

Article

An Implementation Framework for On-Site Shield Spoil Utilization—A Case Study of a Metro Project

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Abstract: A majority of metro projects have been constructed to reduce urban traffic congestion and to improve the convenience of public transportation, but these projects also produced a significant amount of engineering slag and mud. The shield construction method could improve the efficiency and safety; this technique has been frequently used in tunnel excavation projects. However, the spoil produced during the shield construction is challenging to deal with. In literature, though there has been an increasing number of studies on the technologies of utilizing shield spoil, the on-site utilization of shield spoil is still a subject of little research. This study introduced an implementation framework for the on-site utilization of shield spoil based on successful case experiences. It aims to assist project managers in efficiently implementing on-site resource utilization projects and to address the gaps in the relevant field. A case study was conducted in the Shenzhen Metro Line 13 North Extension Project; this study collected data through six semi-structured interviews and field research, analyzed the data, and constructed a framework using thematic analysis and focus group discussions. The three components of the implementation framework are project planning, project construction, and project closing, and each section describes what must be accomplished during that phase. Additionally, three recommendations—(1) combining intelligent technology to optimize the existing equipment, (2) utilizing lean technology in project execution, (3) establishing strategic partnerships with construction waste recycling enterprises—are also made for the development of the shield spoil utilization project. This study uses the Shenzhen Metro Line 13 North Extension Project as a model to theoretically underpin future research on shielding spoil on-site during resource utilization projects and to achieve the repeatable promotion of shield spoil utilization technology in Shenzhen.

Keywords: shield spoil; on-site resource utilization project; case study; implementation framework



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1. Introduction

With the acceleration of urbanization, the rapid expansion of urban areas, and the high-speed population growth, the existing urban transportation system in our country is currently facing unprecedented pressure. Considering the scarcity of urban land resources in our country, the utilization rate of urban underground space is rapidly increasing, and the proportion of subway projects in urban construction investments is gradually growing [1].

Urban development is rapidly expanding into deep spatial dimensions, and the construction of rail transportation has entered a period of high-speed development. In particular, the significance of metro construction in the process of urbanization is increasing. While this helps alleviate urban traffic congestion and enhance the convenience of public transportation, it also brings a series of potential impacts on the environment and safety

during the construction process. Notably, the construction of metro systems produces enormous amounts of engineering slag and mud. By the end of 2021, the total length of urban rail transit lines under construction nationwide reached 6096.4 km, with operational lines spanning 9206.8 km. It is estimated that by 2030, the accumulated volume of excavated soil and sediment will exceed 200 million m³ [2]. Among these figures, the southern and eastern regions, experiencing the highest economic and population growth rates, are expected to account for approximately 60% of the national total, making it the largest proportion.

Currently, 47 Chinese cities have urban rail transit systems in place, with shield method construction serving as the primary technique for tunnel excavation. This process produces 45,000 m³ of engineering slag and mud for every kilometer of the shield [3]. According to the “Special Planning for Construction Waste Management in Shenzhen (2020–2035)”, the predicted total volume of construction waste generated by metro construction projects from 2020 to 2035 is estimated to be 85.43 million m³, with an average annual production of 5.3396 million m³ of construction waste generated by metro construction projects [4]. Shenzhen has to set aside around 10 million square meters of land area for the landfill disposal of such a significant amount of construction waste if the entire amount of construction debris created by the metro construction is carried to a fixed disposal site. Undoubtedly, Shenzhen faces a challenging issue given that “every square inch of land is worth an inch of gold” [5].

Moreover, shield spoil is a highly water-saturated and low-permeability plastic soil containing foaming agents, clay minerals, and polymer-modified materials. Direct discharge of shield tunneling waste soil would occupy land, and the presence of hazardous substances in the waste soil can infiltrate the soil, thereby degrading soil quality. The foam agents or bentonite present in shield spoil, if released into water bodies, can contaminate and disrupt aquatic environments. Improper stacking of shield spoil can also lead to varying degrees of soil erosion and landslide hazards [6]. Therefore, the shield spoil requires some treatment at the construction site before it can be transported off-site.

However, mixed landfill is the primary current treatment and disposal method for engineering slag and mud, an important component of urban construction waste for which China has not yet introduced reasonable and effective management policies and programs [7,8]. This shoddy management method not only consumes a substantial amount of the city’s limited land resources and makes recycling and reuse extremely difficult but also consumes a substantial amount of soil and rocks [9].

The goal of treatment was to reduce quantification according to studies conducted in the 1950s on the treatment and disposal of shield spoil. In the past, high-speed centrifugal dewatering, coagulation and flocculation dewatering, or injection into the safety layer for discharge were the principal treatments for shield spoil. The use of shield spoil can benefit the environment and the economy today, according to numerous academics. Riviera et al. [10] encouraged using shield spoil as a base material for roads. Instead of using traditional bricks, Guillen and Rojas [11] suggested using shield spoil to create new blocks, which also reduces carbon emissions from fire, etc. Liu et al. [12] attempted to study the potential of slurry as a sustainable material in the context of Kerala; Backe et al. [13] characterized cured cement slurry by electrical conductivity. Magnusson et al. [14] used the results of a detailed review of research related to urban spoil and rock using material flow models and literature-combing methods, indicating that current research has focused on the waste flow of construction materials, with little understanding of the overall management practices of excavation spoil and a lack of understanding by managers and local governments of the volume and generation characteristics of excavation spoil in urban areas.

Even with the same resource utilization procedure and conditions, the physical and chemical characteristics of shield spoil of various types and origins vary greatly. As a result, the resource utilization effect varies greatly. In the study of resource utilization of shield spoil, some researchers have dried the raw materials. However, this approach is less cost-effective and is challenging to implement in construction sites. The research on

the utilization of shield spoil lacks a process method that is quick and easy, affordable and effective, and suited for use on site because relying on drying and natural drying takes a long time, is arduous, and is not very steady [15]. Especially for mud, it is important to establish an implementation management plan for on-site resource utilization projects to effectively avoid the repetitive steps of “dewatering first and adding water later” and the waste of resources.

Although there is a lot of technical research on shield spoil utilization, there aren’t enough case studies to back it up and show how to do it successfully on the ground. Shield spoil utilization can only be successfully implemented in the field with an efficient implementation plan for on-site resource treatment.

This study aims to comprehensively investigate the successful implementation of a “zero-emission” metro construction project, specifically the Shenzhen Metro Line 13 North Extension Project. Through desk research, semi-structured interviews, and on-site investigations, the key lessons and best practices for the efficient implementation of on-site utilization projects for shield spoil are summarized and consolidated. Building upon the findings from focused group discussions, an implementation framework for on-site resource utilization of shield spoil is developed, thereby addressing the research gap in on-site management of such projects.

The structure of this paper is as follows: Section 1 summarizes the background of the study and reviews the existing research related to shield spoil utilization, Section 2 describes the data collection and processing methods used in the case study, Section 3 presents the results obtained from the field research and interviews and identifies the key points to focus on for the implementation of the on-site shield spoil utilization project, Section 4 constructs the on-site shield spoil utilization implementation framework and discusses the limitations of the framework. Directions for future research are discussed in Section 4, and the conclusions of the study are drawn in Section 5.

2. Research Methodology

A case study is an empirical research method in which the researcher delves further and examines the available information or a survey form to ascertain the essence and important elements of the case to develop or enhance the pertinent theory [16,17]. Since there are few cases of “zero construction waste” of resources from construction sites, the topic of how to handle shield spoil generated by metro construction is critical. The single-case study approach can analyze the issues raised by the study through extensive observation and analysis and then make an explanatory and exploratory investigation of the pertinent theories [18]. As a result, this paper makes an effort to summarize through a single-case study the successful experience of on-site shield spoil utilization initiatives. This study uses the theme analysis method with a constructivist epistemology. The theme analysis method believes that themes are constructed by the words and phrases in the text and that their meanings are constructed by people [19].

2.1. Case Description

Following the guiding principles of typicality, revelation, and data accessibility, this study chooses the Shenzhen Metro Line 13 North Extension “Zero Construction Waste” Shield Spoil Utilization Project as a case study [20].

Three stations and three intervals are part of the Shenzhen Urban Rail Transit Line 13 Phase II (northern extension) project in the fourth work area. The line’s total length is 3689.61 m. The application term for the shield spoil utilization project is three intervals and is approximately one year and six months. According to Shenzhen’s “Notice of Several Measures to Further Strengthen the City’s Construction Waste Disposal Work”, “Shenzhen Construction Waste Disposal Program”, and “Shenzhen Engineering Slag and Mud Receiving Site Construction and Operation Management Measures”, it is necessary to achieve an external abandoned shield spoil content of less than 40% in order to be suitable for direct transport by self-dumping vehicle without mud leakage.

The difficulties encountered by Shenzhen's other metro projects are quite similar to those of the Line 13 North Extension Project. The waste produced by the shield construction is composed primarily of worn sandstone intermingled with mudstone, mixed granite, and sand. It also includes earth pressure shield spoil and muddy water shield spoil. The shield spoil contains a lot of mud and has a high water content as a result of the geological circumstances. If the shield spoil is carried away from the project, there will be issues such as high cost, poor efficiency, ease of spilling, and environmental pollution while in transit.

Therefore, Shenzhen Metro Line 13 North Extension Project has developed a shield spoil reduction and utilization technology for sand-bearing strata, which consists of three major systems: mud and water separation, sand washing, and filter pressing. The mud, sand, and water in the slag and mud are separated, and the resources are utilized in four steps using different technical principles.

2.2. Data Collection

The Shenzhen Metro Line 13 North Extension Shield Spoil Utilization "Zero Construction Waste" Project's primary data sources are as follows: (1) interviews and discussions with project participants and researchers; (2) a survey of the project's sites; (3) pertinent information kept during the operation of the project, such as construction plans, work methods, etc.; and (4) literature in the Science Citation Index (SCI)/Social Sciences Citation Index (SSCI)/China National Knowledge Infrastructure (CNKI) and other academic databases. To assure the accuracy and validity of the information, the information from various sources was compared and evaluated, and the "triangulation method" was used to confirm the accuracy and dependability of the information [20].

Six semi-structured interviews were conducted for this study. Due to the small number of interviewees in inevitable professions the interviewees were selected from two groups. The first group was construction personnel with extensive experience in on-site resource management, and the other group was academics who study construction waste management. Due to the epidemic, most of the interviews were conducted online, and the questions were mostly targeted and aimed at understanding the experience of implementing shield spoil utilization management projects. For example:

- Can you briefly describe the implementation experience of a shield spoil utilization project you were previously involved in?
- What should we prioritize when implementing the project, in your opinion?
- Which of these factors should you pay particular attention to?
- What problems may arise during the actual implementation?

Following the interviewees' informed agreement, all interviews were taped. A site survey of the Shenzhen Metro Line 13 North Extension Resource Utilization Project was organized after the interviews [21]. The data obtained from the previous semi-structured interviews, combined with the data from site survey, were collectively utilized to distill the key implementation factors for the on-site resource utilization of shield tunneling waste soil [22]. Information on the evaluation plan, work method, and construction plan prepared for the project was also collected for analysis, and a decision framework for the implementation of the on-site shield spoil utilization project was developed.

2.3. Data Analysis

After the completion of the interviews, the recorded interviews and data from on-site investigations were transcribed into text form. These text data were then combined with archived construction plans, methods, and other records from the project implementation process for thematic analysis. Prior to the analysis, the text was transformed into coded statements for thematic generation. Following the approach of V. Braun and V. Clarke, two researchers independently transcribed the interviews [19]. Firstly, the researchers extensively reviewed the interview texts and had brief discussions to generate a coding manual. Secondly, group coding was conducted to facilitate the identification of data saturation, and the Nvivo12 software was utilized to standardize and streamline the coding

process. During the coding process of the final group, no new codes emerged, indicating that data saturation had been achieved in this study. Thirdly, the two researchers separately evaluated and named the defined core themes. Typically, a theme is considered a core theme if it is discussed in approximately 50% of the interview samples, although this proportion can be adjusted based on the actual circumstances to prevent the omission of meaningful themes [19]. Fourthly, the researchers met to discuss and compare the coded interview findings, examining whether preliminary themes could be further consolidated into core themes, if the identified themes had distinct characteristics and universal representativeness, and other considerations. As a result, four themes and twenty core categories were preliminarily identified. The inter-rater reliability of categorization in this study was assessed using the kappa coefficient among different coders, and all twenty categories exceeded 0.65, indicating that the coding in this study was reliable.

Subsequently, experts who participated in the on-site investigation were invited for discussions on the coding results. In conjunction with the Shenzhen Metro Line 13 North Extension project, a decision framework for project implementation was established, and recommendations and prospects for the future implementation of on-site utilization of shield spoil were provided. The discussion centered on the following issues:

- Are the phases of project implementation reasonably divided?
- Are all of the items from each phase included?
- What are the framework's limitations?
- What elements of the shield on-site spoil utilization project can still be improved?

After discussing, the focus group ultimately determined 4 themes and 17 core categories and renamed the themes. Additionally, we suggested that future project implementation could incorporate the lean construction and PDCA cycle concepts as theoretical support for project management.

3. Practical Experience

This study conducted comprehensive research for the Shenzhen Metro Line 13 North Extension Project in order to provide a standardized management framework for the on-site utilization of shield spoil and came to four conclusions from the practical experience: The importance of (a) selection of technology and equipment, (b) economic benefit calculation, (c) facility construction, and (d) operation management is not sequential.

3.1. Selection of Technology and Equipment

The first step in deciding the planning of construction waste following on-site recycling is the selection of resource utilization technology and equipment, which will subsequently influence the specific implementation processes, such as facility construction and personnel. Table 1 summarizes the main factors and selection criteria used by respondents to choose technology and equipment.

Table 1. Key points for choosing technology and equipment.

Key Points	Number of Supporters
Whether the products produced have sufficient economic benefits	6
Mud cake treatment	4
Whether the products produced meet the needs of the industry	4
Maturity of the technology	3
Stability and modularity of the equipment	3

The quality and marketing of the products produced by the act of resource utilization are particularly significant, achieving both regulatory compliance and financial gain. This process involves selecting technologies that are economically efficient and in high demand. The disposal of mud cake, a byproduct of resource utilization, poses a future concern due to the sand content in the shield spoil. Options for disposal include transferring it to nearby docks or sintered brick plants. Alternatively, innovative mud ingenuity technologies, such

as light-wave bricks or mud-curing soil, can be explored. Recycled products, though relatively new, require consideration of their performance, durability, adherence to national standards, and potential impact on project quality.

The practicality of implementing resource utilization depends on the maturity of the technology, considering factors such as real-world experience, prevalence, and the presence of well-established procedures and systems. Choosing stable equipment is crucial to avoiding cost escalation, accumulation of unprocessed sludge, and disruptions to regular construction. Modular system equipment is recommended for construction units, providing quick installation and simplified site planning. Combining modular components optimizes production efficiency.

When building the integrated shield spoil utilization system for the Shenzhen Line 13 Metro North Extension Project, the project team combined three modular pieces of equipment: mud and water separation system, wash-out sand system, and filtration system. They chose the more advanced shield spoil recycling technology, engineering sludge sand making technology, and sewage recycling technology available on the market. It is not only simple to put together but also stable, requiring less staff and fewer maintenance procedures. The subsequent adoption of light wave brick-making technology—using the light wave interference between the combination mode of slag particles to avoid the slag coarse and fine particles enrichment into a group—causes the slag to be mixed uniformly, quickly, and adequately, forming a good brick-making materials. Figure 1 shows some of the photos taken during the site survey.



Figure 1. Shenzhen Metro Line 13 North Extension Project captured by on-site survey: (a) slurry separation; (b) mud swirling and screening; (c) flocculation–sedimentation; (d) filtration.

To summarize the above, effective resource utilization involves ensuring product quality, complying with regulations, and generating project revenue. Attention should be given to mud cake disposal, exploring various options and innovative technologies. The viability of resource utilization technology depends on its maturity and practical application. Equipment stability is essential for cost control and site management. Embracing modular system equipment enhances efficiency in resource utilization projects.

3.2. Economic Benefit Calculation

One of the most significant objectives and the biggest barrier to project implementation is economic indicators. Possessing favorable economic outcomes can encourage the contractor to adopt creative practices on the job site in order to satisfy regulatory standards, lessen the amount of waste disposed of in landfills, and safeguard the environment. The points expressed by interviewees about the economic measurement factors are listed below in Table 2.

Table 2. Key points for measuring the economy.

Key Points	Number of Supporters
Equipment, personnel follow-up placement	5
Payback period	4
Selection of product sales channels	3
Cost console account	2

The calculation of economic benefits in resource utilization initiatives is a critical aspect that was discussed. One key factor emphasized is the “payback period”, which measures the time required to recover the initial investment through income generation. Accurately calculating the payback period enables the project to generate income at the earliest feasible time.

Furthermore, the interviews highlighted the importance of considering various cost factors when evaluating economic benefits. These factors include the purchase price of equipment, ongoing maintenance costs, and the expenses associated with replacement parts. A comprehensive analysis of these costs is necessary to make informed decisions and select cost-effective options.

In addition to the payback period and cost considerations, it is crucial to control expenses and boost efficiency to maximize economic benefits. Strategies such as broadening the sources of revenue and reducing operating costs were suggested. This involves managing major expenditures, such as equipment acquisition, installation, and the disposal and treatment of by-products. Careful evaluation and comparison of different options based on cost-effectiveness are essential during the project planning phase.

Shenzhen Line 13 North Extension Project has made strict calculations on economic benefit measurement, including the procurement of equipment operation and maintenance, sales or self-use of products, and the placement of equipment personnel after the end of the project have been mandatory and feasibility analysis. In addition, the project team also set up a phased economic measurement ledger—for example, a cost ledger for the phased construction of the facility before the payback period and a sales ledger for the products after the payback period. They compare and analyze the target measurement with the actual situation, summarize the key points of cost control in the next phase, and form a summary plan.

Overall, the interviews emphasized the significance of economic benefit calculation in resource utilization initiatives. The determination of the payback period, consideration of cost factors, and implementation of cost-control measures are crucial for ensuring a successful and economically viable project. By effectively managing economic aspects, project stakeholders can optimize their financial returns and contribute to sustainable resource utilization.

3.3. Facility Construction

Other crucial challenges are how to optimize the effectiveness of product manufacturing, lessen the impact of building, and arrange the architecture of the production line in the constrained space. The interviewees proposed the following ideas for the building of the plant in Table 3.

Table 3. Key points for building facilities.

Key Points	Number of Supporters
Facility layout	6
Shield spoil utilization scale	5
Planning area	3
Phased construction	3

The placement of shield spoil utilization facilities is crucial and should adhere to guidelines to ensure environmental safety. The chosen site should be away from sensitive areas and have ample space, as emphasized in the “Standard for construction and operation of comprehensive utilization facilities of construction and demolition waste”. Locating the facility near the construction site reduces transportation distances and improves efficiency while minimizing noise and dust impact on the surroundings. Equipment placement should consider the production sequence to optimize space utilization.

Integrating facility construction with the planning area is essential. Considerations should include construction areas, office space, supply yards, and roadways. Adequate storage space, including equipment footprint, sludge yard, product yard, and general yard, should be allocated to prevent construction-generated sludge accumulation from affecting the project’s progress.

To control schedule and cost, phased construction is advisable. Building the reduction treatment facility and shield sludge yard should be prioritized. Funds generated from the sale of recycled aggregates can then be used to construct the resource utilization production line and product yard using recycled aggregates as raw materials. This approach eases the capital burden and optimizes labor allocation.

The temporary shield structure construction at Xiacun Station is carried out in three phases, the first of which satisfies the need for flowing mud and contains the primary facilities for shield structure spoil disposal. The shield spoil sorting zone can separate the gravel and sand in the shield spoil; the mud–water separation zone can achieve effective separation of sand and mud in the shield circulation mud, and the separated mud can be used by the mud–water shield machine again through modulating slurry; the modulating mud zone can treat the shield mud separated from mud–water by modulating slurry equipment to achieve mud circulation, and the filtering zone can treat the excess shield. The filter-pressing treatment area can treat the excess waste slurry through filter-pressing equipment to ensure zero construction waste. The mud cake is further compressed and stored in the second and third construction phases. To prevent delays in the construction schedule caused by the inability to transport the slag and mud produced by the shield structure away from the project site, phased construction can effectively relieve construction pressure, prioritize the needs of the metro construction project, and then realize the brick-making of the mud cake. Additionally, the phased construction makes it simple to optimize the workforce, which is helpful for capital recovery and cash flow distribution and raises economic efficiency. Figure 2 demonstrates the schedule setting and layout of the construction of the shield spoil utilization facility for the northern extension of Shenzhen Metro Line 13.

In summary, the placement of shield spoil utilization facilities should adhere to guidelines, considering space requirements and environmental impact. Estimating the facility scale based on standards and integrating construction with the planning area are important. Phased construction, focusing on essential components, helps control schedule and cost. These considerations contribute to the successful implementation of resource utilization projects.

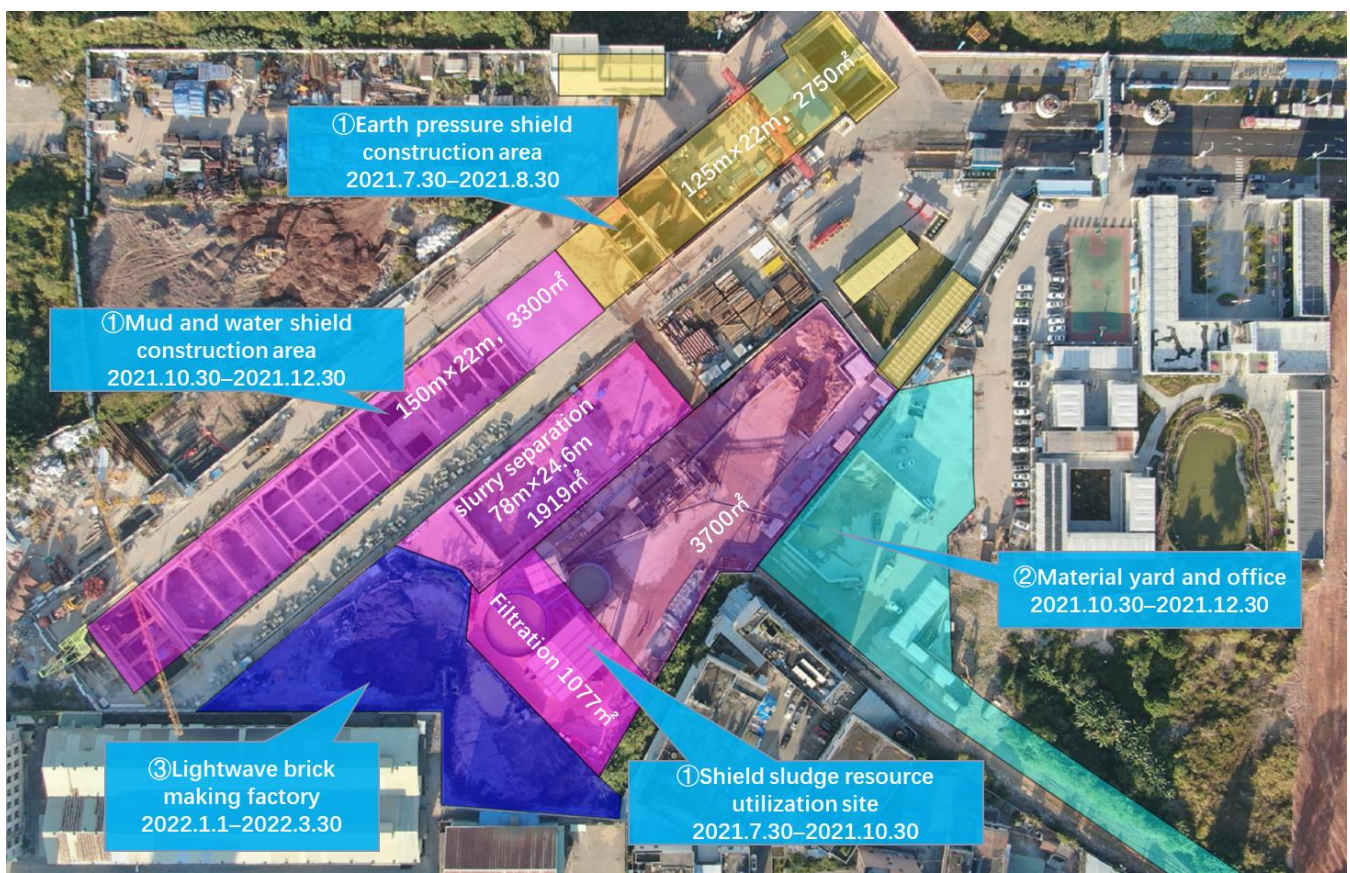


Figure 2. General layout plan of Shenzhen Metro Shield Spoil Utilization Project.

3.4. Operation Management

A majority of unplanned problems will inevitably arise during the implementation of resource utilization projects, and a complete and reasonable project operation and management plan is needed to deal with them efficiently. The following points were raised by the interviewees for the operation management during the implementation process in Table 4.

Table 4. Key points for operation management.

Key Points	Number of Supporters
Quality, safety, schedule, and environmental protection control measures	6
HR management	4
PDCA cycle	4
Intelligent system	2

According to the discussions, integrating specific project management goals into resource utilization projects is essential. Progress control ensures that waste does not impede cost reduction, while quality control monitors recycled product quality. Safety measures address equipment operation risks, and environmental concerns include dust and waste recycling. HR management is crucial for effective operation management, facilitating coordination between staff from resource utilization and construction projects. The resource utilization project can adopt a hierarchical organizational structure, with the plant manager reporting directly to the project manager.

Technical obstacles limit the connection between the resource utilization project and other components. The project finance department oversees financial aspects, while the plant manager collaborates with the project manager on technical handovers. Implementing the PDCA cycle is important, involving meticulous ledger control, data analysis, and

adjustment of implementation plans. Treatment processes are tailored based on soil characteristics, waste output, and product yield. Sales ratios and product practicality are adjusted based on project demand and customer requirements.

Intelligent technology plays a significant role in shield spoil utilization projects, allowing for centralized control systems that monitor module operations, adapt to different conditions, and enable automatic operation. These systems feature chain start–stop, status monitoring, and alarm functions, requiring a small team for daily management.

The Shenzhen Metro Line 13 North Extension Resource Utilization Project employed a three-tiered staffing structure, with a plant manager overseeing all resource utilization activities and reporting to the metro construction project manager and three deputy plant managers reporting to him for maintenance, product quality, and sales. The specific organization chart is shown in Figure 3. The maintenance deputy plant manager is in charge of the three project goals of schedule, safety, and the environment; the product deputy plant manager is in charge of the quality of the products and is also under the management of the metro construction project’s material department for self-use products, and the sales deputy plant manager oversees all of the project’s financial work and is under the supervision of the metro construction project’s finance department. Although the resource utilization project is relatively independent in the metro project, it is bound and managed by the metro construction project, especially in the aspect of safe and civilized construction.

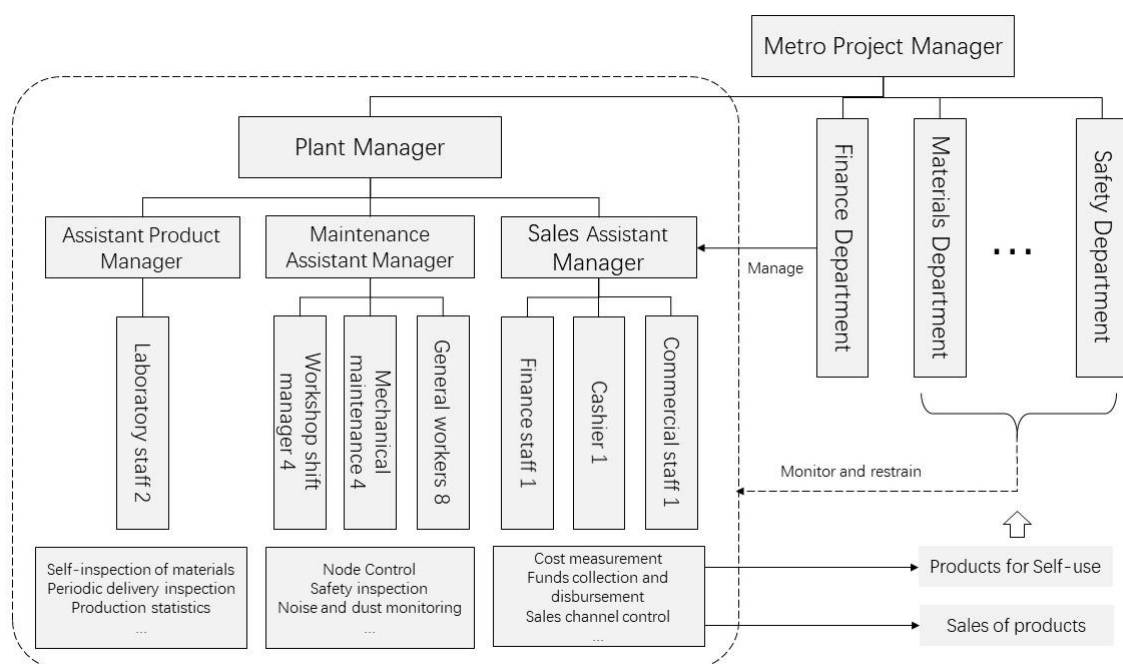


Figure 3. Shenzhen Metro Resource Utilization Project organization chart.

Resource utilization projects integrate project management goals, prioritize HR management, implement the PDCA cycle, and leverage intelligent technology. These approaches optimize cost reduction, ensure quality control, address safety and environmental concerns, facilitate project integration, and enhance operational efficiency.

4. Framework for the Implementation of the Shield Spoil Utilization Project

4.1. Development Framework

This study combines interviews with desk research, site surveys, and focus groups to give readers a thorough insight into the on-site resource utilization project for the Shenzhen Metro Line 13 North Extension. A creative project implementation framework was created in order of execution using the important aspects of project implementation at various

phases that were gleaned from the interviews and blended with lean construction concepts. The decision framework was obtained, and after being given the first draft, it was shared, discussed, and validated with the Shenzhen Metro Line 13 North Extension Project to determine its applicability. The three phases of the project's implementation—project planning, project implementation, and project closure—were divided into the final version depicted in Figure 4 following collaborative changes.

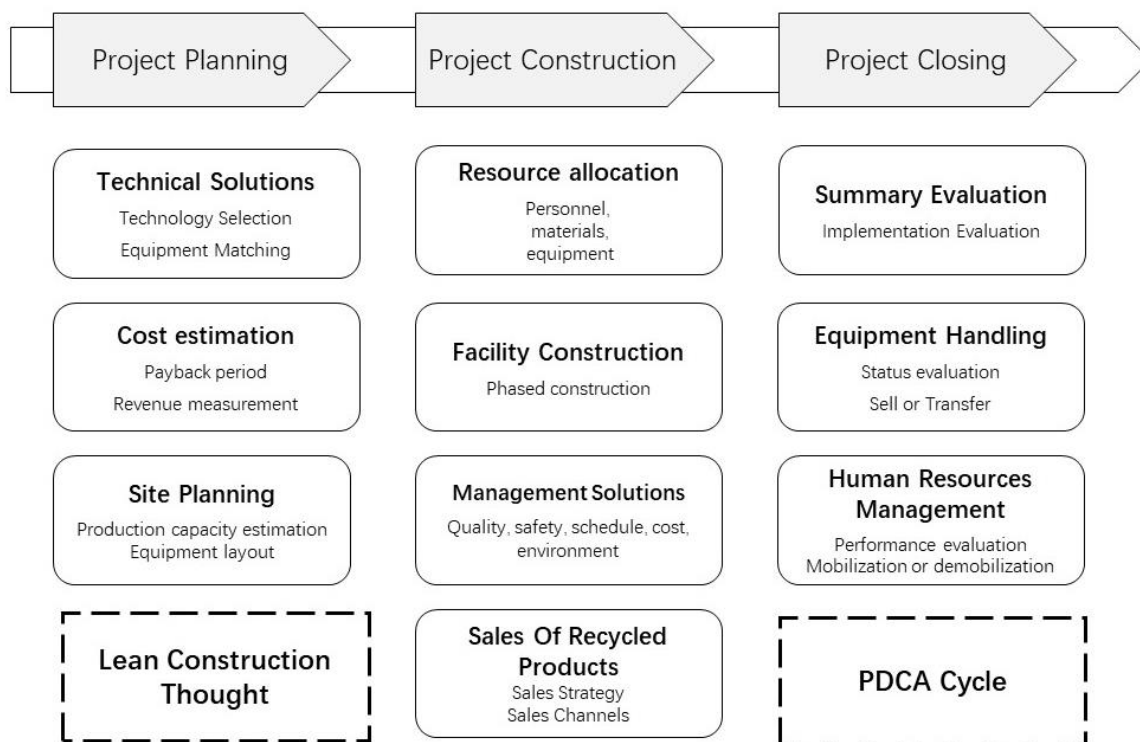


Figure 4. Framework for on-site shield spoil resource utilization.

4.1.1. Project Planning

The project team must decide during the project planning stage whether it is necessary and practical to use on-site resource utilization in conjunction with the findings of the cost measurement. The general layout of the resource utilization program involves the choice of technology, apparatus, planning for on-site amenities, and financial advantages. If necessary, the solution should be modified and improved by combining with other internal project requirements and researching relevant cases.

Government mandates and suitable site conditions were taken into consideration while deciding how to conduct the on-site resource utilization project for the Shenzhen Metro Line 13 North Extension Project. In order to reduce shield spoil, established and reliable technologies and apparatuses were chosen, and the equipment's modularity and intelligence significantly decreased the need for operators [23]. We selected light wave brick production as the technique for shield spoil recycling based on a market analysis of product sales, and we effectively attained "zero construction waste" of industrial waste. The resource utilization project's payback duration and capacity were calculated with the demands of nearby projects in mind, and the current site had a sufficient recycling facility [24].

4.1.2. Project Construction

Before the formal construction of the project, it is necessary to allocate the labor, materials, and machinery required for the project, determine the functions and authority of each personnel, check the quality of incoming equipment and materials, and set a plan for the subsequent demand. The construction of recycling facilities is phased according

to the needs of the metro construction project, and the labor and costs required for the construction of temporary facilities are reasonably controlled [25]. During the project construction process, the management plan is continuously adjusted according to the actual situation and project objectives, and feedback on the construction of the management plan is provided using the Last Planner System.

According to the company's demand for shield spoil disposal for projects around the world in the next five years, and reference to the "Standard for construction and operation of comprehensive utilization facilities of construction and demolition waste" issued by Shenzhen City to build a small resource utilization facility, the project will be divided into three phases of construction in the premise of meeting the demand for shield spoil treatment through the sale of recycled aggregates to alleviate the financial pressure of the later construction. Twenty-five people should be allocated to the recycling facility executive staff according to the work content decomposition of the main jobs content into three parts and assign them to the maintenance deputy director, product deputy director, and sales deputy director of the plant. Setting quality, schedule, safety, management, financial, and environmental goals as well as management programs and adjusting them in response to input from ledger analysis were all part of the resource utilization project's construction. Other information and tasks are gathered by the plant manager for negotiation, except the sales department, which receives direct control from the metro construction project's finance department.

4.1.3. Project Closing

The exit of various materials and personnel at the end of the project is also an issue to be considered. Due to the technical barriers of the resource utilization project, the personnel in the project cannot be deployed with the construction project and can only be transferred as a whole according to the resource utilization project. Similarly, the equipment must be evaluated according to the status of the project after implementation and then considered for transfer or sale. As part of the metro project, it is also necessary to evaluate and analyze the project to provide experience and a basis for the implementation of similar projects in the future. The evaluation is based on various objectives as well as the condition of the equipment and the performance of the personnel.

Resource utilization project mentions continuing to offer shield spoil disposal services for the company's neighboring sites after the Shenzhen Metro Line 13 North Extension Project is completed and allowing outside parties to evaluate the equipment before the expiration of the temporary land period. The equipment will be sold once the project is finished because there is nowhere nearby that would be a good placement site. As opposed to equipment workers who have more flexibility, project personnel will be assigned to different resource utilization projects inside the organization. The business will also review the resource utilization project internally at the same time, summarizing the implementation's experience and issues.

4.2. Recommendations

According the focus group discussion, the implementation of shield spoil utilization project can be optimized in the following three aspects: (1) combining intelligent technology to optimize the existing equipment, (2) utilizing lean technology in project execution, and (3) establishing strategic partnerships with established construction waste recycling enterprises.

4.2.1. Combining Intelligent Technology to Optimize the Existing Equipment

The current shield spoil resource utilization equipment lacks intelligent product quality analysis of the spoiled products, including the function of feeding the product data to the central control room for equipment operation condition adjustment. This includes data on course and fine aggregate particle gradation and mud content [26]. The particle size distribution of course and fine aggregate products can later be determined using a 3D laser

scanner and an image recognition system, and this information can be fed back in real-time to the central control module [27].

At present, mud cakes obtained from resource utilization technology are still disposed of through outbound transportation, and there is no practice of on-site resource utilization. Even if the mud cake is shipped out for further resource utilization, it still needs to be adjusted for moisture content, crushed, and mixed, which is energy- and time-consuming [28]. Although there are many technologies for resource utilization of mud cake, such as light wave brick making and liquefied solid soil. However, the equipment and process of new technologies are not yet stable and the quality and use of the products still need to be tested. However, the development and improvement of new technologies have positive significance for efficient resource utilization.

4.2.2. Utilizing Lean Technology in Project Execution

Lean construction ideas are integrated into the resource utilization project implementation framework, and lean construction-related techniques can be incorporated into the implementation and execution according to the needs [29]—for example, standardized management, parallel engineering, 6S management techniques, etc.

In resource utilization projects, work standards are set for each process so that workers have strict equipment work standards as a reference when working. Just-in-time technology emphasizes the supply of materials, mechanical equipment, human resources, etc., needed to meet the project construction at the right time and strictly follow the process requirements to reduce the accumulation of shield spoil and products, which can optimize the plant layout [30].

Parallel engineering mode questions the traditional “series” mode of engineering construction, which has the limitation of sequence, and when there is a problem in one of the links, it will affect the progress of the following links, which has a profound impact on the project construction schedule. By adopting the “parallel” mode of construction and implementing parallel engineering, we can ensure the quality of the previous schedule and intervene in the later schedule in advance so multiple tasks can be performed together, which improves the efficiency of construction and implements the concept of lean construction.

The 6S method of site management involves creating a high-quality environment at the construction site through the use of staff, machinery, and equipment, as well as materials, to raise the overall quality of projects’ construction.

4.2.3. Establishing Strategic Partnerships with Construction Waste Recycling Enterprises

Currently, most Shenzhen metro projects currently use their own purchased equipment to handle shield spoil; in reality, some skilled construction waste recycling companies also offer on-site recycling services. The resource utilization project can be performed in conjunction with recycling businesses since it is relatively independent condition within the metro project [31]. These recycling organizations will surely be more professional than the building units that are new to this industry since they have more developed and reliable technologies, staff who have received professional training, and a calculated and chosen equipment mix. Future construction units may decide to work with skilled and knowledgeable recycling companies, which can both increase the processing of engineering waste and product production capacity and effectively address the issue of staffing and equipment placement after the project is completed. Additionally, professional recycling businesses have expert sales channels that can guarantee product sales and revenue and create win–win situations [32].

4.3. Limitations

This study has several limitations. The first issue pertains to the applicability of the framework, as it is primarily based on data from the Shenzhen Metro Line 13 North Extension project, which limits the data source’s diversity. While the interviewees provided

valuable insights on similar projects, the framework's applicability still needs to be tested on other projects [33]. Furthermore, as a decision-making framework, it is necessary to establish mathematical models to provide solutions that reflect dynamic and quantifiable benefits [34]. However, the current research field lacks a quantifiable evaluation system. Therefore, this study serves as exploratory research in resource utilization project management, identifying key implementation factors and establishing a macro-level decision-making framework. In the future, this research can be combined with system dynamics simulation or agent-based simulation to develop dynamic models for project implementation, exploring the dynamic decision-making processes. Lastly, this study primarily focuses on the internal implementation of projects without considering external environmental impacts. Therefore, future research should consider the influence of stakeholders on project implementation and investigate factors that hinder or promote project implementation.

5. Conclusions

In this study, the key points of resource utilization implementation were obtained through interviews with practitioners and experts experienced in the implementation of on-site shield spoil resource utilization projects. Taking the on-site resource utilization of shield spoil of Shenzhen Metro Line 13 North Extension as an example, the key points of project implementation were summarized, organized, and verified employing archival research, sites survey, and focus groups. An implementation framework was finally developed to propose the issues to be focused on during the engineering of the resource utilization project implementation, aiming to help the project manager determine the implementation of the resource utilization project on-site.

The framework divides the project into three phases according to the process of project implementation—namely, project planning, project implementation, and project closing—and identifies four key points in technical, economic, construction, and management aspects. The Shenzhen Metro Line 13 North Extension Project is used as a case study to explain and illustrate the content of the framework and to provide a global description of the implementation of the shield spoil utilization project. The project manager can follow this framework to plan and implement the resource utilization project. It is recommended that future research revise the implementation framework with more case studies and develop mathematical models to quantify the dynamic decision-making process and explore the influence of external factors on the implementation of the reuse project. The paper concludes with some perspectives on the implementation of on-site shield spoil utilization projects, hoping that future projects can optimize existing processes and equipment, combine lean construction techniques, and cooperate with recycling companies to help more projects achieve “zero construction waste” of shield spoil.

Testing was primarily conducted using data from the Shenzhen Metro Line 13 North Extension Project as a single source of data. Although the responders have a wealth of opinions on related projects, the framework's applicability must be evaluated on further projects. This study, an exploratory study of resource utilization project management, delves into the crucial aspects of project execution and provides a macroscale decision-making framework because the existing research area has not yet established a quantitative evaluation system. Future research can build a dynamic model of project implementation to investigate the dynamic decision-making process of project implementation by combining this study with system dynamics simulation or subject-based simulation.

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