ISSN 2663-1563 Vol. 8, Issue 1: 104-111, DOI: 10.25236/AJAGE.2026.080113

Embodied Carbon Footprint Comparative Analysis: Screw Piles Versus Cast-in-Place Piles in Foundation Engineering

Jiaxin Lu[1], Dengke Pu[2,*]

[1]*School of Civil Engineering, Southwest Jiaotong University, Chengdu, 610031, China*
[2]*Sichuan Yanjiang Yijin Expressway Co., Ltd., Xichang, 615099, China*

Abstract: *To address the carbon neutrality objectives within the highway construction sector, this research employs a three-tier analytical framework to resolve the debate concerning carbon emissions associated with screw piles and cast-in-place piles. Utilizing methodologies such as quota-based data modeling, and engineering functional adaptability assessment, the study consolidates emission factors across the entire lifecycle chain—encompassing material production, transportation, construction, and processing. This integration enables the development of a refined carbon accounting model for the pile materialization stage. Monte Carlo simulation is leveraged to quantify the impact of parameter uncertainty, incorporating a case study from highways in the Hang-Jia-Hu Plain. This approach establishes, for the first time, a carbon performance assessment framework benchmarked against bearing capacity requirements. Static analysis reveals that under equal volume conditions, the carbon emissions of screw piles primarily originate from steel consumption, with a total carbon footprint 2.78 times higher than that of cast-in-place piles. Sensitivity analyses indicate that cast-in-place pile emissions exhibit significant sensitivity to transport distance, material recovery rate, and vehicle type, whereas the prefabricated nature of screw piles results in considerably weaker parametric responses.*

Keywords: *Highway Engineering; Carbon Footprint; Cast-in-Place Piles; Screw Piles*

1. Introduction

Against the backdrop of a globally advancing carbon neutrality strategy, China, as the country with the world's largest highway construction scale, faces an increasingly urgent need to manage carbon emissions from its infrastructure[1,2]. Research indicates that carbon emissions during highway construction predominantly originate from structural components such as bridges and tunnels[3]. Among these, the embodied stage of pile foundation engineering is particularly critical. This stage alone accounts for 82% to 95% of the carbon emissions throughout the entire life cycle[4].

Helical piles have emerged in recent years as an efficient construction technology capable of reducing earthwork excavation, shortening project durations, and mitigating on-site pollution, thereby exhibiting considerable potential for carbon emission reduction[5]. However, there remains ongoing debate regarding their actual comparative carbon performance relative to conventional cast-in-place piles. Scientifically assessing the differences in carbon emissions between helical and cast-in-place piles is a key technical requirement for promoting low-carbon construction and serves as an essential basis for pile type selection in engineering practice. Existing research typically employs Life Cycle Assessment (LCA) for static analysis, wherein total carbon emissions are calculated based on fixed, predefined parameters. Limited available studies have indicated that under certain conditions, helical piles may demonstrate superior carbon reduction potential compared to cast-in-place piles; however, this advantage may be diminished by the high carbon intensity associated with steel production, particularly for large-diameter piles or under complex geological conditions[6]. Within static assessment frameworks, preliminary quantitative evaluations of the carbon footprints of both pile types remain insufficient, especially due to the lack of foundational research on helical piles, underscoring the need for additional empirical data. Currently, there is a paucity of research employing probabilistic methods like Monte Carlo simulation to conduct systematic probabilistic comparisons of how the embodied-stage carbon footprints of helical and cast-in-place piles respond to dynamic driving factors under identical project scenarios.

This study focuses on the challenge of analyzing carbon emissions during the embodied stage of

ISSN 2663-1563 Vol. 8, Issue 1: 104-111, DOI: 10.25236/AJAGE.2026.080113

pile foundation engineering. Addressing the limitations of existing research—which predominantly relies on static parameters and often overlooks practical engineering performance constraints—this research proposes an innovative three-tier analytical framework that integrates quota-based data modeling, and functional engineering adaptability. By systematically incorporating emission factors across the full lifecycle chain—including material production, transportation, construction, and processing—the framework quantifies the impact of key parameter uncertainties. It also transcends the traditional equal-volume comparison benchmark by incorporating actual bearing capacity requirements into the carbon performance evaluation. Using a highway embankment project located on the Jiahu Plain as a case study, the proposed method establishes a scientifically grounded decision-making paradigm for low-carbon pile type selection in highway engineering.

2. Static Carbon Emission Estimation Model for the Embodied Stage of Pile Foundations

2.1 System Boundary and Accounting Framework for the Embodied Stage

This study calculates the embodied-stage carbon emissions of cast-in-place piles and helical piles based on construction quota data[7]. It is important to note that the analysis does not adopt a full life cycle assessment (LCA) approach. The primary rationale is that empirical evidence from existing literature indicates that the embodied stage accounts for approximately 82% to 95% of total life cycle carbon emissions in foundation engineering, making it the core focus of carbon footprint analysis. Furthermore, the fundamental differences between helical piles and cast-in-place piles lie in the energy consumption associated with steel versus concrete production and the construction processes of screwing versus casting. These differences are most pronounced during the embodied stage.

The system boundary in this study comprises four main components. The first is the material production and on-site construction stage; the second is the transportation stage; the third is the material processing stage. The material production and processing stage includes the carbon emissions generated during the manufacturing of primary materials used in pile components—specifically, steel smelting and rolling for helical piles, and the production of cement, aggregates, and reinforcement steel for cast-in-place piles[4]. The transportation stage accounts for carbon emissions from the movement of raw materials and intermediate products from their sources or suppliers to the construction site[8]. This involves consideration of energy consumption and emission factors related to trucks and transport modes. The on-site construction stage focuses on the emissions associated with the energy consumed in converting materials into installed pile structures[4]. This includes, for helical piles, the mechanical energy consumed during screwing operations, and for cast-in-place piles, energy used by drilling machines, slurry pumping, and in-situ concrete casting equipment[9]. The material extraction and processing stage addresses emissions from on-site operations such as the extraction, crushing, and washing of aggregates in the raw material chain of cast-in-place piles[10]. The specific system boundary configuration is illustrated in Figure 1.

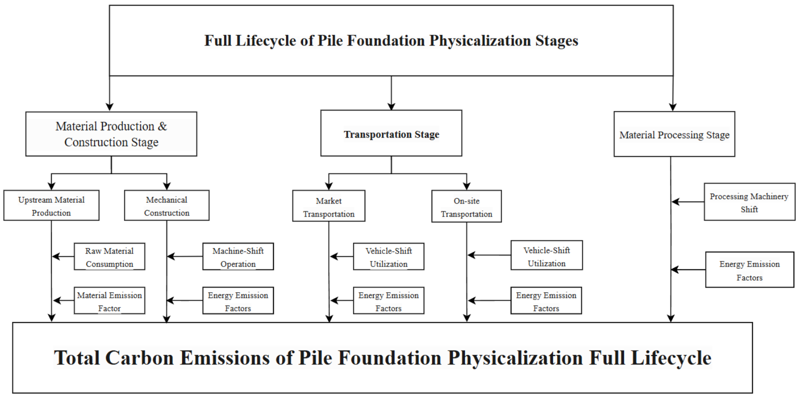


Figure 1 System Boundary for Embodied Carbon Accounting in Pile Foundation Construction

2.2 Quota-Driven Refined Carbon Emission Accounting System

2.2.1 Quota Basis and Emission Factor Sources

This study selects the “Highway Engineering Budget Quota” as the primary data source for

ISSN 2663-1563 Vol. 8, Issue 1: 104-111, DOI: 10.25236/AJAGE.2026.080113

quantities related to materials, machinery operating hours, and other engineering metrics in the pile foundation carbon emission model[7]. The selection is mainly due to its industry authority, standardization, and quantifiability. Such standardization helps prevent deviations caused by case-specific differences or subjective estimates. The quota's authoritative and universal nature ensures that the calculated results reflect the industry average level, thereby enhancing the scientific validity of the study and providing a comparable basis for cross-project carbon emission assessments. The quota data naturally encompass the key emission stages within the study's system boundary—namely, material production, transportation, and on-site construction. Its detailed resource decomposition structure supports refined accounting for each stage. Basing calculations on quota data is essential to guarantee that the model's foundational data are accurate, objective, comparable, and supported by engineering practice [11].

Emission factors serve as supporting background parameters, with their values derived from government documents, various databases, and relevant academic literature. Commonly used databases include the official database of China's Ministry of Ecology and Environment (MEE), the Intergovernmental Panel on Climate Change (IPCC) database, and the Ecoinvent database. In addition to these professional databases, a substantial body of research in both domestic and international literature provides emission factor data. For instance, Ju Ying and Zhang Tao from Tongji University have compiled emission factors for various energy sources and construction materials. Gao Yuanxue from Tsinghua University employed input–output analysis based on the CLCD and IPCC guidelines to estimate the emission factors of upstream construction products[12]. Furthermore, the Ministry of Housing and Urban-Rural Development of the People's Republic of China has issued the Standard for Building Carbon Emission Calculation, which offers methodological guidance for relevant studies[13]. Based on these standards and literature sources, this study compiles and summarizes the required carbon emission factors, as shown in Table 1, to support subsequent calculations.

Table 1 Emission Factors for Different Materials and Energy Sources

Material/Energy	Emission Factor	Unit
Electric welding rod	4	$kgCO_2/kg$
Iron parts	1.4	$kgCO_2/kg$
Water	0.168	$kgCO_2/m3$
Sawn timber	150	$kgCO_2/m3$
Clay	1.921	$kgCO_2/m3$
Medium-coarse sand	1.673	$kgCO_2/m3$
Crushed stone (4cm)	1.453	$kgCO_2/m3$
32.5 cement	621	$kgCO_2/t$
Steel pipe	2050	$kgCO_2/t$
Steel plate	1.99	$kgCO_2/kg$
Diesel	4.369	$kgCO_2/kg$
Gasoline	3.943	$kgCO_2/kg$
Electricity	0.972	$kgCO_2/kWh$

2.2.2 Development of a Quota-Based Three-Stage Carbon Accounting Model

The calculation of carbon emissions in this study considers three main components: pile foundation construction, material transportation, and material processing and treatment. The input quantities and corresponding carbon emissions related to the construction and material production of a given pile foundation type are calculated using Equation (1) and Equation (2), respectively.

$$TRE_{\mathrm{u}} = \sum_{\mathrm{j}} M_{\mathrm{j}} + \sum_{\mathrm{k}} E\mathrm{q}_{\mathrm{k}} \times EC_{\mathrm{k}} \tag{1}$$

$$TCE_{\mathrm{u}} = \sum_{\mathrm{j}} M_{\mathrm{j}} \times EF_{\mathrm{j}} + \sum_{\mathrm{k}} E\mathrm{q}_{\mathrm{k}} \times EC_{\mathrm{k}} \times EF_{\mathrm{k}} \tag{2}$$

Where: TRE_u—Total resource inputs during pile construction and material production cycles

TCE_u—Total carbon emissions generated during pile construction and material production cycles

M_j—Mass/volume of j-th material input category

Eq_k—Number of equipment shifts for k-th construction machinery type

EC_k—Energy consumption per equipment shift for k-th machinery

ISSN 2663-1563 Vol. 8, Issue 1: 104-111, DOI: 10.25236/AJAGE.2026.080113

EF_j—Material-specific emission factor for j-th material category

EF_k—Energy-related emission factor per energy unit for k-th machinery

In the formulated equations, both M_j and Eq_k can be sourced directly from the Highway Engineering Budgetary Quota[7]. Meanwhile,EC_k are referenced from the Highway Engineering Machinery Operating Hour Cost Quota[14]. For emission factors EF_j and EF_k, refer to the consolidated dataset in Table 1.

Equation (1) and Equation (2) quantify carbon emissions specifically during construction and material production phases, deliberately excluding logistical transport considerations. This omission warrants explicit justification given that transporting bulk materials, prefabricated components, and equipment from origin to construction sites constitutes a substantial carbon emission source. Such emissions exhibit significant variations contingent upon geospatial distance, transportation modalities, and logistical efficiency. Material transport can be categorized into two distinct operational scopes based on project boundaries, with supply chain procurement transport representing one critical classification. The corresponding computational methodologies are detailed in Equation (3) and Equation (4).

$$TRE_{\mathrm{m1}} = \sum_{\mathrm{j}} \mathrm{m_j} \times DS_{\mathrm{j}} \times FU_{\mathrm{j}} \tag{3}$$

$$TCE_{\mathrm{m1}} = \sum_{\mathrm{j}} \mathrm{m_j} \times DS_{\mathrm{j}} \times FU_{\mathrm{j}} \times EF_{\mathrm{j}} \tag{4}$$

Where: TRE_{m1}—Total energy inputs for transporting construction materials from market sources to the tunnel construction site

TCE_{m1}—Carbon emissions generated during material transport from market sources to tunnel site

m_j—Transport quantity of the j-th material category

DSj—Transport distance (km) between material source and project site for j-th material

FUj—Fuel/energy consumption rate per tonne-kilometer for j-th material transport

EFj—Carbon emission factor per energy unit for the transport vehicle of j-th material

Table 2 enumerates the values of FU_j , derived through computational methods specified in the national standard Standard for Building Carbon Emission Calculation and corroborating literature sources[13]. The second transport category pertains to on-site material hauling operations, with corresponding resource inputs and emissions quantified by Equation (5) and Equation (6), respectively.

$$TRE_{\mathrm{m2}} = \sum_{\mathrm{j}} (E\mathrm{q_{j1}} + E\mathrm{q_{j2}} \times \mathrm{k}) \times FU_{\mathrm{j}} \tag{5}$$

$$TCE_{\mathrm{m2}} = \sum_{\mathrm{j}} (\mathrm{Eq_{j1}} + E\mathrm{q_{j2}} \times \mathrm{k}) \times FU_{\mathrm{j}} \times EF_{\mathrm{j}} \tag{6}$$

Where: TREm2—Energy inputs for on-site material hauling during pile construction

TCEm2—Carbon emissions from on-site material hauling during pile construction

Eqj1—Equipment shifts consumed for transporting j-th material over base haul distance

Eqj2—Additional equipment shifts consumed for transporting j-th material over excess haul distance

k—Excess haul distance coefficient

FUj—Energy consumption rate per equipment shift for hauling j-th material

EFj—Carbon emission factor per energy unit for hauling equipment of j-th material

Specific values for Eq_{j1}, Eq_{j2}, and k are directly sourced from the Highway Engineering Budgetary Quota[7]. Meanwhile, FU_j values are referenced from the Energy Consumption Coefficients section of the Highway Engineering Mechanical Shift Cost Quota , with EF_j obtained from the consolidated database in Table 1[14].

In practical pile construction operations, not all requisite materials are procured through commercial markets. Notably, aggregates such as sand and gravel for cast-in-place piles can often be obtained

ISSN 2663-1563 Vol. 8, Issue 1: 104-111, DOI: 10.25236/AJAGE.2026.080113

through on-site quarrying and extraction, thereby necessitating the inclusion of specialized calculation formulas for material processing and refinement.

$$TRE_{\mathrm{r}} = \sum_{\mathrm{j}} E\mathrm{q}_{\mathrm{j}} \times EC_{\mathrm{j}} \tag{7}$$

$$TCE_{\mathrm{r}} = \sum_{\mathrm{j}} E\mathrm{q}_{\mathrm{j}} \times EC_{\mathrm{j}} \times EF_{\mathrm{j}} \tag{8}$$

where: TREr—Energy inputs for material processing during pile construction

TCEr—Carbon emissions from material processing during pile construction

Eqj—Equipment shifts for processing machinery of j-th material

ECj—Shift-level energy consumption of machinery processing j-th material

EFj—Carbon emission factor per energy unit for processing machinery of j-th material

The Highway Engineering Budget Quota directly references quantified values of Eqj, while the Highway Engineering Machinery Operating Hour Cost Quota specifies both energy types and consumption values for ECj[7,14]. Corresponding EFj parameters are accessible in Table 1 per standardized documentation protocols.

To account for the dual-origin material procurement—partially sourced through commercial supply chains and partially extracted on-site—Equation (9), Equation (10) and Equation (11) implement adaptive corrections to the core computational frameworks governing construction/material production stages, market transport phases, and on-site processing operations.

$$TCE_{\mathrm{z}} = TCE_{\mathrm{u}} \times (1 - \mathrm{h}) \tag{9}$$

$$TCE_{\mathrm{x}} = TCE_{\mathrm{m1}} \times (1 - \mathrm{h}) \tag{10}$$

$$TCE_{\mathrm{c}} = TCE_{\mathrm{r}} \times \mathrm{h} \tag{11}$$

where: TCEz—Modified carbon emissions from pile construction and integrated material production

TCEx—Modified carbon emissions from market-to-tunnel material transport

TCEc—Modified carbon emissions from on-site material processing

h—Material processing yield ratio

Through the computational framework established above, the cumulative embodied carbon emissions for any given pile type can be derived using Equation (12).

$$TCE = TCE_{\mathrm{z}} + TCE_{\mathrm{x}} + TCE_{\mathrm{m1}} + TCE_{C} \tag{12}$$

Where: Total carbon emissions generated during the embodied stage of pile construction

Other variables retain definitions consistent with preceding equations.

Table 2 Transportation Fuel Consumption in the Vehicle Market

Vehicle Type	FUj	Energy Type
Electric locomotive	0.010 kWh /(t km)	Electricity
Diesel locomotive	0.003 kg /(t km)	Diesel
Medium-duty gasoline truck (8t payload)	0.029 kg /(t km)	Gasoline
Heavy-duty gasoline truck (18t payload)	0.026 kg /(t km)	Gasoline
Medium-duty diesel truck (8t payload)	0.041 kg /(t km)	Diesel
Heavy-duty diesel truck (30t payload)	0.017 kg /(t km)	Diesel
Heavy-duty diesel truck (46t payload)	0.013 kg /(t km)	Diesel

ISSN 2663-1563 Vol. 8, Issue 1: 104-111, DOI: 10.25236/AJAGE.2026.080113

2.3 Static Model Construction and Result Analysis

2.3.1 Implementation of the Python Computing Platform and Key Parameter Settings

With the carbon emission calculation formulas established for each stage, the carbon emissions during the embodied stage of pile foundation construction can be computed using the Python platform. Python offers numerous advantages: it provides a wealth of scientific computing libraries such as Pandas and NumPy, enabling efficient processing of complex material inventories and energy consumption data during the construction phase; it features flexible visualization tools like Matplotlib and Seaborn, which allow intuitive representation of carbon emission distributions and stage-wise contribution rates; its strong integration capabilities support interoperability with BIM models or database systems for automated parameter extraction. Moreover, Python's concise syntax significantly reduces the cost of model iteration and cross-team collaboration, making the entire life cycle carbon emission workflow—including data cleaning, batch calculation, and result validation—more efficient and precise, thus enhancing analytical outcomes[15]. Additionally, the Python platform supports subsequent dynamic analyses such as Monte Carlo simulations , where NumPy can efficiently generate probabilistic samples of carbon emission parameters, and visualization tools provide clear depictions of carbon emission risk probability distributions, offering quantitative support for uncertainty analysis[16].

Helical Pile Driving And Pile Splice Connection

Bill of Quantities (BOQ) Unit

Item Sequence No.	Resource Description	Unit	Resource Code	Electric Winch Pile Driving Pile Diameter ≤ 40 cm Pile Length ≤ 25 m		Helical Pile Splice Connections
				Soil Class I	Soil Class II	
				Per 10 Piles		Per 10 Connections
				1	2	3
1	Labor	man-day	1001001	29.8	35.1	21.2
2	Structural Steel	t	2003004	0.004	0.004	-
3	Steel Plate	t	2003005	0.002	0.002	0.353
4	Helical Pile Shaft	t	2003021	19.24	19.24	-
5	Welding Electrodes	kg	2009011	17.1	17.1	41.2
6	Steel Fasteners	kg	2009028	0.2	0.2	-
7	Construction Nails	kg	2009030	88.9	88.9	-
8	Round Timber	m3	4003001	0.26	0.26	-
9	Sawn Timber	m3	4003002	0.78	0.78	-
10	Helical Drilling Rig	Equipment-Shift	8011064	2.06	2.42	-
11	32kVA AC Arc Welder	Equipment-Shift	8015028	2.16	2.55	4.44

Figure 2 Supplementary Quotation for Spiral Piles(Excerpt)

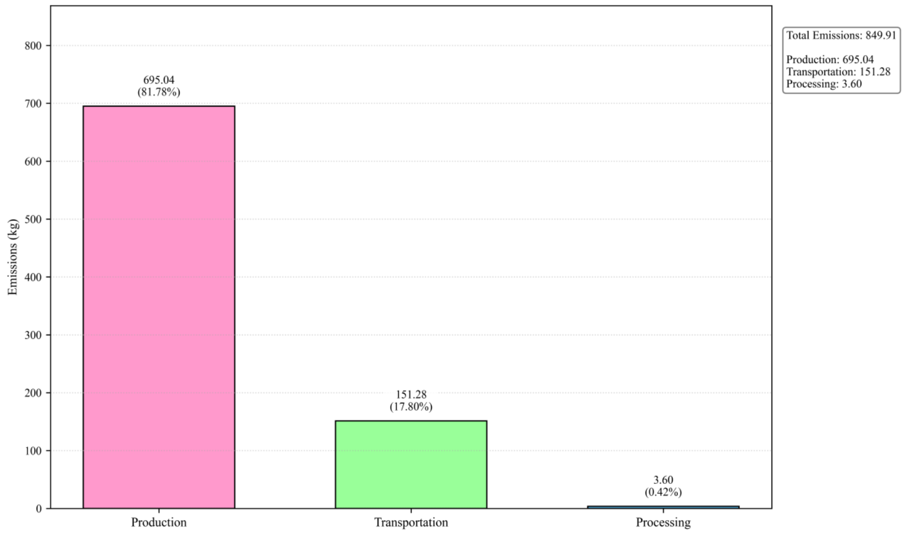
The Highway Engineering Budget Quota provides comprehensive quota specifications for cast-in-place piles; however, helical piles, as a newer pile type, are not yet included in the latest quota editions. This study utilizes field-measured data specific to helical piles provided by a certain company and, by referencing quota standards, develops supplementary quotas to ensure that the consumption of labor, materials, and machinery accurately reflects the characteristics of this novel construction technique[7]. A portion of the developed supplementary quotas is illustrated in Figure 2. The study compares carbon emissions of cast-in-place piles and helical piles with a diameter of 0.4 m and length of 10 m. Based on the above formulas and consumption data of materials and equipment shifts from the quotas, carbon emissions during pile construction and material production can be calculated. It should be noted that, according to the Standard for Building Carbon Emission Calculation, the default transportation distance for construction materials in the transport stage is 500 meters, with concrete-related materials having a default distance of 40 meters[13,17]. Transport vehicles are assumed to be 30-ton and 46-ton heavy-duty diesel trucks, with corresponding carbon emission factors also available in the Standard for Building Carbon Emission Calculation. The Highway Engineering Budget Quota specifies that on-site transportation distances do not exceed 15 km[7]. The on-site material processing recovery rate is uniformly set at 0.5. Carbon emission factors for all remaining materials

ISSN 2663-1563 Vol. 8, Issue 1: 104-111, DOI: 10.25236/AJAGE.2026.080113

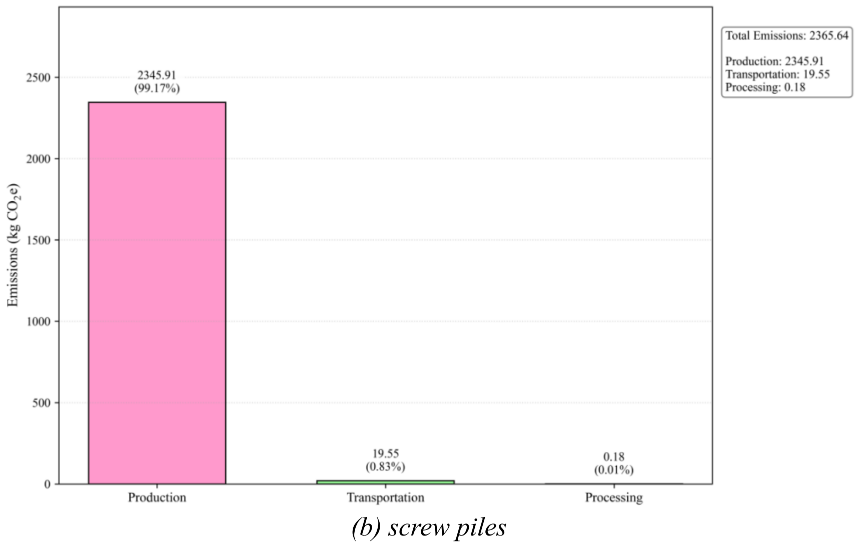
and machinery can be found in Table 1.Critical methodological parameters are defined as follows: Per Standard for Building Carbon Emission Calculation, default transport distances are 500m for construction materials (40m for concrete constituents). Transport vehicles: 30t and 46t heavy-duty diesel trucks with emission factors referenced from the aforementioned standard. On-site hauling distance is capped at 15km according to Highway Engineering Budgetary Quota. Material processing yield ratio is uniformly set at h=0.5. All remaining material and machinery emission factors are referenced from Table 1[13].

2.3.2 Analysis of Carbon Emission Intensity Differences in Pile Foundations

All data were input into Python for static calculations. The results, shown in Figure 3, indicate that the total carbon emission for cast-in-place piles is 849.91 kg. Among this, the construction and material production stage contributes the largest share of 695.04 kg, accounting for 81.78% of the total emissions. The transportation stage follows with 151.28 kg, representing 17.80%, while the material processing and treatment stage accounts for only 3.60 kg, or 0.42% of the total emissions. This demonstrates that the construction and material production stage is the primary source of carbon emissions. The transportation stage's emissions are relatively significant due to the increased weight from large amounts of clay and aggregates, which results in higher transportation loads and associated emissions. The material processing and treatment stage has the lowest emissions due to the minimal amount of raw materials requiring processing. In contrast, carbon emissions for helical piles are more concentrated in the construction and material production stage, totaling 2345.91 kg and accounting for 99.17% of the total emissions. Emissions from the transportation and material processing stages are much lower, at 19.55 kg (0.83%) and 0.18 kg (0.01%), respectively.



(a) cast-in-place piles



(b) screw piles

Figure 3 Comparison of Carbon Emissions in the Materialization Stage of Pile Foundations

ISSN 2663-1563 Vol. 8, Issue 1: 104-111, DOI: 10.25236/AJAGE.2026.080113

3. Conclusion

This study establishes a static carbon emission analysis model for pile foundations, systematically comparing helical and cast-in-place piles' embodied-stage emission performances and evolutionary characteristics. Static analysis reveals helical piles exhibit 2.78× higher emissions than cast-in-place piles under equivalent volumes, attributable to steel's substantially greater carbon intensity (1592-2460 $kgCO_2e/t$) versus concrete (496-745 $kgCO_2e/t$) during material processing and production.

Crucially, in multi-pile systems achieving equivalent load-bearing capacity, helical piles' 2.55× higher bearing capacity (825.9 kN vs 648.9 kN) yields 61% lower carbon intensity per kN (3.2 $kgCO_2e/kN$ vs 8.3 $kgCO_2e/kN$), confirming their low-carbon superiority in engineering applications. This research bridges future dynamic assessment gaps by quantifying parameter interactions, delineating helical piles' applicability boundaries as low-carbon technology, and advancing practical pathways toward construction industry carbon neutrality.

References

[1] Intergovernmental Panel on Climate Change (IPCC). (2022). Climate change 2022: Mitigation of climate change. Cambridge University Press. https://doi.org/10.1017/9781009157926

[2] Zhang, H.-N., Shen, R.-R., Zhang, X.-P., Kang, J.-J., & Yuan, J.-H. (2022). Implications and pathways of China's carbon neutrality: A review. Climate Change Research, 18(2), 240–252. https://doi.org/10.12006/j.issn.1673-1719.2021.058

[3] Gao, S. (2024). Quantitative analysis of carbon emissions from highway construction based on life cycle assessment. Sustainability, 16(14), 5897. https://doi.org/10.3390/su16145897

[4] Li, X.-J., & Zheng, Y.-D. (2019). Using LCA to research carbon footprint for precast concrete piles during the building construction stage: a China study. Journal of Cleaner Production, 245, 118754. https://doi.org/10.1016/j.jclepro.2019.118754

[5] Nascimento, M. F., Mota, E. G., Silva, D. R., & Lima, J. (2024). Review on carbon footprint in deep foundations: Case study for helical piles in Brasília, DF. In Proceedings of ECSMGE XVIII.

[6] Lyu, F., Shao, H., & Zhang, W. (2022). Comparative analysis about carbon emission of precast pile and cast-in-situ pile. Energy Reports, 8, 514–525.https://doi.org/10.1016/j.egyr.2022.03.101

[7] Ministry of Transport of the People's Republic of China. (2018a). Highway engineering budget quota (JTG/T 3832-2018). China Communications Press.

[8] Zhang, Y., Peng, T., Yuan, C., & Yang, P. (2023). Assessment of carbon emissions at the logistics and transportation stage of prefabricated buildings. Applied Sciences, 13(1), 552. https://doi.org/10.3390/app13010552

[9] Hong, J., Shen, G. Q., Peng, Y., Feng, Y., & Mao, C. (2016). Uncertainty analysis for measuring greenhouse gas emissions in the building construction phase: A case study in China. Journal of Cleaner Production, 129, 183–195.https://doi.org/10.1016/j.jclepro.2016.04.085

[10] de Bortoli, A., Bouhaya, L., & Feraille, A. (2025). A life cycle model for high-speed rail infrastructure: environmental inventories and assessment of the Tours-Bordeaux railway in France. International Journal of Life Cycle Assessment.

[11] Zhang, X., Wang, Y., & Liu, Z. (2019). Quota-based carbon tracing model for construction processes in China. Building and Environment, 160, 106183.

[12] Guo, C., & Xu, J. (2020). Study on calculation method and prediction model of carbon emission from highway tunnel construction [Doctoral dissertation, Southwest Jiaotong University]. Southwest Jiaotong University, Chengdu. https://doi.org/10.27414/d.cnki.gxnju.2021.000024

[13] Standardization Administration of China. (2019). Building carbon emission calculation standard (GB/T 51366-2019). China Standards Press.

[14] Ministry of Transport of the People's Republic of China. (2018b). Highway engineering machinery operating hour cost quota. China Communications Press.

[15] Bao, X., Shen, J., & Zhang, Y. (2024). GHG emission analysis of an optimal arrangement of stiffened composite pile group based on bearing capacity: A case study. Journal of Cleaner Production, 380, 140860. https://doi.org/10.1016/j.jclepro.2024.140860

[16] Marsh, E., Orr, J., & Ibell, T. (2021). Quantification of uncertainty in product stage embodied carbon calculations for buildings. Energy and Buildings, 251, 111340.

[17] Yu, X., Hu, X. D., Xie, W., Pan, A. C., Li, X. K., & Wang, H. J. (2025). Carbon emission modeling of excavation and non-excavation techniques in overall repair of drainage pipelines. Systems and Soft Computing, 7, 200213. https://doi.org/10.1016/j.sasc.2025.200213