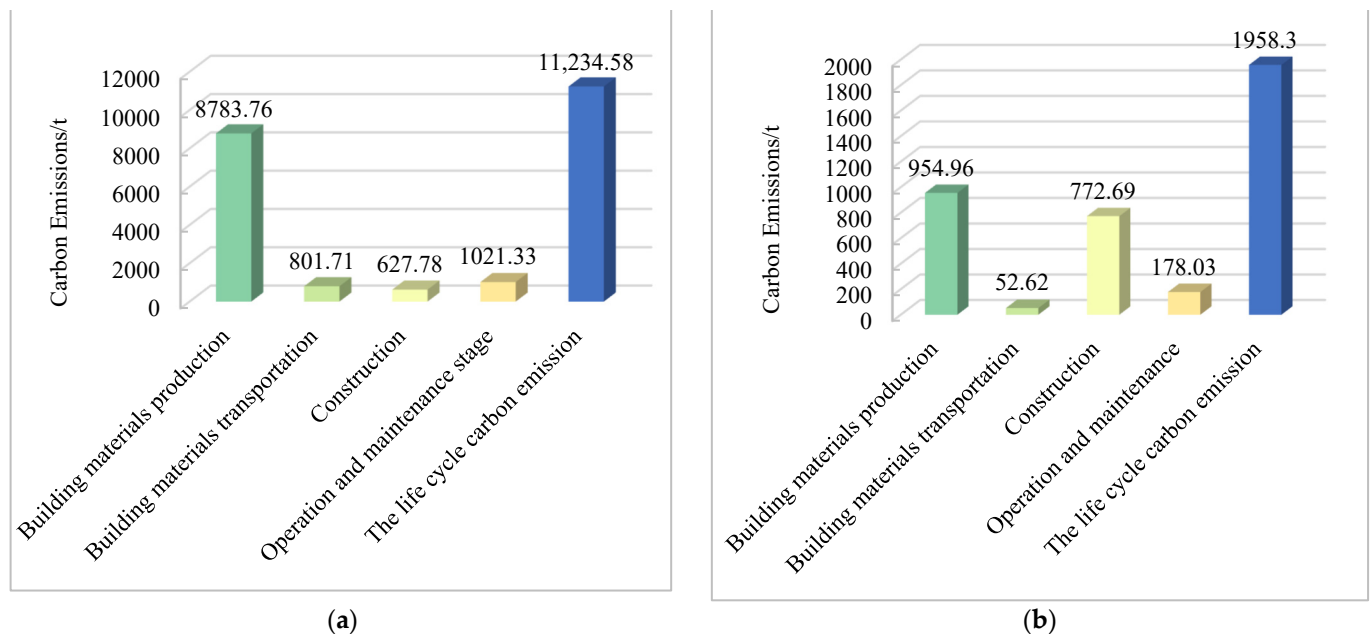


Figure 8. Carbon emissions from railway subgrade engineering. (a) Carbon emissions from the filled embankment scheme. (b) Carbon emissions from the excavated graben scheme.

5.1. Impacts and Challenges of Adopting Ecological Slopes for Railway Subgrade Engineering

The use of an ecological slope in railway subgrade engineering can significantly reduce carbon emissions, and the implementation of this carbon reduction measure has far-reaching impacts and positively promotes the realization of the carbon neutrality goal; however, the use of ecological slopes in railway subgrade engineering also faces certain challenges.

5.1.1. Contribution to Carbon-Neutral Targets

Direct reduction of carbon emissions: Ecological slope vegetations absorb carbon dioxide from the atmosphere through photosynthesis, which directly reduces greenhouse gas emissions. The widespread adoption of ecological slopes in railway subgrade engineering will have a positive impact on reducing carbon emissions in the entire transportation industry.

Enhancement of ecosystem services: The construction of ecological slopes on railway foundations helps to restore and enhance the services of damaged ecosystems such as soil and water conservation, air purification, climate regulation, and biodiversity protection. The enhancement of these services is of great significance for maintaining regional ecological balance and safeguarding human well-being.

Promoting green infrastructure construction: The implementation of ecological slopes on railway subgrade engineering has promoted the popularization and practice of the concept of green infrastructure construction. In addition to meeting the basic requirements of safety and functionality, railway engineering construction should also focus on the protection and restoration of the ecological environment. It helps to guide the whole society to form a consensus on green development and promote the green transformation of the economy and society.

5.1.2. The Challenges Ahead

Operation and maintenance challenges: When selecting ecological slope vegetation for railway subgrade engineering, a detailed ecological adaptability assessment of the vegetation is required, including consideration of the plant's adaptability to soil types,

tolerance to extreme climatic conditions (e.g., cold, heat, drought, rain, etc.), and potential impacts on local biodiversity. Reasonable seeding times and seeding methods can ensure high survival rates of vegetation, and advanced seeding technologies, such as hydraulic spraying, ecological bag planting, etc., can improve vegetation coverage and growth rates. Ecological slope vegetation is more fragile in the early stage of growth and requires regular weeding, fertilization, and irrigation. In arid areas, the establishment of efficient water management systems and the adoption of advanced water-saving irrigation techniques, among other things, can be used to ensure that the vegetation receives sufficient water.

Safety challenges: Soil erosion on ecological slopes of railway subgrade engineering can be controlled through biological or chemical measures such as laying vegetation nets and using soil stabilizers. Ecological restoration techniques such as vegetation restoration and soil improvement can also be utilized to improve the erosion resistance of the slope soil. The stability and resistance of the railway subgrade engineering slope ecosystem can also be improved by planting multiple types of slope vegetation to form diverse vegetation communities. In order to ensure the continuous coverage and soil-fixing capacity of the vegetation on the side slope of the railway subgrade engineering, a regular vegetation renewal plan can be formulated according to the growth cycle and degradation of the side slope vegetation.

5.2. Research Significance

5.2.1. Theoretical Significance

Railways are an important part of low-carbon transportation; thus, the study of carbon emissions from railway subgrade engineering is crucial for a comprehensive assessment of the carbon emissions of railway engineering. This paper fills in a gap in existing investigations on the measurement of carbon emissions from railway subgrade engineering and proposes carbon reduction measures that can provide new ideas for the low-carbon development of other transportation infrastructure areas. By quantitatively assessing the carbon emissions and carbon reduction potential of railway subgrade engineering projects, the environmental impact of railroad infrastructure construction can be more clearly recognized.

5.2.2. Practical Significance

Comparing the carbon emissions of the railway subgrade engineering filled embankment scheme and excavated graben scheme can give a scientific basis for the green design of railway subgrade engineering. Railway subgrade engineering designers can choose the railway subgrade structure form with lower carbon emission and optimize the design scheme according to the natural conditions of the railway subgrade engineering construction site, construction conditions, and environmental protection requirements. At the same time, this paper puts forward railway subgrade engineering excavation graben scheme carbon reduction measures that can be applied to the actual project to efficiently reduce the carbon emissions caused by the construction of railway subgrade engineering for the promotion of energy-saving and carbon emission abatement in the railroad industry to achieve sustainable development.

5.3. Future Research Directions

This paper only analyzes the carbon reduction potential of adopting ecological slopes for railway subgrade engineering projects; in the future, it can comprehensively sort out carbon reduction measures for railway subgrade engineering projects and quantitatively analyze the impact of each carbon reduction measure on the carbon emission of railway subgrade engineering projects. In the production stage of building materials, the use of recycled materials (e.g., waste tire particles and recycled aggregates from construction waste) can be promoted as the filling materials of railway subgrade engineering projects to reduce the demand for raw resources [51–53]. In the transportation stage of building materials, carbon emissions can be reduced by optimizing the transportation routes and

adopting low-carbon transportation methods [32,54]. Carbon emissions in the construction stage will be reduced by promoting the use of energy-efficient construction equipment (e.g., electric or hybrid excavators, loaders, etc.) and promoting the use of clean energy (e.g., solar energy, wind energy, etc.) [55–58]. Increasing the amount of carbon sequestered by vegetation during the operation and maintenance stage through the use of ecological slopes, the preferential selection of high carbon-consolidating vegetation for slopes, and increasing the vegetation slope coverage rate will also reduce carbon emissions [59]. Promoting and implementing the above carbon reduction measures in railway subgrade engineering and quantitatively evaluating the effects of the implementation of carbon reduction measures can provide theoretical support for the sustainable development of the railroad industry.

The following are examples of the carbon reduction potentials of carbon reduction measures: Through sensitivity analysis of carbon emission factors and transportation distance of building materials for the railway subgrade filled embankment scheme and excavated graben scheme, it can be seen that in the filled embankment scheme, the largest sensitivity coefficient is the carbon emission factor for ordinary silicate cement, and in the excavated graben scheme, the largest sensitivity coefficient is the diesel carbon emission factor. In this paper, low-carbon building materials and electric construction machinery are considered to be applied to the filled embankment scheme and the excavated graben scheme, respectively. The carbon emission factor for slag silicate cement is $0.503 \text{ tCO}_2\text{e/t}$, which is significantly lower than the carbon emission factor for ordinary silicate cement, and it can be determined that the use of slag silicate cement can reduce the carbon dioxide of this filled embankment scheme by 2,459,490 kg. The diesel construction machinery in the excavated graben scheme is replaced by electric construction machinery, of which the energy consumption parameters and carbon emission data for electric construction machinery have been given in Table 5, and it can be determined that the use of electric construction machinery can reduce carbon dioxide by 122,987 kg in this excavated graben scheme.

6. Conclusions

Based on the LCA theory, the carbon emissions of the full life cycles of the railway subgrade engineering filled embankment scheme and excavated graben scheme are divided into the stages of building material production, building material transportation, construction, and operation and maintenance. The carbon emission factor method, relying on the carbon emission evaluation model, is adopted to compute the carbon emissions of each stage and the full life cycles of the railway subgrade engineering filled embankment scheme and excavated graben scheme.

By analyzing the examples of the railway subgrade engineering filled embankment scheme and excavated graben scheme, the carbon emission of the full life cycle of the filled embankment scheme was calculated to be 11,234.58 t, of which carbon emission during the production of building materials, transportation of building materials, construction, and operation and maintenance stages were 8783.76 t, 801.71 t, 627.78 t, and 1021.33 t, respectively. The carbon emission of the whole life cycle of the excavated graben scheme was calculated to be 1958.30 t, of which carbon emissions during the production of building materials, transportation of building materials, construction, and operation and maintenance were 954.96 t, 52.62 t, 772.69 t, and 178.03 t, respectively.

The carbon emission of the excavated graben scheme's whole life cycle is significantly lower than that of the filled embankment scheme. This study took the excavated graben scheme as the research target and analyzed its carbon abatement potential after changing the soil nail wall slope to an ecological slope. After changing the soil nail wall slope to an ecological slope, carbon emissions from the production of building materials, transportation of building materials, and construction stages were 956.57 t, 54.79 t, and 776.03 t, respectively, and the slope vegetation in the operation and maintenance stage had the role of a carbon sink, capturing 5061.77 t of carbon. Because the vegetation carbon sink in the operation and maintenance stage was significantly higher than carbon

emission during the production of building materials, transportation of building materials, and construction stages, there was a sequestration of 3274.38 t of carbon in the whole life cycle of the excavated graben scheme. The results indicate that the ecological slope can efficiently reduce the carbon emission of the life cycle of the excavated graben scheme, and the results of the research can be used as a reference for the low-carbon design of railway subgrade engineering.

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References

- Andrade, C.E.S.D.; D'Agosto, M.D.A. Energy Use and Carbon Dioxide Emissions Assessment in the Lifecycle of Passenger Rail Systems: The Case of the Rio de Janeiro Metro. *J. Clean. Prod.* **2016**, *126*, 526–536. [\[CrossRef\]](#)
- Lou, H.; Shi, X.; Ren, X.; Yang, S.; Cai, M.; Pan, Z.; Zhu, Y.; Feng, D.; Zhou, B. Limited Terrestrial Carbon Sinks and Increasing Carbon Emissions from the Hu Line Spatial Pattern Perspective in China. *Ecol. Indic.* **2024**, *162*, 112035. [\[CrossRef\]](#)
- D'Acierno, L.; Botte, M. A Passenger-Oriented Optimization Model for Implementing Energy-Saving Strategies in Railway Contexts. *Energies* **2018**, *11*, 2946. [\[CrossRef\]](#)
- Bueno, G.; Hoyos, D.; Capellán-Pérez, I. Evaluating the Environmental Performance of the High Speed Rail Project in the Basque Country, Spain. *Res. Transp. Econ.* **2017**, *62*, 44–56. [\[CrossRef\]](#)
- Liu, X.; Schraven, D.; De Bruijne, M.; De Jong, M.; Hertogh, M. Navigating Transitions for Sustainable Infrastructures—The Case of a New High-Speed Railway Station in Jingmen, China. *Sustainability* **2019**, *11*, 4197. [\[CrossRef\]](#)
- Åkerman, J. The Role of High-Speed Rail in Mitigating Climate Change—The Swedish Case Europabanan from a Life Cycle Perspective. *Transp. Res. Part D Transp. Environ.* **2011**, *16*, 208–217. [\[CrossRef\]](#)
- Hu, X.; Zhang, X.; Dong, L.; Li, H.; He, Z.; Chen, H. Carbon Emission Factors Identification and Measurement Model Construction for Railway Construction Projects. *Int. J. Environ. Res. Public Health* **2022**, *19*, 11379. [\[CrossRef\]](#)
- Lee, C.K.; Kim, J.S. A Research on the Greenhouse Gas Emission Reduction of Railway Structure Construction Stage. *J. Korean Soc. Railw.* **2011**, *14*, 425–432. [\[CrossRef\]](#)
- Najafpour Navaei, T.; Blainey, S.; Preston, J.; Powrie, W. Carbon Footprinting of Railway Infrastructure: A Standardized, Consistent Data Collection Method. *Carbon Manag.* **2024**, *15*, 2368839. [\[CrossRef\]](#)
- Wang, Y.-Z.; Zhou, S.; Ou, X.-M. Development and Application of a Life Cycle Energy Consumption and CO₂ Emissions Analysis Model for High-Speed Railway Transport in China. *Adv. Clim. Chang. Res.* **2021**, *12*, 270–280. [\[CrossRef\]](#)
- Lin, J.; Li, H.; Huang, W.; Xu, W.; Cheng, S. A Carbon Footprint of High-Speed Railways in China: A Case Study of the Beijing-Shanghai Line. *J. Ind. Ecol.* **2019**, *23*, 869–878. [\[CrossRef\]](#)
- Kaewunruen, S.; Sresakoolchai, J.; Peng, J. Life Cycle Cost, Energy and Carbon Assessments of Beijing-Shanghai High-Speed Railway. *Sustainability* **2019**, *12*, 206. [\[CrossRef\]](#)
- Cheng, S.; Lin, J.; Xu, W.; Yang, D.; Liu, J.; Li, H. Carbon, Water, Land and Material Footprints of China's High-Speed Railway Construction. *Transp. Res. Part D Transp. Environ.* **2020**, *82*, 102314. [\[CrossRef\]](#)
- Lin, J.; Cheng, S.; Li, H.; Yang, D.; Lin, T. Environmental Footprints of High-Speed Railway Construction in China: A Case Study of the Beijing-Tianjin Line. *Int. J. Environ. Res. Public Health* **2019**, *17*, 105. [\[CrossRef\]](#)
- Chang, Y.; Lei, S.; Teng, J.; Zhang, J.; Zhang, L.; Xu, X. The Energy Use and Environmental Emissions of High-Speed Rail Transportation in China: A Bottom-up Modeling. *Energy* **2019**, *182*, 1193–1201. [\[CrossRef\]](#)
- Chang, B.; Kendall, A. Life Cycle Greenhouse Gas Assessment of Infrastructure Construction for California's High-Speed Rail System. *Transp. Res. Part D Transp. Environ.* **2011**, *16*, 429–434. [\[CrossRef\]](#)

17. Lee, J.-Y.; Lee, C.-K.; Chun, Y.-Y. Greenhouse Gas Emissions from High-Speed Rail Infrastructure Construction in Korea. *Transp. Res. Part D Transp. Environ.* **2020**, *87*, 102514. [\[CrossRef\]](#)
18. Liu, M.; Jia, S.; Li, P.; Liu, X.; Zhang, Y. Predicting GHG Emissions from Subway Lines in the Planning Stage on a City Level. *J. Clean. Prod.* **2020**, *259*, 120823. [\[CrossRef\]](#)
19. Li, Y.; He, Q.; Luo, X.; Zhang, Y.; Dong, L. Calculation of Life-Cycle Greenhouse Gas Emissions of Urban Rail Transit Systems: A Case Study of Shanghai Metro. *Resour. Conserv. Recycl.* **2018**, *128*, 451–457. [\[CrossRef\]](#)
20. Liu, M.; Jia, S.; He, X. A Quota-Based GHG Emissions Quantification Model for the Construction of Subway Stations in China. *J. Clean. Prod.* **2018**, *198*, 847–858. [\[CrossRef\]](#)
21. Liu, M.; Jia, S.; Liu, X. Evaluation of Mitigation Potential of GHG Emissions from the Construction of Prefabricated Subway Station. *J. Clean. Prod.* **2019**, *236*, 117700. [\[CrossRef\]](#)
22. Jia, S.; Liu, M. Embodied GHG Emissions of High Speed Rail Stations: Quantification, Data-Driven Prediction and Cost-Benefit Analysis. *J. Clean. Prod.* **2022**, *366*, 133006. [\[CrossRef\]](#)
23. Wu, N.; Zhang, J.; Li, X.; Wang, X.; Liu, C.; Yang, K.; Kuang, D.; Feng, K. Carbon Emissions Assessment Study of Standard Ring Materialization Stage of Assembled Subway Stations. In Proceedings of the ICCREM 2022, Virtual Conference, 15 December 2022; American Society of Civil Engineers: Reston, VA, USA, 2022; pp. 193–203.
24. Wang, N.; Satola, D.; Houlihan Wiberg, A.; Liu, C.; Gustavsen, A. Reduction Strategies for Greenhouse Gas Emissions from High-Speed Railway Station Buildings in a Cold Climate Zone of China. *Sustainability* **2020**, *12*, 1704. [\[CrossRef\]](#)
25. Kaewunruen, S.; Sresakoolchai, J.; Yu, S. Global Warming Potentials Due to Railway Tunnel Construction and Maintenance. *Appl. Sci.* **2020**, *10*, 6459. [\[CrossRef\]](#)
26. Wu, H.; Yang, K.; Chen, K.; Zhou, W.; Yu, T.; Wang, K. GHG Emission Quantification and Reduction Pathway of Subway Shield Tunnel Engineering: A Case Study on Guangzhou Metro, China. *Environ. Sci. Pollut. Res.* **2024**, *31*, 54768–54784. [\[CrossRef\]](#)
27. Chen, G.; Li, W.; Yang, F.; Cao, T.; Wu, Z.; Lu, Y.; Wu, C. Study on Resourceful Treatment and Carbon Reduction Intensity of Metro Shield Slag: An Example of a Tunnel Interval of Shenzhen Line 13. *Buildings* **2023**, *13*, 2816. [\[CrossRef\]](#)
28. Pritchard, J.A.; Preston, J. Understanding the Contribution of Tunnels to the Overall Energy Consumption of and Carbon Emissions from a Railway. *Transp. Res. Part D Transp. Environ.* **2018**, *65*, 551–563. [\[CrossRef\]](#)
29. Ortega, A.; Blainey, S.; Preston, J. Assessing Whole-Life Carbon Footprint of Under Sleeper Pad Installation for Ballasted Track. *J. Transp. Eng. Part A Syst.* **2018**, *144*, 04018073. [\[CrossRef\]](#)
30. Li, X.; Xie, W.; Xu, L.; Li, L.; Jim, C.Y.; Wei, T. Holistic Life-Cycle Accounting of Carbon Emissions of Prefabricated Buildings Using LCA and BIM. *Energy Build.* **2022**, *266*, 112136. [\[CrossRef\]](#)
31. Li, J.; Li, S.; Wu, F. Research on Carbon Emission Reduction Benefit of Wind Power Project Based on Life Cycle Assessment Theory. *Renew. Energy* **2020**, *155*, 456–468. [\[CrossRef\]](#)
32. Wu, H.; Zhou, W.; Chen, K.; Zhang, L.; Zhang, Z.; Li, Y.; Hu, Z. Carbon Emissions Assessment for Building Decoration Based on Life Cycle Assessment: A Case Study of Office Buildings. *Sustainability* **2023**, *15*, 14055. [\[CrossRef\]](#)
33. Zhang, Y.; Yan, D.; Hu, S.; Guo, S. Modelling of Energy Consumption and Carbon Emission from the Building Construction Sector in China, a Process-Based LCA Approach. *Energy Policy* **2019**, *134*, 110949. [\[CrossRef\]](#)
34. Liu, W.; Huang, Q. Research on Carbon Footprint Accounting in the Materialization Stage of Prefabricated Housing Based on DEMATEL-ISM-MICMAC. *Appl. Sci.* **2023**, *13*, 13148. [\[CrossRef\]](#)
35. Zhan, Z.; Xia, P.; Xia, D. Study on Carbon Emission Measurement and Influencing Factors for Prefabricated Buildings at the Materialization Stage Based on LCA. *Sustainability* **2023**, *15*, 13648. [\[CrossRef\]](#)
36. Luo, X.; Ren, M.; Zhao, J.; Wang, Z.; Ge, J.; Gao, W. Life Cycle Assessment for Carbon Emission Impact Analysis for the Renovation of Old Residential Areas. *J. Clean. Prod.* **2022**, *367*, 132930. [\[CrossRef\]](#)
37. Li, X.; Wang, C.; Kassem, M.A.; Wu, S.-Y.; Wei, T.-B. Case Study on Carbon Footprint Life-Cycle Assessment for Construction Delivery Stage in China. *Sustainability* **2022**, *14*, 5180. [\[CrossRef\]](#)
38. Hosseinian, S.M.; Faghani, M. Assessing the Effect of Structural Parameters and Building Site in Achieving Low Carbon Building Materialization Using a Life-Cycle Assessment Approach. *J. Build. Eng.* **2021**, *44*, 103318. [\[CrossRef\]](#)
39. Zhang, X.; Xu, J.; Zhang, X.; Li, Y. Life Cycle Carbon Emission Reduction Potential of a New Steel-Bamboo Composite Frame Structure for Residential Houses. *J. Build. Eng.* **2021**, *39*, 102295. [\[CrossRef\]](#)
40. Cao, J.; Zhu, Y.; Zhang, J.; Wang, H.; Zhu, H. The Sustainability Study and Exploration in the Building Commercial Complex System Based on Life Cycle Assessment (LCA)–Emergy–Carbon Emission Analysis. *Processes* **2023**, *11*, 1989. [\[CrossRef\]](#)
41. Liu, K.; Leng, J. Quantitative Research on Embodied Carbon Emissions in the Design Stage: A Case Study from an Educational Building in China. *J. Asian Archit. Build. Eng.* **2022**, *21*, 1182–1192. [\[CrossRef\]](#)
42. Raja, J.; Dixon, N.; Fowmes, G.; Frost, M.; Assinder, P. Obtaining Reliable Embodied Carbon Values for Geosynthetics. *Geosynth. Int.* **2015**, *22*, 393–401. [\[CrossRef\]](#)
43. Zhou, F.; Ning, Y.; Guo, X.; Guo, S. Analyze Differences in Carbon Emissions from Traditional and Prefabricated Buildings Combining the Life Cycle. *Buildings* **2023**, *13*, 874. [\[CrossRef\]](#)
44. Han, Q.; Chang, J.; Liu, G.; Zhang, H. The Carbon Emission Assessment of a Building with Different Prefabrication Rates in the Construction Stage. *Int. J. Environ. Res. Public Health* **2022**, *19*, 2366. [\[CrossRef\]](#)
45. Yang, H.; Kikuta, K.; Hayashi, M. Research on the Whole Lifecycle Emission Reduction Effect of Buildings with Different Structures in Severely Cold Regions—A Case Study in China. *Energies* **2023**, *16*, 5285. [\[CrossRef\]](#)

46. TZJ 2000-2017; Railway Engineering Budget Quota—Railway Subgrade Engineering. Chinese Standard: Beijing, China, 2017.
47. TZJ 3004-2017; Railway Engineering Construction Machinery Bench Cost Quota. Chinese Standard: Beijing, China, 2017.
48. Yang, X.; Liu, Y.; Liu, K.; Wei, J.; Hu, G.; Pei, S. Application and Configuration Analysis of Electric Muck Transfer Equipment in Plateau Railway Tunnel: A Case Study in Southwest China. *Sci. Rep.* **2024**, *14*, 7222. [[CrossRef](#)]
49. Rungskunroch, P.; Shen, Z.-J.; Kaewunruen, S. Getting It Right on the Policy Prioritization for Rail Decarbonization: Evidence From Whole-Life CO_{2e} Emissions of Railway Systems. *Front. Built Environ.* **2021**, *7*, 638507. [[CrossRef](#)]
50. Zhang, X.; Zhang, X. Comparison and Sensitivity Analysis of Embodied Carbon Emissions and Costs Associated with Rural House Construction in China to Identify Sustainable Structural Forms. *J. Clean. Prod.* **2021**, *293*, 126190. [[CrossRef](#)]
51. Voit, K.; Kuschel, E. Rock Material Recycling in Tunnel Engineering. *Appl. Sci.* **2020**, *10*, 2722. [[CrossRef](#)]
52. Tawk, M.; Qi, Y.; Indraratna, B.; Rujikiatkamjorn, C.; Heitor, A. Behavior of a Mixture of Coal Wash and Rubber Crumbs under Cyclic Loading. *J. Mater. Civ. Eng.* **2021**, *33*, 04021054. [[CrossRef](#)]
53. Vukićević, M.; Popović, Z.; Despotović, J.; Lazarević, L. Fly Ash and Slag Utilization for the Serbian Railway Substructure. *Transport* **2016**, *33*, 389–398. [[CrossRef](#)]
54. Xu, P.; Zhu, J.; Li, H.; Xiong, Z.; Xu, X. Coupling Analysis between Cost and Carbon Emission of Bamboo Building Materials: A Perspective of Supply Chain. *Energy Build.* **2023**, *280*, 112718. [[CrossRef](#)]
55. De Bortoli, A.; Agez, M. Environmentally-Extended Input-Output Analyses Efficiently Sketch Large-Scale Environmental Transition Plans: Illustration by Canada's Road Industry. *J. Clean. Prod.* **2023**, *388*, 136039. [[CrossRef](#)]
56. Fu, S.; Li, Z.; Lin, T.; Chen, Q.; Ren, H. A Positive Flow Control System for Electric Excavators Based on Variable Speed Control. *Appl. Sci.* **2020**, *10*, 4826. [[CrossRef](#)]
57. Lin, T.; Lin, Y.; Ren, H.; Chen, H.; Chen, Q.; Li, Z. Development and Key Technologies of Pure Electric Construction Machinery. *Renew. Sustain. Energy Rev.* **2020**, *132*, 110080. [[CrossRef](#)]
58. Trinh, H.-A.; Truong, H.V.A.; Do, T.C.; Nguyen, M.H.; Phan, V.D.; Ahn, K.K. Optimization-Based Energy Management Strategies for Hybrid Construction Machinery: A Review. *Energy Rep.* **2022**, *8*, 6035–6057. [[CrossRef](#)]
59. Blair, J.; Roldan, C.; Ghosh, S.; Yung, S.-H. Greening Rail Infrastructure for Carbon Benefits. *Procedia Eng.* **2017**, *180*, 1716–1724. [[CrossRef](#)]

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