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Decarbonizing the Geological Premium: A Scenario-Based Carbon Footprint Assessment of Low-Carbon Vertical Nodes in Microtunneling Projects

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Abstract

Trenchless technologies are critical for global urban sewerage construction; however, existing Life Cycle Assessments (LCA) predominantly focus on horizontal segments under standard soft soil conditions, neglecting the massive embodied carbon of "vertical nodes" in extreme geology. Based on EN 15804, this study conducts an upfront carbon (A1–A5) inventory and scenario analysis of microtunneling shafts in Hualien, Taiwan, characterized by deep excavations (10–12 m) and hard gravel formations (SPT $N > 50$). The research reveals a dual climate challenge induced by extreme geology: the "Geological Premium" resulting from increased machinery energy consumption, and the "Forced Carbon Lock-in Effect" triggered by the necessity of high-strength permanent structures. Empirical results demonstrate that the product stage (A1–A3) of vertical nodes accounts for 51.1% of total emissions, while the construction stage (A5) contributes 42.5%. Consequently, a material-based compensation mechanism is proposed. Scenario simulations verify that introducing geopolymer precast manholes (50% cement replacement) generates a "Green Premium" that effectively neutralizes the construction's geological premium. This study fills the LCA gap for underground infrastructure, providing scientific support for integrating geological variables and low-carbon materials into Green Public Procurement (GPP) policies.

Keywords: microtunneling; life cycle assessment (LCA); upfront carbon; geological premium; forced carbon lock-in; green public procurement (GPP); geopolymer; vertical nodes

1. Introduction

1.1. Global Context of Sewerage Infrastructure and the Challenge of Upfront Carbon

Climate change has emerged as one of the most critical global challenges, compelling industries worldwide to implement urgent decarbonization strategies. To construct climate-resilient modern cities, the development of underground pipeline and public sewerage systems is being accelerated by governments globally. However, unprecedented challenges in asset investment and sustainable development are currently confronting the global water and sewerage sector. A high degree of strategic vision must be integrated into future infrastructure planning to mitigate potential risks associated with climate change regulations, energy price volatility, and escalating capital and operational costs. In this context, maximizing the carbon efficiency of sewerage infrastructure projects—particularly through the adoption of low-emission construction methods such as trenchless technologies—has been recognized as a critical priority to overcome industry constraints and achieve long-term sustainability goals.

As infrastructure upgrades are pursued, a profound paradigm shift is being observed within the carbon emission structure of the construction sector. As a primary consumer of energy and natural resources, the construction industry accounts for nearly 40% of total global carbon emissions [1]. As operational carbon is gradually reduced through the implementation of various energy-efficiency measures, the proportion of embodied carbon, generated from material production and construction processes, is exhibiting a steady upward trend. According to the definition by the World Green Building Council (WorldGBC), the A1–A5 stages of the life cycle (encompassing raw material extraction, transportation, manufacturing, and construction installation) are collectively defined as "upfront carbon." For heavy civil and underground infrastructure, this represents the entirety of the embodied carbon footprint prior to the formal operation of the facility, serving as the most critical control domain in current decarbonization initiatives.

Unlike operational carbon, which retains potential for long-term optimization, the upfront carbon associated with underground pipeline projects is characterized by a high degree of irreversibility. Once "practical completion" is achieved, the greenhouse gases generated during the A1–A5 stages are fully released into the atmosphere, establishing a climate cost that cannot be offset by subsequent operational energy conservation. Furthermore, although the low-carbon potential of trenchless technologies has been widely recognized internationally, existing assessment models are frequently constrained by standardized geological assumptions. Most evaluations focus predominantly on the jacking energy consumption of horizontal pipe segments, thereby severely neglecting the profound impact of regional geological variations on overall energy consumption. Especially when extreme geological conditions are encountered, the "vertical nodes" (e.g., manholes and working shafts)—which serve as the structural core and stress interfaces of the pipeline network—generate massive embodied carbon and construction premiums during material selection and excavation processes. To date, this immense carbon burden remains a significant academic gap that has not been adequately quantified or addressed within existing Life Cycle Assessment (LCA) frameworks.

1.2. Research Gap

Despite the critical role of trenchless technologies in sustainable infrastructure construction, a significant "spatial imbalance" is widely observed in the definition of system boundaries within existing Life Cycle Assessment (LCA) literature.

Overemphasis on horizontal segments: Previous studies and international carbon footprint technical manuals (e.g., the Japanese JSWA standards) are predominantly concentrated on the primary structural pipe materials and the pure jacking energy consumption of horizontal jacking segments [2]. Undeniably, horizontal main pipes constitute the physical bulk of underground pipelines; furthermore, recent empirical studies indicate that reinforced concrete pipe (RCP) materials alone account for 23.53% of the total carbon footprint in jacking projects [2]. However, this evaluation inertia—prioritizing "lines" over "points"—substantially restricts the comprehensiveness of decarbonization strategies.

Severe underestimation of "vertical nodes" as carbon hotspots: The immense climate costs associated with "vertical nodes" (e.g., working shafts, precast manholes, entrance seals (mirror frames), and other subsidiary structures), which serve as critical hubs within pipeline networks, are frequently overlooked by both academia and industry. Although the UK PJA carbon calculator proactively incorporates manholes into its assessment boundaries, it predominantly relies on standard consumable materials as default parameters [3]. In fact, field inventory data reveals that in deep-buried sewerage projects, the embodied carbon of vertical nodes (working shafts and manholes) can reach up to 53% of that of horizontal segments (jacking pipes), as demonstrated in the case of this study. Neglecting these essential nodes, which are mandated for accommodating pipeline elevation differentials and directional changes, results in a severe distortion of LCA inventory outcomes.

Assessment blind spots in extreme geological formations: Existing LCA models and decarbonization benchmarks (e.g., JSWA and UKSTT) are predominantly established upon assumptions of standard soft soil layers (Standard Penetration Test, SPT N-value < 20) and shallow excavations [3,4]. When extreme strata (such as hard gravel formations with $N > 50$) are encountered, the construction of vertical nodes necessitates the deployment of ultra-high-strength permanent structures (e.g., precast manholes with a concrete compressive strength reaching 280 kgf/cm^2) or

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robust temporary shoring materials (e.g., tubular steel casing shafts). Furthermore, the processes of deep excavation, alongside the lifting and pressing of heavy machinery, induce a substantial "Geological Premium" [2]. Currently, there is a severe scarcity in international literature of high-resolution quantitative models that couple the embodied carbon of high-strength materials (Stages A1–A3) with the energy consumption of highly challenging construction processes (Stage A5) for vertical structures.

This research gap highlights the dual limitations of current LCA evaluations for underground infrastructure in both spatial and geological dimensions. Consequently, shifting the perspective from horizontal "lines" to vertical "points" and precisely inventorying the true carbon contribution of vertical nodes in extreme geological formations represents an urgent academic void to be filled, which is essential for advancing Green Public Procurement (GPP) and achieving global net-zero emission goals.

1.3. The Dual Challenge of Geological Premium and Vertical Nodes

Within the Life Cycle Assessment (LCA) framework for underground infrastructure, a cross-examination of the "spatial dimension" (vertical nodes) and the "environmental dimension" (extreme geology) is crucial for revealing the true climate costs of engineering projects. This study indicates that current initiatives to promote low-carbon sewerage engineering are confronted with a "Dual Challenge" resulting from the intersection of these two major variables:

1. From the "spatial dimension": Vertical nodes (including working shafts, manholes, and joints) serve as indispensable hubs within urban infrastructure networks. Compared to long-distance horizontal jacking segments, vertical nodes involve significantly higher engineering complexity in practice. Their excavation processes typically necessitate intricate shoring systems, groundwater control (e.g., deep well dewatering), and vertical transportation operations. Consequently, these areas are transformed into "high-pressure points" characterized by intensive construction energy consumption and material utilization.
2. From the "environmental dimension": Regional geological conditions exert a decisive influence on construction carbon emissions. Existing international carbon footprint benchmarks (e.g., the UK PJA or Japan JSWA) are predominantly established under default assumptions of standard soft soil layers (Standard Penetration Test, SPT N-value < 20) and shallow excavations [3,4]. However, when extreme strata (such as hard gravel formations with $N > 50$) are encountered, the mechanical work required for rock fragmentation and overcoming soil friction escalates dramatically. Recent empirical research has formally defined this phenomenon as the "Geological Premium," quantitatively demonstrating that hard gravel formations cause the energy intensity of machinery during the construction stage (A5) to surge by 18.7% compared to standard geological conditions [2].

When the construction of vertical nodes intersects with extreme geology, this "dual challenge" triggers a severe "Forced Carbon Lock-in Effect." In standard strata, low-carbon temporary works with high recovery rates (such as steel sheet piles) can still be utilized by engineering units as shoring facilities; however, when extreme strata with $N > 50$ are encountered, traditional steel sheet piles fail due to their inability to penetrate the formations. These forces engineering designs to adopt high-strength, carbon-intensive permanent structures—such as secant piles or diaphragm walls—to maintain excavation stability [5]. This engineering compromise, dictated by "geological reality," not only directly inflates diesel and electricity consumption during the construction stage (A5), but also results in the massive carbon emissions of concrete and steel from the product stage (A1–A3) being irreversibly "locked" underground.

Therefore, neutralizing this dual challenge under the constraints of extreme geology through the introduction of advanced low-carbon materials (e.g., geopolymers) and innovative construction methods remains an urgent imperative for reducing the upfront carbon of underground engineering. In the empirical case study of the urban sewerage project in Hualien, Taiwan—which is characterized

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by narrow streets—an innovative construction method utilizing recyclable circular steel casings was adopted for the working shafts. The constructability of this method is superior to that of steel sheet piles, and it more effectively addresses the issue of groundwater ingress.

1.4. Research Objectives

In light of the aforementioned research gaps and the dual challenge posed by extreme geology, this study aims to integrate the civil engineering sustainability assessment framework of ISO 21931-2 [6] with the quantitative standards of EN 15804:2012+A2:2019 and EN 15978:2011 [7,8]. The primary objective is to establish a high-resolution carbon emission assessment model specifically targeted at the "vertical nodes" in underground pipeline engineering. The specific objectives of this study encompass the following four dimensions:

1. Establishing a systematic LCA framework for vertical nodes: Following the specifications of EN 15978 regarding the integrated environmental performance of civil engineering works, the assessment boundary is defined as the upfront carbon (Modules A1–A5) prior to practical completion. Critical processes, including vertical shaft excavation, auxiliary shoring facilities, and precast manholes, are comprehensively incorporated into the system boundary.
2. Quantifying the "Geological Premium" of vertical structures in extreme strata: Utilizing a hard gravel formation with a depth of 12 m and an SPT *N*-value > 50 as the empirical baseline, the impact of high formation resistance on vertical excavation energy consumption (Stage A5) is quantified. Consequently, the forced carbon emission increments induced by extreme geology are explicitly determined.
3. Evaluating the decarbonization potential and "Green Premium" of advanced low-carbon materials: Adhering to the EN 15804 product-level benchmarks, scenario simulations are utilized to compare the embodied carbon differences between traditional Ordinary Portland Cement (OPC) precast manholes and Geopolymer precast manholes. Through this comparison, the "Green Premium" is defined and quantified as a functional mechanism to offset the geological premium.
4. Proposing a multi-dimensional decarbonization decision tool based on ISO 21931-2: By synthesizing the possibilities of construction method comparisons (e.g., tubular steel casing shafts vs. traditional steel sheet piles) and material substitutions (e.g., geopolymers), a precise decarbonization roadmap is provided. This roadmap, strictly aligned with scientific evidence and international standards, is intended to facilitate Green Public Procurement (GPP) and carbon budget management.

2. Literature Review and Case Study

2.1. Low-Carbon Characteristics and Durability of Geopolymer in Underground Environments

2.1.1. Decarbonization Pathways and Mitigation Potential in the Product Stage (Stages A1–A3)

Geopolymers, characterized as novel green materials composed of alkali-activated materials, have been demonstrated to offer significant advantages in the decarbonization process of underground infrastructure [9]. Compared to Ordinary Portland Cement (OPC), industrial by-products (e.g., fly ash and ground granulated blast-furnace slag) are utilized as precursors by geopolymers, circumventing the high-temperature calcination process required for traditional clinker. Consequently, the embodied carbon in the product stage (Stages A1–A3) is substantially reduced. In existing underground pipeline projects, the utilization of high-strength precast concrete structures exhibits particular efficacy in significantly lowering product-level carbon emissions. It has been indicated by numerous international LCA studies that greenhouse gas (GHG) emissions can be effectively reduced by 43% to 64% when traditional OPC precast components are substituted with geopolymers [9,10]. This significant material-level carbon mitigation benefit provides a critical buffer space for offsetting the construction premium induced by extreme geological formations.

2.1.2. Chemical Durability and Life Cycle Benefits in Sewerage Environments

Sewerage systems are situated in extremely harsh underground environments, where vertical nodes are perpetually subjected to biogenic sulfuric acid attack. Hydrogen sulfide (H_2S), generated anaerobically in sewage, is oxidized to produce sulfuric acid. Under such acidic conditions, the calcium-rich carbonate hydration products within traditional OPC structures are highly susceptible to dissolution and cracking, which subsequently leads to rebar corrosion and the rapid deterioration of pipeline facilities [11]. Not only is the service life of the infrastructure shortened by this deterioration, but the carbon emission burden in Module B (the use and operational stage) is also significantly increased. It has been confirmed by research that geopolymers, due to their unique 3D alumino-silicate polymeric network structure, are vastly superior to traditional concrete in terms of acid and sulfate resistance [11,12]. In strong acid exposure experiments, an extremely low mass loss rate is exhibited by geopolymers, and the further penetration of acidic protons is effectively blocked by the amorphous silica-rich layer formed on their surface [12]. This exceptional durability not only enhances the structural stability of vertical nodes but also, from the long-term perspective of the "integrated environmental performance of the life cycle (EN 15978 framework)," effectively reduces the embodied carbon emissions derived from frequent maintenance or premature replacements.

2.1.3. Material Compensation Mechanism Against the "Geological Premium"

When hard gravel formations with an SPT *N*-value > 50 are encountered by microtunneling projects, the energy intensity during the construction stage (Stage A5) is inevitably increased by approximately 18.7%, a phenomenon formally defined as the "Geological Premium" [2]. As for the carbon emissions associated with the Geological Premium faced by vertical nodes (working shafts and precast manholes), such data is rarely documented in existing literature. Therefore, the current carbon emission status of vertical nodes is empirically investigated in this study, and an attempt is made to propose a compensation mechanism: by introducing low-carbon and highly durable geopolymer materials into vertical nodes, the significant emission reductions achieved in Stages A1–A3 (i.e., the "Green Premium") are utilized to neutralize the carbon emission increments induced by geological challenges in Stage A5. Through this innovative application at the material level, the overall carbon budget allocation can be optimized by engineering units via a "material pathway"—without altering the geological reality—thereby ensuring that underground engineering complies with increasingly stringent Green Public Procurement (GPP) requirements.

2.2. Current Status and Limitations in the Assessment of Underground Shafts and Vertical Nodes

2.2.1. Spatial Boundary Discrepancies in International Carbon Footprint Assessment Frameworks

In the Life Cycle Assessment (LCA) of underground pipeline and sewerage engineering, the fidelity of the carbon footprint inventory is directly determined by the definition of system boundaries. Currently, two major mainstream assessment benchmarks are predominantly relied upon internationally for the carbon emissions of trenchless technologies; however, significant spatial boundary discrepancies are observed in their treatment of "vertical nodes".

The most restrictive boundary constriction is adopted by the technical manual of the Japan Sewage Works Association (JSWA), where the assessment model is almost entirely focused on the machinery energy consumption (Stage A5) of the "pure jacking operation," while the carbon emissions derived from working shaft excavation, shoring facilities, and subsequent Controlled Low-Strength Material (CLSM) backfilling are directly excluded [4]. In contrast, a more macroscopic perspective is provided by the Carbon Calculator jointly developed by the Pipe Jacking Association (PJA) and the United Kingdom Society for Trenchless Technology (UKSTT), wherein vertical structures, such as manholes and shafts, are explicitly incorporated into the inventory boundaries of EN 15804 [3].

However, the PJA model is primarily constructed upon standard soft soil layers ($N < 20$), such as the typical homogeneous clay or chalk found in the UK, and shallow excavation depths are utilized as the default [2]. Consequently, when specific sites in Asia and Taiwan characterized by deep burial (e.g., depths exceeding 10 m) and extreme geological conditions (e.g., hard gravel formations) are encountered, the true carbon emission contributions of vertical nodes are frequently and severely underestimated by these existing models.

2.2.2. The Dilemma of Construction Method Decision-Making Between Open-Cut Shafts and Jacking Working Shafts

Within the literature concerning pipeline engineering, the comparison of carbon emissions between jacking methods and traditional open-cut methods has persistently remained a core issue. It has been confirmed by the majority of studies that greenhouse gas (GHG) emissions can be reduced by an average of 78% to 88% through trenchless technologies compared to open-cut methods, primarily because earthwork excavation volumes, asphalt pavement damage, and traffic disruptions are significantly minimized [13]. However, such LCA comparisons are predominantly established upon the functionality of "linear pipe segments," whereas independent methodological comparisons specifically targeting "vertical nodes (shafts)" are rarely conducted. In engineering practice, vertical working shafts (i.e., launch and reception shafts) must inevitably be relied upon during microtunneling operations for the lowering of machinery and pipe materials.

In standard geological strata, steel sheet piles are typically utilized as shoring facilities for the construction of nodes via the open-cut method. As steel sheet piles are classified as removable and reusable temporary works, their carbon emissions during the LCA product stage (Stages A1–A3) can be amortized according to their frequency of reuse; consequently, the burden of material embodied carbon is relatively alleviated [14]. However, when this construction methodology logic is applied to extreme geological conditions, a massive assessment blind spot is inevitably generated.

2.2.3. The "Forced Carbon Lock-in Effect" Under Extreme Geological Formations

When hard gravel and cobble formations with an SPT N-value > 50 are encountered, such as those in the Hualien region, a severe "Forced Carbon Lock-in Effect" is triggered from the perspective of Life Cycle Assessment (LCA). Under these extreme geological conditions, to achieve the "functional equivalence" of establishing a 12 m-deep vertical node, low-carbon temporary works are forced to be abandoned by the open-cut method. Instead, heavy shoring structures (permanent structures)—such as secant piles or diaphragm walls—must be adopted. Consequently, their massive embodied carbon from Stages A1–A3 must be fully recognized (100%) within the climate costs of that specific vertical node [3,15]. Furthermore, energy consumption during the construction stage (Stage A5) is precipitously escalated by the accompanying massive earthwork excavation and deep well dewatering operations [13].

When the decarbonization benefits of trenchless technologies are evaluated in existing studies, this forced carbon emission increment—transferred from the "Geological Premium" to "material selection"—is frequently overlooked. As a result, the immense carbon footprint of microtunneling in extreme geological strata has not been adequately highlighted or quantified.

2.3. Spatial Boundary Discrepancies Between International Assessment Benchmarks and Local Engineering Environments

2.3.1. Urban Underground Space Congestion and Spatial Crowding-Out by Flood Mitigation Facilities

Existing international carbon emission assessment models for trenchless technologies (e.g., JSWA in Japan and PJA in the UK) are predominantly constructed on the premise of shallow soft soil zones with an average depth of 3 to 6 meters [3,4]. However, in the engineering practice of sewerage systems in high-density Asian metropolitan areas such as Taiwan, deep burial requirements reaching depths of 10 to 12 meters or more are frequently encountered. This significant "spatial boundary discrepancy" is primarily driven by the dual impacts of urban development chronology and the requirements for extreme climate flood mitigation.

Firstly, regarding the chronology of urban development, the earlier development of sewerage systems in pioneer countries like the UK and Japan allowed the more economical shallow underground spaces to be preferentially occupied. Conversely, the construction of sanitary sewers in Taiwan was initiated relatively late; consequently, the shallow spaces (0 to 5 meters) in metropolitan areas have long been saturated with complex existing lifeline utility networks, including tap water, electricity, telecommunications, and natural gas [16]. To circumvent the engineering risks and social costs associated with large-scale utility relocation, primary and secondary sanitary sewer mains are forced to be deployed into deeper underground spaces.

Secondly, situated in a subtropical monsoon climate zone, Taiwan faces urban flooding triggered by typhoons and extreme rainfall; thus, storm sewers were preferentially constructed by local governments in the early stages. To discharge surface runoff into rivers via the shortest possible routes, massive stormwater box culverts have already occupied a vast amount of shallow space [17]. Based on the characteristics of gravity-flow systems, subsequently constructed sanitary sewers must adopt a grade-separated crossing approach, passing directly beneath existing stormwater box culverts. Consequently, the baseline burial depth for sanitary sewer mains is substantially lowered.

2.3.2. Hydraulic Theory Limitations and the Phenomenon of "Depth Multiplication"

In addition to the spatial crowding-out effect, the inevitability of deep burial is further exacerbated by topographical conditions and hydraulic requirements. Metropolitan areas in Taiwan are mostly concentrated in flat plains or basins, lacking sufficient natural elevation drops. To maintain the minimum self-cleansing velocity required for the gravity flow of sewage within the pipes (typically mandated to be greater than 0.6 m/s to prevent the deposition of solid suspended matter) [18], the burial depth inevitably accumulates as the pipeline advances further downstream in the system. To reduce the operational energy consumption (Stage B6 carbon emissions) and land acquisition difficulties derived from the installation of intermediate pumping stations, the jacking distance of a single pipeline is frequently extended in practice. This results in the depths of working shafts at downstream and river-crossing segments easily exceeding 10 to 15 meters [19].

2.3.3. The Risk of Carbon Emission Underestimation from Blindly Applying Shallow LCA Models

Synthesizing the aforementioned factors, the unique "Depth Multiplication" phenomenon in Taiwan's sewerage engineering directly induces environmental challenges associated with deep construction. When excavation depths exceed 10 meters, high-strength hard gravel formations are often directly penetrated. This not only triggers extremely high construction machinery energy consumption (i.e., the "Geological Premium") [2] but also renders low-carbon temporary works suitable for shallow layers (such as recyclable steel sheet piles) ineffective due to their inability to penetrate the strata.

To maintain the stability of deep excavations, permanent heavy shoring structures (such as diaphragm walls or secant piles) are forced to be introduced by engineering units, which subsequently triggers a massive "Forced Carbon Lock-in Effect" [3]. Therefore, if international LCA models constructed on shallow premises are blindly applied to Taiwan or similar Asian metropolitan areas, the immense carbon emission increments transferred from "Depth Multiplication" to "material compromises" will be neglected. This leads to a severe underestimation of the true climate costs of underground infrastructure.

2.4. Project Background and Geological Environment of the Hualien Case Study

2.4.1. Geographical Location and Scope

The empirical case study selected for this research is the sewerage project located in the Beipu area of Xincheng Township, Hualien County (coordinates: 24°2'N, 121°36'E). The inventory scope of the carbon emission activities for this project [2] is illustrated in Figure 1 (the red line in the photograph indicates the installation route of the reinforced concrete pipes, RCP). The depths of the working shafts range from 10 to 12 meters. Photographs of the construction site, displaying (a) the casing oscillator and (b) the tubular steel casing, are presented in Figure 2.

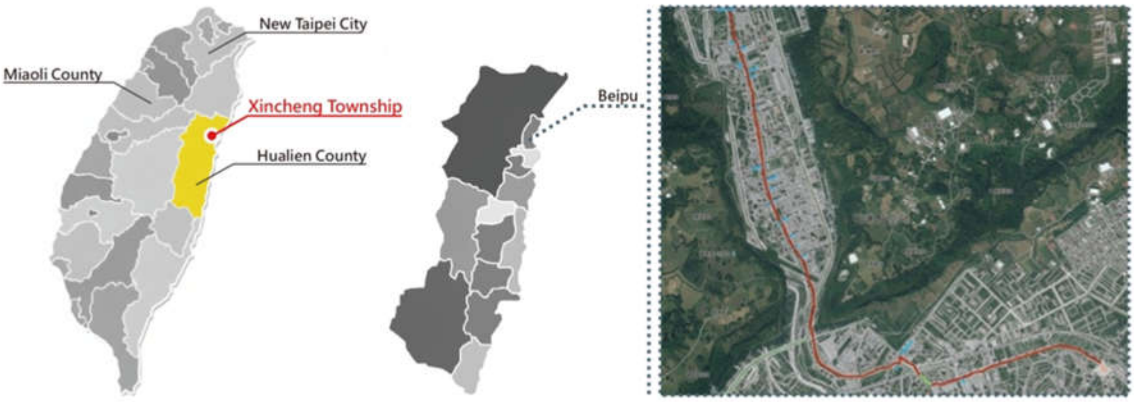

Figure 1. Schematic diagram of the project site and the carbon footprint inventory scope.


(**a**) (**b**)

Figure 2. On-site photographs of key construction machinery and equipment deployed at the Hualien project site. (**a**) Casing Oscillator; (**b**) Tubular steel casing.

2.4.2. Severe Challenges Posed by the Geological Environment

Based on the analytical results derived from the Geological Drilling Report of this project, the strata distribution below Ground Level (GL) -0.2 m is entirely characterized as a "gravel layer with silt and coarse sand." The geological characteristics at the designated pipeline burial depth (GL -10 m to -12 m) and their subsequent impacts on the carbon emission assessment are analyzed as follows:

1. Increased excavation energy consumption induced by extremely high soil hardness (Impact on Stage A5 Emissions): It is indicated by the drilling records that within the pipeline jacking depth range, the gravel and cobble formations are highly compact. Consequently, to overcome the extreme formation resistance during the pressing-in process of the tubular steel casing, exceedingly high torque and thrust must be outputted by the casing oscillator. This results in a significant escalation of the diesel consumption coefficient during Stage A5.

2. Groundwater levels and the decarbonization benefits of the construction method: Significant variations in the groundwater level are observed at the project site, fluctuating between GL -2.0 m and -10.0 m; in the majority of the area, the water table is situated above the pipeline burial depth. Had the traditional open-cut method been adopted for this project, extensive and prolonged wellpoint dewatering operations would have inevitably been necessitated, thereby generating massive carbon emissions from pumping electricity. Instead, an "oscillating and pressing-in" construction method utilizing a tubular steel shaft was adopted, by which the groundwater pressure is effectively balanced and the energy consumption associated with dewatering operations is completely circumvented. Compared to the open-cut method, this represents a crucial hidden decarbonization benefit of the microtunneling method during Stage A5.

2.5. Short Pipe Jacking Method

2.5.1. Construction Machinery Configuration and Green Materials

This project involves the working shaft construction for the Short Pipe Jacking Method, which serves as a prerequisite operation for the installation of reinforced concrete pipes (RCP). Heavy machinery utilized in this project includes a casing oscillator, cranes, and power generators. Regarding transportation vehicles, 43-ton and 35-ton heavy trucks, 15-ton dump trucks, and 35-ton dump trucks specifically designed for gravel are deployed. In terms of material selection, P-1200 and P-1500 type precast concrete manhole products are employed for the working shafts in this project. The concrete utilizes a 20% mineral admixture replacement for cement, possessing a compressive strength of 280 kgf/cm^2.

2.5.2. Characteristics of Transportation Logistics

Due to its location in eastern Taiwan, separated by the Central Mountain Range, Hualien is geographically isolated. Consequently, the majority of the primary construction materials and machinery must be transported over long distances to reach the construction site. Transport distances were calculated based on actual hauling routes using Google Maps. The primary transportation scenarios are outlined as follows:

1. Heavy machinery: Equipment including the complete casing oscillator set, decking panels, and diesel generator sets is dispatched from New Taipei City to the site, with a one-way transport distance of approximately 173 km.
2. Tubular steel shafts: The steel casings are supplied by a specialized manufacturing plant in Kaohsiung City, with a one-way transport distance of approximately 314 km.
3. Entrance seals (mirror frames): Supplied by a specialized manufacturing plant in New Taipei City, with a one-way transport distance of 188 km.
4. Manhole covers and frames: Supplied by a specialized manufacturing plant in Taichung City, with a one-way transport distance of 308 km.
5. Precast concrete manholes: The manhole products are composed of multiple segmental units, including top tapered sections (TH), adjusting straight sections (AP), bottom straight sections (AP), and base slabs (BS). These are supplied by local manufacturers in Hualien, with a one-way transport distance of 4.7 km.
6. Ready-mixed concrete: Sourced locally as a regional material, the transport distance is approximately 2.5 km, with a product carbon emission factor of 7.84 kg CO_2e/tkm.
7. Waste earthwork (Construction surplus soil): The excavated soil and rock are legally transported to a Soil and Gravel Resource Stacking Site located 27.2 km away, with a transportation carbon emission factor of 5.80 kg CO_2e/tkm.

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3. Methodology

3.1. Assessment Framework and Functional Unit

The assessment framework of this study complies with the standardized Life Cycle Assessment (LCA) methodology defined by ISO 14040:2006 and ISO 14044:2006 [20], and integrates the sustainability construction standards established by the European Committee for Standardization (CEN/TC 350). The calculation logic at the engineering level is derived from the frameworks of EN 15804:2012+A2:2019 [7], EN 15978:2011 [8], ISO 14067:2018 [21], and ISO 21931-2 [6], whereby the interactions between geological conditions and construction machinery are incorporated into the system evaluation. The core product data utilized herein relies on Environmental Product Declarations (EPDs) and Product Category Rules (PCRs). For carbon emission factors, the "Carbon Emission Factor Database for Common Products in Public Works," published by the Public Construction Commission (PCC) of Taiwan, is prioritized [22]. As for site-specific data, it is rigorously extracted from the contractor's daily construction logs.

To ensure "functional equivalence" in the scenario simulations, the Functional Unit (FU) defined in this study is: "The safe construction of a single underground vertical node, reaching a depth of 10–12 m under specific geological conditions, inclusive of shoring facilities and the completed installation of P-1200 and P-1500 type precast manholes." All inventories of material flows and energy flows are normalized based on this single vertical node as the baseline.

3.2. System Boundaries and Life Cycle Inventory (LCI) Framework

3.2.1. Temporal Scope and Input–Process–Output (IPO) Modeling

In accordance with the framework defined by the World Green Building Council (WorldGBC), the system boundary for this study is strictly established as the upfront carbon generated from "Cradle-to-Practical Completion," which encompasses Stages A1 through A5 (refer to Figure 3) [24]. To ensure a systematic accounting of environmental impacts, the Life Cycle Inventory (LCI) is operationalized through an Input–Process–Output (IPO) model, as detailed in the step-by-step process diagram in Figure 4 [2].

1. System Boundary:
    (1) Product Stage (A1–A3): All permanent and temporary engineering materials required for the vertical nodes are encompassed. This includes the precast manholes of the main structure, ready-mixed concrete utilizing Type II underwater cement (210 kgf/cm^2) with a carbon emission factor of 359 kg CO$_2$e/m^3 [22,24], and Type I underwater cement (140 kgf/cm^2) with a carbon emission factor of 256 kg CO$_2$e/m^3 [22,24]. The carbon mitigation parameters of geopolymers are also introduced in this stage to conduct a substitution analysis [9].
    (2) Transport Stage (A4): The mobilization and demobilization of heavy machinery, as well as the transportation distances and fuel consumption of materials (such as tubular steel casings and ready-mixed concrete) from manufacturing plants to the construction site, are covered [2]. Transport distances are estimated via Google Maps, and localized "heavy vehicle ton-kilometer" emission factors provided by the Ministry of Environment are adopted [24].
    (3) Construction Process Stage (A5): The focus is placed on the energy consumption of the casing oscillator, diesel generators (utilized for welding steel casings), and wheel cranes. Additionally, 15-ton dump trucks are deployed for the short-distance transportation of steel casings and excavated soil, while 35-ton gravel-specific dump trucks are responsible for the long-distance transportation of excavated soil to the soil and gravel resource stacking site [2].
2. Data Granularity:

(1) Primary Data: For the construction installation stage (Stage A5), daily fuel consumption records for the casing oscillator, 15-ton dump trucks, wheel cranes (13.6 MT), 35-ton gravel-specific dump trucks, and 50 kVA diesel generators are collected, along with precise records of excavated soil removal volumes and vehicle trip counts.

(2) Secondary Data: For Modules A1–A3, items including precast concrete manholes, cast iron manhole covers, and ready-mixed concrete are encompassed. For Stage A4 (transport to the site), the transportation distances of machinery and materials are estimated via Google Maps, and localized "heavy vehicle ton-kilometer" emission factors provided by the Ministry of Environment (MOENV, Executive Yuan) are adopted [24].

3. Cut-off Criteria:

Individual material or energy flows are neglected if their contribution to the total greenhouse gas emissions of the targeted life cycle is less than 1%, provided that the cumulatively excluded emissions do not exceed 5% [21].

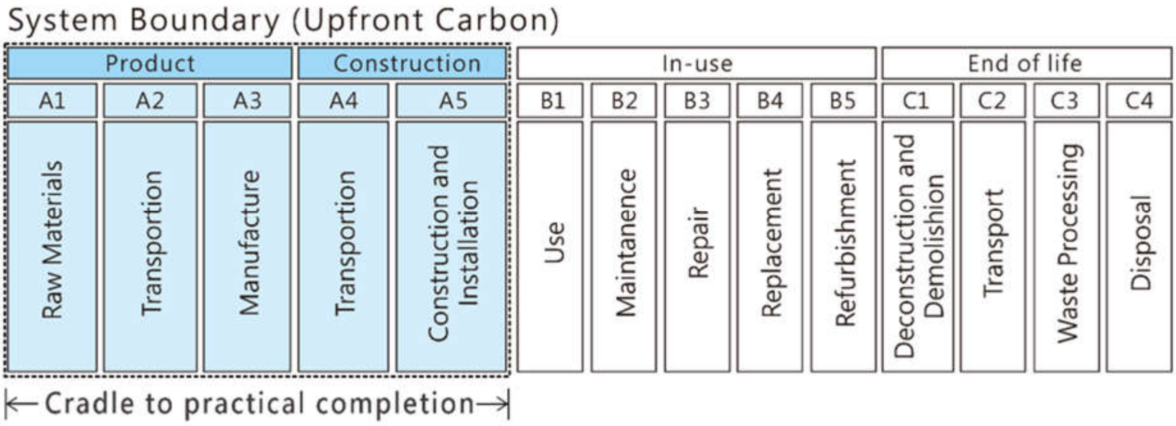
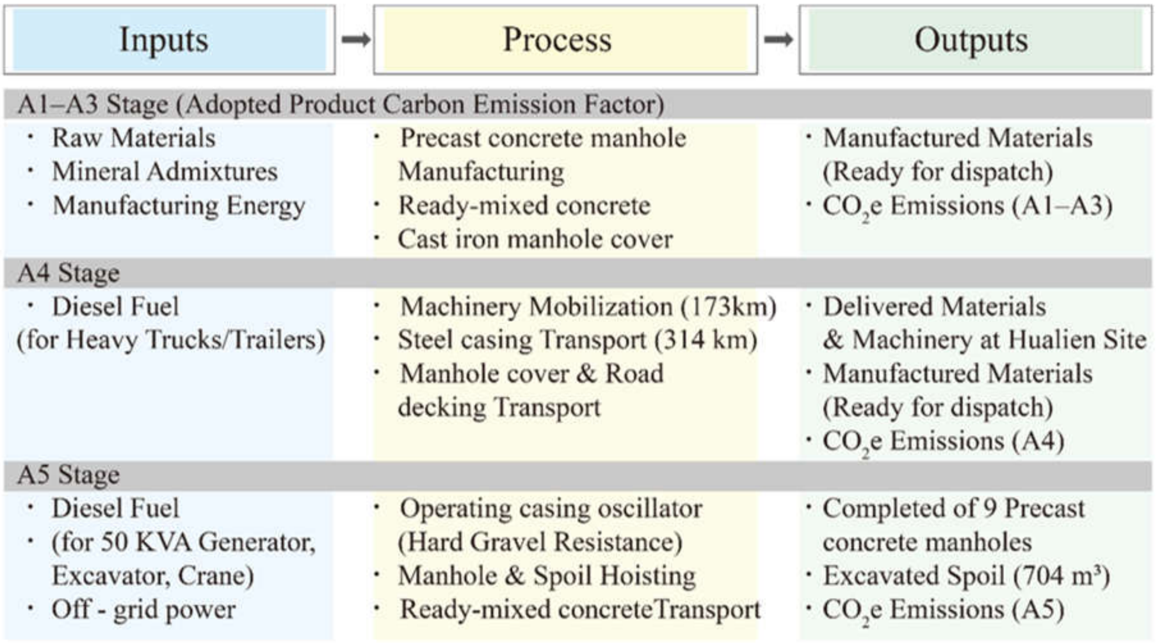


Figure 3. System boundary of this study (Cradle-to-Practical Completion, Stages A1–A5).



Inputs	Process	Outputs
A1–A3 Stage (Adopted Product Carbon Emission Factor)		
· Raw Materials · Mineral Admixtures · Manufacturing Energy	· Precast concrete manhole Manufacturing · Ready-mixed concrete · Cast iron manhole cover	· Manufactured Materials (Ready for dispatch) · CO_2e Emissions (A1–A3)
A4 Stage		
· Diesel Fuel (for Heavy Trucks/Trailers)	· Machinery Mobilization (173km) · Steel casing Transport (314 km) · Manhole cover & Road decking Transport	· Delivered Materials & Machinery at Hualien Site · Manufactured Materials (Ready for dispatch) · CO_2e Emissions (A4)
A5 Stage		
· Diesel Fuel · (for 50 KVA Generator, Excavator, Crane) · Off - grid power	· Operating casing oscillator (Hard Gravel Resistance) · Manhole & Spoil Hoisting · Ready-mixed concreteTransport	· Completed of 9 Precast concrete manholes · Excavated Spoil (704 m^3) · CO_2e Emissions (A5)

Figure 4. Step-by-step process diagram based on the Input-Process-Output (IPO) model, highlighting main material/energy inputs and environmental outputs from cradle to practical completion (Modules A1–A5).

3.3. Mathematical Quantification Model

The total Global Warming Potential (GWP_{total}) is calculated utilizing a summation method, with the overarching formula expressed as follows:

$$GWP_{total} = GWP_{A1-A3} + GWP_{A4} + GWP_{A5} \quad \cdots\cdots (1)$$

where:

GWP_{total}: Total Global Warming Potential, expressed in kg CO_2e;
GWP_{A1-A3}: represents the carbon emissions during the product manufacturing stage;
GWP_{A4}: denotes the carbon emissions during transportation to the construction site;
GWP_{A5}: indicates the carbon emissions during the construction process stage.

To account for the dual variables introduced in this study, the modified model is defined as follows:

$$GWP_{scenario} = [Q_{node} \times EF_{OPC} \times (1 - R_{mat})] + GWP_{A4} + [E_{base} \times EF_{fuel} \times (1 + K_{geo})] \cdots\cdots (2)$$

where:

Q_{node}: The quantity of materials utilized for the vertical nodes.
EF_{OPC}: The carbon emission factor of traditional Ordinary Portland Cement (OPC) materials.
R_{mat}: The Material Reduction Factor of geopolymers (set within a range of 44%–64% for sensitivity analysis, based on existing literature) [9].
E_{base}: The baseline construction energy consumption under standard geological conditions (SPT N-value < 20) [3].
K_{geo}: The Geological Premium Factor. When $N > 50$, it is empirically set to 0.187 based on data from the Hualien pipe jacking project; when $N < 20$, it is set to 0 [2].

3.4. Integration of Carbon Emission Data Sources

In this study, carbon emission databases from the Public Construction Commission (PCC) [22] and the Ministry of Environment (MOENV) [24] of Taiwan were compiled. Furthermore, authoritative international sewerage data was gathered to facilitate a comparative analysis. The primary international data sources comprise benchmarks and technical reports from the United Kingdom Pipe Jacking Association (PJA) and the United Kingdom Society for Trenchless Technology (UKSTT) [25], as well as the Japan Sewage Works Association (JSWA) [26,27]. The integrated datasets possess the following characteristics:

1. Material Embodied Carbon: Localized factors from the PCC [22] are primarily cited, as the emissions derived from construction materials are most significantly influenced by the local electricity grid mix and production processes.
2. Benchmarking of Decarbonization Benefits: A study by the UKSTT [3] is cited, wherein the standard energy-saving percentages of the short pipe jacking method, as compared to the open-cut method, are explicitly defined.
3. Energy Consumption Details: The decarbonization manual published by the JSWA [25] is referenced, which provides precise technical parameters regarding the electricity and fuel consumption of short pipe jacking machinery commonly utilized in the Asian region.
4. Geological and Operational Variations: According to the study by the UKSTT [26], typical geological conditions consist of London Clay or chalk formations (SPT $N < 20$), with common excavation depths ranging from 1.2 to 6 m. In the study by the JSWA [27], the geological conditions comprise standard sand and cohesive soil layers ($N < 20$), with common depths ranging from 3 to 6 m. Conversely, in the case study of Hualien, Taiwan [2], the geological environment is characterized by hard gravel formations ($N > 50$), with excavation depths reaching 10 to 12 m.

5. Electricity and Fuel Carbon Emission Benchmarks (Table 1): The electricity and fuel carbon emission factors published by the UK Department of Energy [28] and the Ministry of the Environment and the Ministry of Economy, Trade and Industry of Japan [29,30] are cited. These are compared against Taiwan's 2024 electricity carbon emission factor [31] to evaluate the impact of differences in national energy structures on construction efficiency assessments.

Table 1. Electricity and fuel carbon emission benchmarks for the United Kingdom, Japan, and Taiwan.

Country/Region	Benchmark Source	Grid Electricity Emission Factor ($kgCO_2e/kWh$)	Diesel Fuel Emission Factor ($kgCO_2e/L$)
United Kingdom	UK Department of Energy [28]	0.19~0.22	2.512
Japan	MOE/METI, Japan [29,30]	0.44~0.47	2.585
Taiwan	MOENV, Taiwan [31]	0.495	3.29~3.30

3.5. Scenario Design and Baselines

To elucidate the interactive effects among the geological premium, construction method selection, and low-carbon materials, a multi-dimensional "geology × system" scenario matrix was designed in this study. This matrix aims to reveal the "Forced Carbon Lock-in Effect" under extreme geological conditions and to verify the mitigation potential of the "Green Premium":

1. Scenario I (Theoretical Baseline Group): Standard Soft Soil Layer × Steel Sheet Pile Shoring System × Traditional OPC Manhole
   Settings: The geological condition is assumed to be an SPT *N*-value < 20. Low-carbon, removable, and recyclable "steel sheet piles" coupled with H-beam supports are adopted for the shoring facilities. This represents the ideal default scenario frequently observed in international standards (e.g., PJA) [3].
2. Scenario II (Construction Method Decarbonization): Extreme Hard Gravel Formation × Oscillating and Pressing-in Tubular Steel Shaft × Supplementary Cementitious Materials (20% SCMs) Manhole
   Settings: The geological condition is characterized by an SPT *N*-value > 50. To overcome the geological obstacles, a "tubular steel casing shaft" for microtunneling is adopted. This scenario aims to quantify how the carbon emission disaster typically associated with extreme geology can be circumvented by the tubular steel casing method through the reduction of excavation scopes and shoring materials. Simultaneously, however, the 18.7% "Geological Premium" induced by the cutting of hard gravel will be highlighted [2].
3. Scenario III (Optimized Solution): Extreme Hard Gravel Formation × Oscillating and Pressing-in Tubular Steel Shaft × Geopolymer Concrete Manhole
   Settings: Building upon the foundation of Scenario II, the material of the precast manhole is substituted from OPC to geopolymer concrete. As the core innovative solution of this study, this scenario is designed to demonstrate that the inevitably high energy consumption associated with extreme strata construction (Stage A5) can be effectively neutralized through the "Green Premium" of advanced materials [9].

4. Results, Scenario Analysis, and Discussion

4.1. Analysis of Carbon Emissions from Vertical Nodes Under the Empirical Baseline

4.1.1. Environmental Characteristics of Hualien: Engineering Challenges of Environmental Determinism

The geological conditions of this project dictated the adoption of trenchless technologies to meet the technical requirements for "high strength" and "high durability." Consequently, this directly led to a high reliance on the performance of precast concrete pipe materials during the product stage, with the associated carbon emissions being directly reflected in Stages A1–A3. Regarding construction, the shoring facilities must withstand immense lateral soil pressure, groundwater ingress, and the destructive effects of buoyancy during deep excavation operations. This renders the carbon emission challenges of the shoring facilities significant and not to be underestimated, with their carbon emissions being primarily reflected in the construction stage (Stage A5).

4.1.2. Results of the Carbon Footprint Inventory

The empirical project in this study adopted the construction method decarbonization of Scenario II (Extreme Hard Gravel Formation × Jacking Shaft × Supplementary Cementitious Materials (20% SCMs) Manhole). The inventory results indicate that from "Cradle to Practical Completion," 9 working shafts were completed. Within the 614 m-long RCP short pipe jacking project, one working shaft was constructed approximately every 77 m on average.

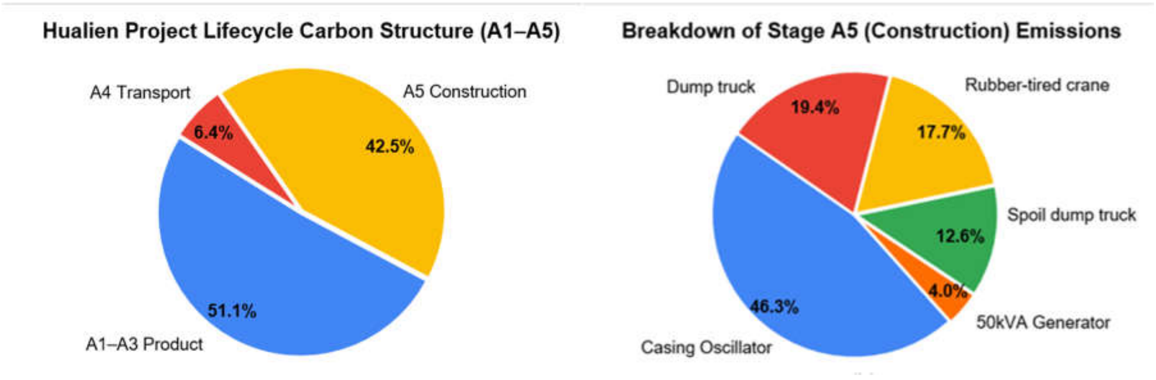
The total carbon emissions for the working shaft engineering amounted to 113,995 kgCO$_2$e. This is distributed as follows: emissions from the product stage (Stages A1–A3) were 58,226 kgCO$_2$e (accounting for approximately 51.1% of the total carbon emissions of the working shaft engineering); emissions from the transportation stage (Stage A4) were 7,297 kgCO$_2$e (approximately 6.4%); and emissions from the construction stage (Stage A5) were 48,472 kgCO$_2$e (approximately 42.5%).The emissions for each stage are illustrated in Table 2 and Figure 5. The carbon emission hotspots are analyzed as follows:

1. Product Stage (Stages A1–A3) (51.1%): As the largest emission source for the overall tubular steel shaft engineering, this stage's carbon emission hotspots are primarily contributed by the product carbon emissions of two types of precast concrete manholes. The carbon emissions for the P-1200 mm precast concrete manholes were 15,040 kgCO$_2$e (with a single-unit carbon emission of 4,683.44 kgCO$_2$e), accounting for approximately 25.8% of the product carbon emissions in Stages A1–A3. The carbon emissions for the P-1500 mm precast concrete manholes were 30,632 kgCO$_2$e (with a single-unit carbon emission of 5,906 kgCO$_2$e), accounting for approximately 52.6% of the product carbon emissions in Stages A1–A3.
2. Transportation Stage (Stage A4) (6.4%): These emissions are predominantly contributed by the mobilization transportation of heavy construction machinery and equipment (e.g., casing oscillators and tubular steel casings). The combined transportation carbon emissions for the two types of tubular steel casings were 3,284 kgCO$_2$e, accounting for approximately 45.0% of the emissions in Stage A4, representing the largest hotspot. The transportation carbon emissions for the casing oscillator were 1,853 kgCO$_2$e, accounting for approximately 25.4% of the emissions in Stage A4, representing the second largest hotspot.
3. Construction Process Stage (Stage A5) (42.5%): The fuel consumption carbon emissions of the casing oscillator were 22,443 kgCO$_2$e, accounting for 46.3% of the construction stage, rendering it the largest carbon emission hotspot in Stage A5. This is followed by the 15-ton dump trucks responsible for transporting the tubular steel casings (each section measuring 2.4 m, with each working shaft requiring approximately 4–5 sections to be welded or cut) and the short-distance transportation of excavated soil for temporary storage; their fuel consumption carbon emissions were 9,412 kgCO$_2$e, accounting for 19.4% of the emissions in Stage A5. The wheel crane (13.6 MT) was utilized for the lifting operations of the steel casings, with its fuel consumption carbon emissions amounting to 8,566 kgCO$_2$e, accounting for approximately 17.7% of the construction stage. The total volume of excavated surplus soil from the 9 working shafts was 704 m^3; the transportation carbon emissions generated by utilizing 35-ton gravel-specific dump trucks to transport this soil to the resource stacking site were 6,126 kgCO$_2$e, accounting for approximately 12.6% of the construction stage.

Table 2. Proportions of carbon emissions across Stages A1–A5 for the tubular steel shaft engineering in the Hualien project.

Assessment Stage (EN 15804)	Carbon Emissions (kg CO_2e)	Total (%)	Proportion	Primary Construction Items in Stage	Carbon Emissions (kg CO_2e)	Proportion within Stage (%)
A1–A3 Product Stage	58,226	51.1		Precast concrete manhole (P-1200)	15,040	25.8
				Precast concrete manhole (P-1500)	30,632	52.6
				Precast manhole cover (Ø750 mm)	8,307	14.3
				Ready-mixed concrete, Type II underwater (140 kgf/cm²)	768	1.3
				Ready-mixed concrete, Type II underwater (210 kgf/cm²)	2,872	4.9
A4 Transportation Stage	7,297	6.4		Casing oscillator (PC300LC)	1,853	25.4
				Tubular steel casing (Ø1890 mm)	1,642	22.5
				Tubular steel casing (Ø2090 mm)	1,642	22.5
				Decking panels	926	12.7
				Cast iron manhole cover (Ø750 mm)	605	8.3
				Entrance seal (mirror frame) (Ø600 mm)	281	3.9
				Ready-mixed concrete, Type II underwater (140 kgf/cm²)	81	1.1
				Ready-mixed concrete, Type II underwater (210 kgf/cm²)	122	1.7
A5 Construction Stage	48,472	42.5		Casing oscillator (PC300LC)	22,443	46.3
				Dump truck (15-ton)	9,412	19.4
				Wheel crane (13.6 MT)	8,566	17.7
				Gravel-specific dump truck (35-ton)	6,126	12.6
				Diesel generator (50 kVA)	1,925	4.0
Total	113,995	100%			113,243	99.4%

Note: Items contributing less than 1% to the total carbon emissions are excluded from this table.



(**a**) Stages A1–A5 (**b**) Stages A5

Figure 5. Proportion of carbon emissions across the "Cradle to Practical Completion" stage for the Hualien project.

4.2. Scenario Analysis of Carbon Footprints

To elucidate the interactive effects of geological conditions, construction method selection, and advanced materials on the carbon footprints of vertical nodes, a quantitative comparison was conducted in this study based on the three major scenarios established in Section 3.5. Through the analytical results, not only are the transitional pathways of carbon emission hotspots among different scenarios revealed, but the existence of the "Geological Premium" and the compensatory potential of the "Green Premium" are also concretely verified.

4.2.1. Quantifying the Geological Premium and the Forced Carbon Lock-in Effect

1. From the perspective of the product stage (Stages A1–A3):

Forced Carbon Lock-in Effect: Even though 20% Supplementary Cementitious Materials (SCMs) were preliminarily introduced as a cement replacement in the material selection for precast manholes within Scenario II, the carbon emissions in Stages A1–A3 remained as high as 58,226 kgCO$_2$e. Among these, 78% of the emissions (45,672 kgCO$_2$e) were contributed by the two types of precast manholes. This demonstrates that during deep excavations in extreme strata, the mandatory deployment of high-strength permanent materials to maintain structural safety inevitably triggers a severe "Forced Carbon Lock-in Effect." Consequently, the massive upfront carbon associated with these materials cannot be effectively mitigated solely by primary admixture proportions. As illustrated in Table 3, the variations in the carbon emissions of precast manhole products are directly influenced by the cement replacement rate (i.e., the utilization of mineral admixtures).

Table 3. Carbon emissions of precast manhole products in Stages A1–A3 under different scenarios.

Scenario (Type)	Precast Manhole (Model)	Concrete Volume per Unit (m^3)	Concrete Density (t/m^3)	Emission Factor [24] (kg CO$_2$e/t)	Carbon Emissions (kg CO$_2$e/unit)	Cement Replacement Rate (%)
I	P-1200	4.8	2.15	433.785	4,477	0
I	P-1500	7.5	2.15	433.785	6,995	0
II	P-1200	4.8	2.15	366.285	3,780	20
II	P-1500	7.5	2.15	366.285	5,906	20
III	P-1200	4.8	2.15	252.995	2,611	50
III	P-1500	7.5	2.15	252.995	4,080	50

2. From the perspective of the construction stage (Stage A5):

In Scenario I, owing to the geological conditions being characterized as a standard soft soil layer ($N < 20$), low-carbon steel sheet piles possessing a high recycling rate could be adopted as the shoring facilities. The steel sheet pile shoring system is classified as temporary works (thus, the product carbon emissions in Stages A1–A3 are excluded). A construction method utilizing Type IV steel sheet piles combined with H-beam walers and struts was adopted. The declared unit factor for its installation and dismantling carbon emissions (Stage A5) is 39.637 kgCO$_2$e/m^2 [22]. Assuming an installation area of 96 m^2 per shaft, the carbon emissions of the steel sheet pile shoring system are calculated to be 3,805 kgCO$_2$e/unit.

In Scenario II (the empirical case in Hualien) and Scenario III, the tubular steel shaft method was adopted. By allocating the combined carbon emissions of the casing oscillator and diesel generators in Stage A5 (24,368 kgCO$_2$e) to the Ø1890 mm and Ø2090 mm tubular steel casings, values of 2,071 kgCO$_2$e/unit and 3,217 kgCO$_2$e/unit are derived, respectively. The carbon emissions in Scenario II are significantly superior to those in Scenario I. Compared to Scenario I, the carbon emissions of the Ø1890 mm and Ø2090 mm working shafts in Scenarios II and III are reduced by 46% and 16%, respectively, as presented in Table 4.

Table 4. Carbon emissions of tubular steel shaft engineering in Stage A5 under different scenarios.

Scenario (Type)	Working Shaft (Specification)	Declared Factor (kg CO$_2$e/m^2)	Quantity (Unit)	Carbon Emissions (kg CO$_2$e/unit)
I	Steel sheet pile shoring system	39.637	96	3,805
I	Steel sheet pile shoring system	39.637	96	3,805
II	Ø1890 mm	1	式	2,071
II	Ø2090 mm	1	式	3,217
III	Ø1890 mm	1	式	2,071
III	Ø2090 mm	1	式	3,217

4.2.2. Optimal Solution: Compensation Mechanism of the Green Premium

Confronted with the inevitably high "Geological Premium" (Stage A5) and "Forced Carbon Lock-in" (Stages A1–A3) presented in Scenario II, a breakthrough material pathway is proposed in this study within Scenario III (Optimized Solution: Extreme Hard Gravel Formation × Oscillating and Pressing-in Tubular Steel Shaft × Geopolymer Concrete Manhole).

In Scenario III, the precast manholes of the vertical nodes are entirely replaced with geopolymer concrete featuring a cement replacement rate of 50%. Based on the established material parameters, its concrete carbon emission factor can be substantially reduced to 252.995 kgCO$_2$e/m^3. Compared to the OPC manholes in Scenario I and the 20% SCMs manholes in Scenario II, a highly significant potential for carbon reduction is created by Scenario III in the product stage (Stages A1–A3).

The decarbonization benefit unleashed by such advanced low-carbon materials (i.e., the "Green Premium") plays a critical "compensatory" role at the system level. Through the substantial compression of the embodied carbon footprint in Stages A1–A3, the massive fuel consumption carbon emissions generated in Stage A5—resulting from the casing oscillator combating the hard gravel formation—are successfully neutralized in Scenario III. This scenario analysis verifies that, under the dual constraints of extreme geology (unalterable strata conditions) and deep burial requirements (unalterable spatial conditions), "substantial decarbonization on the material side" serves as the sole effective solution to offset the high energy consumption on the construction side and optimize the overall life cycle carbon emissions of the vertical nodes (Figure 6).

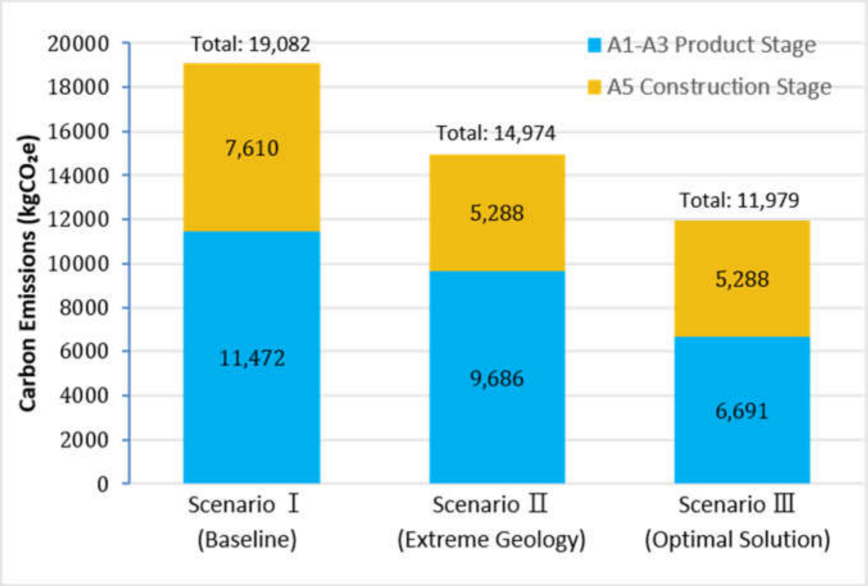


Figure 6. Comparison of stacked carbon emissions across Stages A1–A3 and A5 for vertical nodes under different scenarios. **Note:** This figure visually elucidates the dual impact of extreme strata on the carbon emission structure. Observing the transition from Scenario I to Scenario II, it is evident that extreme geological conditions induce a massive surge in construction energy consumption during Stage A5 (i.e., the "Geological Premium"). However, through the introduction of the optimized solution in Scenario III (geopolymer concrete with a 50% cement replacement rate), a substantial capacity for carbon reduction is liberated within Stages A1–A3 (i.e., the "Green Premium"). This liberated capacity not only completely offsets the incremental construction carbon emissions in Stage A5 but also reduces the total carbon footprint of the overall vertical node to a level significantly lower than that of the theoretical baseline group. Consequently, the exceptional efficacy of the material pathway acting as a compensation mechanism is concretely verified.

4.3. Empirical Validation of the Dual Challenges and the Forced Carbon Lock-in Effect

The decarbonization bottlenecks encountered by underground infrastructure, when confronted with the dual challenges of "extreme geology" and "deep burial," are concretely verified by the inventory results of this study.

Firstly, the irreversibility and severity of the upfront carbon are highlighted by the empirical data. In the empirical case of Hualien, the total carbon emissions for the working shaft engineering reached a staggering 113,995 kgCO$_2$e, among which the emissions from the product stage (Stages A1–A3) accounted for 51.1% of the overall carbon emissions. A harsh engineering reality is thereby revealed: prior to the sewerage system officially entering the operational stage (Module B), over half of its life cycle carbon footprint has already been entirely released into the atmosphere, which can hardly be compensated through subsequent operational energy savings.

Secondly, the remarkably high product carbon emissions (51.1%) do not stem from redundancies in engineering design; rather, they are dictated by the "Forced Carbon Lock-in Effect" induced by extreme geological conditions. As the pipeline jacking depth reaches 10 to 12 m and penetrates the hard gravel formations ($N > 50$), engineering units are compelled to adopt permanent, high-strength precast concrete and tubular steel shafts to withstand the immense lateral earth pressure and groundwater pressure associated with deep excavations. Such an engineering compromise, grounded in "geological reality," forces massive quantities of steel materials and OPC manholes to be irretrievably "locked" within the subterranean space. It is verified by the analysis in this section that unless revolutionary low-carbon alternatives, such as geopolymers, are introduced at the material stage (Stages A1–A3), the engineering sector will remain incapable of escaping the carbon emission trap set by extreme geology.

4.4. Policy Implications and Recommendations for Green Public Procurement

Based on the scenario analysis and empirical findings of this study, the following policy implications and practical recommendations are proposed for the carbon emission management and decision-making frameworks of future underground pipeline engineering:

4.4.1. Establishing Localized Carbon Emission Benchmarks Considering the "Geological Premium"

Current international LCA carbon footprint assessment models (e.g., JSWA or PJA) are predominantly constructed upon the default premises of shallow excavations and standard soft soil layers. If such benchmarks are blindly applied to high-density Asian metropolitan areas like Taiwan—which are characterized by complex geology and confronted with deep burial demands—the surge in fuel and electricity consumption induced by cutting through extreme hard strata during the construction stage (Stage A5) will be severely underestimated. Therefore, it is recommended that relevant competent authorities (e.g., the PCC and MOENV) accelerate the establishment of localized carbon emission databases for infrastructure. Furthermore, the "Geological Premium Factor" should be formally incorporated into the carbon footprint inventory regulations for public works to ensure the authenticity and accuracy of Carbon Budget assessments.

4.4.2. Incorporating "Embodied Carbon" and the "Green Premium" into Green Public Procurement (GPP)

The scenario simulation in this study verifies that the "Green Premium" created by geopolymers in Stages A1–A3 can effectively neutralize the inevitably high energy consumption associated with extreme strata construction. Therefore, it is strongly recommended that governments implement a "dual-track assessment of financial and climate costs" when promoting Green Public Procurement (GPP). For low-carbon building materials capable of significantly reducing upfront carbon emissions and possessing high durability against acid corrosion, substantial score weightings or financial subsidies should be granted in the selection criteria. This approach will drive the decarbonization transition of the construction industry from an institutional level.

4.5. Sensitivity Analysis of Key Parameters

To evaluate the robustness of the "Green Premium compensation mechanism" established in this study when confronted with practical engineering uncertainties, a one-at-a-time (OAT) sensitivity analysis is conducted in this section. This analysis focuses on two core parameters with high variability potential within the quantitative model (Equation 2): the material emission reduction rate of the geopolymer (R_{mat}) and the Geological Premium Factor (K_{geo}).

4.5.1. Sensitivity Effects of the Geopolymer Emission Reduction Rate (R_{mat})

According to the literature review (Section 2.1.1), due to variations in precursor sources (e.g., the ratio of fly ash to slag) and alkali activator formulations, the emission reduction potential of geopolymers compared to OPC ranges between 44% and 64%. In the optimized scenario (Scenario III) of this study, a moderate baseline value was initially established. To investigate the impact of these technological maturity differences on the overall system carbon emissions, this analysis sets R_{mat} under a conservative scenario (40% reduction) and an optimistic scenario (65% reduction) for boundary testing. The analytical results indicate that the total carbon emissions in the product stage (Stages A1–A3) exhibit extremely high sensitivity to R_{mat}. As the emission reduction rate increases from 40% to 65%, not only do the carbon emissions of the individual precast manholes decrease significantly, but the carbon budget margin of the "Green Premium" is also further expanded. Even under the most conservative scenario (R_{mat} = 40%), the carbon emissions saved by the geopolymer remain sufficient to fully offset the Stage A5 construction increment generated by the high load of the casing oscillator. This result strongly supports the conclusion that regardless of how the geopolymer

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formulation is fine-tuned, its role as a breakthrough solution to the "Forced Carbon Lock-in Effect" possesses unquestionable stability.

4.5.2. Uncertainty Testing of the Geological Premium Factor (K_{geo})

The Hualien formation where this empirical case is situated consists of extreme hard gravel layers ($N > 50$), with a measured Geological Premium Factor (K_{geo}) of 18.7%. However, in practical underground engineering, if occasional boulders or rock formations of even higher strength are encountered, the mechanical work and diesel consumption during Stage A5 may exhibit a non-linear surge.

To address this, the testing interval for K_{geo} was extended in this study to an extremely adverse scenario ($K_{geo} = 30\%$) and adjusted downward to a moderate hardness scenario ($K_{geo} = 10\%$). Sensitivity testing indicates that while the total carbon emissions in Stage A5 fluctuate significantly and show a positive correlation with K_{geo}, the proportion of Stage A5 within the total carbon footprint of the vertical nodes (42.5%) remains lower than that of the product stage (Stages A1–A3, 51.1%). Consequently, even if geological resistance triggers a 30% surge in construction-related carbon emissions, the system's carbon emission hotspot remains anchored within the material stage. This reaffirms the central argument of this research: when confronted with uncontrollable and highly variable subterranean geological environments, concentrating carbon reduction resources on the upfront product stage (e.g., by adopting low-carbon materials) serves as the most effective strategy to mitigate the risks associated with construction energy consumption uncertainties (Figure 7).

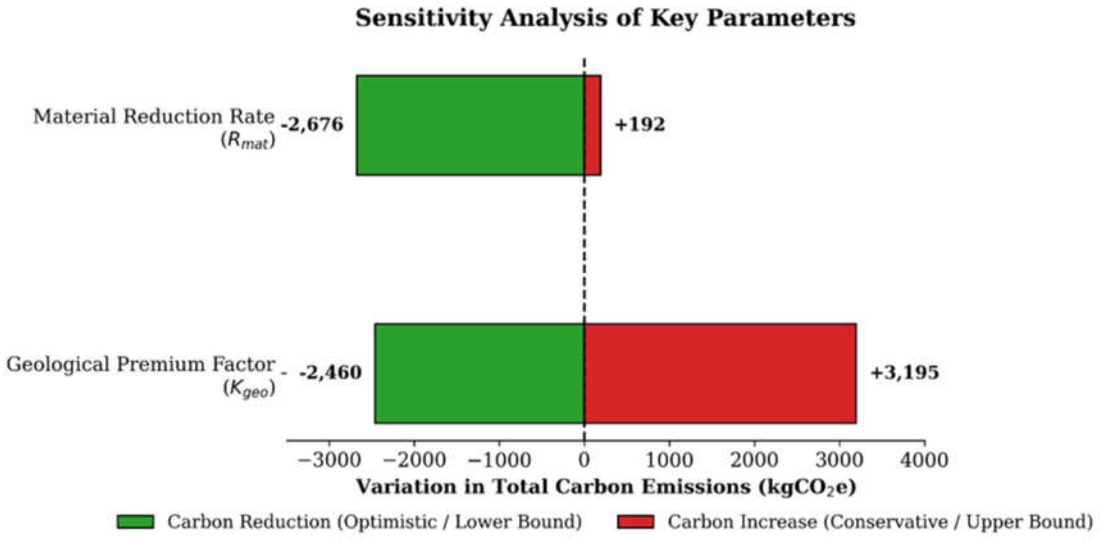

Figure 7. Tornado chart for the one-at-a-time sensitivity analysis of key parameters. Note: This figure illustrates the impact magnitude of the Geological Premium Factor (K_{geo}) and the geopolymer emission reduction rate (R_{mat}) on the total carbon footprint under extreme boundary testing. The optimized solution of Scenario III serves as the baseline (zero point) in this chart. The results indicate that even under the most adverse geological conditions ($K_{geo} = 30\%$)—which significantly increase the total carbon emissions—further optimizing the cement replacement rate on the material side (i.e., elevating R_{mat} to 65%) generates a Green Premium compensation margin sufficient to offset the majority of the increment in construction carbon emissions. Consequently, it is verified that the "material compensation mechanism" proposed in this study possesses a high degree of system stability and decision-making robustness.

4.5.3. Comprehensive Implications of Sensitivity Results for Decision-Making

Synthesizing the cross-analysis of the sensitivity matrix for the two aforementioned parameters, it is evident that the "material compensation mechanism" established in this study is not invalidated by parameter extremization. When confronted with the risk of deteriorating geological conditions

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(i.e., an increase in K_{geo}), the carbon neutrality targets of the overall vertical nodes can be maintained by engineering decision-makers by requiring suppliers to increase the substitution rate of industrial by-products within the geopolymers (i.e., elevating R_{mat}). This analysis not only establishes the boundary stability of the assessment model but also provides engineering consultants and government procurement entities with a decarbonization management tool characterized by flexible, dynamic adjustment capabilities.

5. Conclusions

This study integrates the life cycle assessment (LCA) frameworks of ISO 21931-2 and EN 15804/EN 15978 to conduct an in-depth upfront carbon (Stages A1–A5) inventory and scenario simulation for "vertical nodes," which are frequently overlooked in microtunneling (short pipe jacking) engineering. Through empirical data derived from deep-buried sewerage projects in the Hualien area (depths of 10–12 m, SPT $N > 50$), this research reveals the dual challenges posed by extreme geology and deep excavation to the decarbonization of infrastructure. The following core conclusions are drawn:

5.1. Core Findings and the Forced Carbon Lock-in Effect

It is confirmed by this research that existing international assessment models (e.g., PJA and JSWA), predominantly constructed upon shallow and soft soil layer assumptions, severely underestimate the actual carbon emissions of deep-buried engineering in high-density Asian metropolitan areas. In extreme hard gravel formations, the adoption of high-strength precast concrete and tubular steel shafts is compelled. This "geological reality" triggers a severe "Forced Carbon Lock-in Effect." Empirical inventory results demonstrate that the carbon emissions from the product stage (Stages A1–A3) of vertical nodes account for 51.1% of the total, while the energy consumption of machinery (Stage A5) generated to overcome extreme strata resistance accounts for 42.5%. This proves that the climate costs associated with deep-buried underground pipelines possess a high degree of irreversibility.

5.2. The "Green Premium" as a Compensation Mechanism for the Geological Premium

Confronted with unalterable extreme geological challenges (the Geological Premium), a compensation mechanism based on material pathways is innovatively proposed in this study. The scenario simulation results indicate that by replacing OPC precast manholes with geopolymer concrete featuring a cement replacement rate of 50%, the significant carbon reduction created in Stages A1–A3 (i.e., the Green Premium) can effectively neutralize the surged fuel consumption carbon emissions in Stage A5 resulting from the high load of the casing oscillator.

5.3. Policy Implications and Green Public Procurement (GPP) Initiatives

The quantitative results derived from this study prompt a fundamental reflection on the current procurement and management mechanisms for underground pipeline engineering. Regarding the green transition of engineering management, the following policy initiatives are proposed:

1. Promoting "Geology-Carbon" Linked Dynamic Carbon Budgeting:

It is confirmed by this research that extreme geology ($N > 50$) triggers a construction-related carbon emission proportion of up to 42.5% and an inevitable "Forced Carbon Lock-in Effect." Consequently, it is recommended that competent authorities for public works, during the initial design phase, should not solely rely on national average carbon emission factors. Instead, consulting firms must be mandated to incorporate the "Geological Premium Factor (K_{geo})" into the inventory of embodied carbon. For tenders encountering extreme geology, a reasonably adjusted "Dynamic Carbon Budget" should be granted to reflect the actual environmental costs.

2. Reforming Award Mechanisms: Transitioning from "Lowest Bid" to "Comprehensive Evaluation of Climate Costs":

Currently, public works are predominantly oriented towards the "lowest construction cost," causing advanced low-carbon materials with "Green Premium" potential (e.g., geopolymer manholes) to be frequently eliminated in competitive bidding due to higher initial procurement unit prices. This study advocates for the comprehensive introduction of the "Most Advantageous Tender (MAT)" framework for deep excavation projects such as sewers. Within this framework, "upfront embodied carbon reduction performance" should be established as a key evaluation criterion. For innovative low-carbon methods and materials that effectively neutralize the geological premium, substantial green subsidies or scoring weightings should be provided by the government at the institutional level.

3. Establishing "Material Passports" and Mandatory EPD Declarations for Underground Infrastructure:

The embodied carbon of materials for vertical nodes accounts for as much as 51.1% of the total, highlighting the critical importance of material source traceability. It is recommended that future public works gradually mandate suppliers of precast concrete (e.g., RCPs and manholes) and temporary shoring materials to provide Environmental Product Declarations (EPD) complying with the EN 15804 standard. This should serve as a fundamental entry threshold for Green Public Procurement (GPP).

5.4. Limitations and Future Work

1. Despite the significant findings regarding the "Geological Premium" and "Green Premium," certain limitations of this study should be acknowledged, which also provide directions for future research: Geographical and Geological Specificity: The empirical data in this study were primarily derived from the hard gravel formations in the Hualien area of Taiwan. While this represents a critical extreme geological scenario, the applicability of the derived Geological Premium Factor (K_{geo}) to other complex strata (such as high-plasticity clay or specific igneous rock formations) requires further cross-regional verification to enhance the universality of the model.
2. Long-term Durability and Carbon Sequestration of Geopolymers: This research focused on the carbon reduction potential of geopolymers during the product (A1–A3) and construction (A5) stages. Future studies should incorporate the Module B (Operational Stage) of the life cycle, specifically investigating the long-term resistance of geopolymer manholes to biogenic sulfuric acid corrosion and their potential for passive carbonation (carbon sequestration) over a 50-year service life.
3. Development of Automated Carbon Budgeting Tools: Building upon the scenario matrix established in this work, future efforts could integrate Building Information Modeling (BIM) with real-time geological sensing data (from TBM or casing oscillators). Such integration would facilitate the development of an automated, dynamic carbon budgeting platform, enabling engineering consultants to optimize "Green Premium" investments during the early design phase.

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