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Posted Date: 12 July 2023

doi: 10.20944/preprints202307.0378.v2

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Article

A Study on the Application of Smart Construction Safety Management System to Tunnel Construction Based on Worker Location Monitoring Technology

Jungwoo Lee [1], Sohyun Park [1], YoJin Chung [2] and Chan Byon [3,*]

[1] Global Safety Innovation Laboratory; elisha.lee@gsil.kr (J.L.); thgus43196@gsil.kr (S.P.)
[2] Department of Safety and Health Convergent Engineering, Soongsil University; cyj47850@gmail.com
[3] Research Center, CBBS, Co., Ltd.
* Correspondence: C Byon, cbyon@cbbs.co.kr; Tel: +82-52-238-0288

Abstract: Due to the inherent risks associated with tunnel construction, including potential collapse, various types of work activities, and challenging visibility and communication conditions, safety management in tunnel projects requires significant investment in terms of cost and time. In this research, we propose and demonstrate a novel smart construction system that utilizes worker location monitoring technology to enhance safety in tunnel construction. The system comprises a wearable beacon integrated into safety helmets, scanners strategically placed at regular intervals inside the tunnel, environmental sensors for monitoring temperature, pressure, and air quality, and mobile devices for collecting and analyzing data on workers and the environment. Through a field demonstration conducted in a Korean tunnel construction site, we validated the effectiveness of the proposed system, which demonstrated real-time monitoring of workers and reliable communication capabilities, leading to improved safety and cost-efficiency in tunnel construction. By implementing the proposed system, we achieved a significant reduction of 37% in monthly construction costs and 77% in annual construction costs compared to conventional methods.

Keywords: tunnel; smart construction; environment; communication; worker monitoring

1. Introduction

The tunnel construction process is a complex undertaking that requires meticulous planning and the implementation of sophisticated technologies, taking into account factors such as safety, economic feasibility, regional characteristics, and construction convenience [1,2]. Unlike general construction sites, tunnel construction involves a wide range of activities, including excavation, blasting, lining formwork, rebar work, concrete work, auxiliary civil work, temporary road work, vertical pit work, shaft work, tunnel reinforcement, tunnel waterproofing, drainage work, grouting work, temporary plant work, environmental management, temporary safety facility work, temporary electrical work, lifting, and dangerous machine tool work [3–5]. As a result, the risks associated with tunnel construction are significantly higher. In recent years, South Korea has witnessed several accidents in tunnel construction sites, highlighting the inherent dangers of such projects. Examples include the collapse of the Jangseong-Honam high-speed rail (Figure 1a) and rock collapse in the Inje tunnel construction (Figure 1b), as illustrated in Figure 1. These incidents serve as a reminder of the critical nature of safety management in tunnel construction, as the consequences of accidents can be severe, leading to prolonged recovery periods and significant financial costs. Given these circumstances, ensuring effective safety management in tunnel construction sites remains a paramount concern in the field of civil engineering.

 doi:10.20944/preprints202307.0378.v2

Figure 1. Examples of hazards and accidents in the tunnel constructions of South Korea: (a) The collapse of the Jangseong Honam high-speed rail (2011); (b) Inje tunnel construction site rock collapse site (2012); (c) collapse of the wheat timber ecological tunnel (2016); (d) Sediment collapse on the entrance slope of the Yeongdeok-Osan wide-area road tunnel (2009).

However, the selection of tunnel construction processes has traditionally been based solely on criteria and design guidelines, with limited consideration given to factors related to stability, which is a crucial criterion for selecting tunnel construction processes. One of the most significant issues is the inadequate assessment of worker status. The use of mobile phones, which rely on cellular networks, is not feasible within the tunnel interior. Additionally, the use of walkie-talkies is limited by their short-range coverage and difficulties in transmitting clear signals due to noise, making it challenging to swiftly communicate tunnel construction status information. Moreover, in emergency situations, the precise location of workers cannot be determined, making it difficult for safety managers to identify worker information and relay rescue signals. Despite the critical importance of assessing the presence of workers in tunnel construction processes as a benchmark for safety management practices, the current method, as depicted in Figure 2, relies on manually updating a notice board, which is inconvenient and inefficient for both workers and safety managers. Furthermore, there is currently no means for workers to send distress signals themselves, and apart from on-site visual confirmation, there are no available methods for tunnel-wide alerts/communications in the event of anomalies.

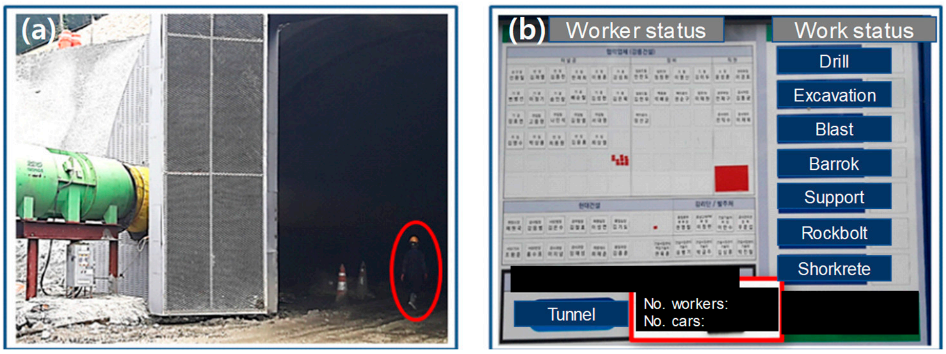

Figure 2. Current tunnel construction status: (a) tunnel entrance; (b) tunnel on-duty worker status board: Manual (hand-written type) status board should be filled out by the safety manager.

In order to enhance the communication status in the tunnel construction area and improve the safety, various studies have been performed. Yum et al. analyzed empirical data of tunnel construction projects in South Korea and assessed the risk of natural disaster-induced losses to the tunnel construction projects [6]. Liu et al. [7] and Gao et al. [8] performed a safety evaluation of subway tunnel construction under an extreme rainfall weather condition. Aygar et al. discussed problems encountered during a railway tunnel excavation [9]. Zhou et al. comprehensively analyzed production safety in the construction industry of China [10]. However, to the best of the authors' knowledge, there is currently no practical demonstration conducted in addition to the methodology development specifically for tunnel construction. This study introduces an innovative smart construction system for enhancing safety management in tunnel construction through worker location monitoring technology. The proposed system incorporates multiple components, including a safety helmet integrated with a wearable beacon, Bluetooth-based positioning scanners strategically positioned at regular intervals within the tunnel, environmental sensors for monitoring temperature, pressure, and air pollution, and a mobile device for collecting data on workers and their surrounding environments. The effectiveness of the proposed system was demonstrated at an actual tunnel construction site in Korea, with its operational reliability validated according to the BWS-16 standards. Furthermore, a quantitative evaluation was conducted to assess the improved safety and economic advantages resulting from the system's implementation.

2. Methods

In this study, we addressed the challenges associated with tracking the positions of workers in tunnel construction and proposed innovative solutions to enhance safety management while improving operational efficiency. We utilized monitoring devices installed at regular intervals within the tunnel work environment, wearable equipment for tunnel workers, and the data acquired from these sources, as depicted in Figure 3. Additionally, we conducted a comprehensive analysis of the tunnel work process and identified potential risk factors based on real-time assessment of the tunnel environment. By integrating risk prediction analysis into the safety management of tunnel construction, we aimed to foster a safe working environment while maximizing the efficiency of tunnel operations. This study was conducted within the framework of the "Development of an Environmentally Friendly Underground Structure Construction Site Support System utilizing 3D Positioning and Wireless Communication Integration Technology," a project implemented by HALLA Construction Co., Ltd., as part of the advanced urban development program of the Ministry of Land, Infrastructure, and Transport of the Republic of Korea. As a participant in the project, we were assigned the objective of developing a wearable module for worker positioning and construction site support system. The research encompassed various aspects, including the development of a wireless signal transmission and reception scanner, as well as an environmental scanner capable of measuring tunnel conditions. Each of the aforementioned items is to be discussed as follows:

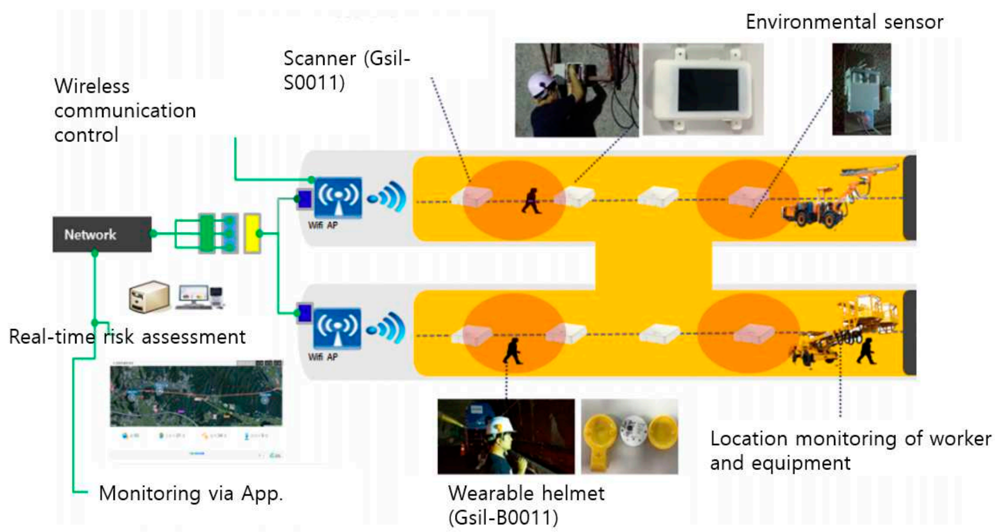

Figure 3. Overview of field application of a smart construction safety management system based on worker positioning in tunnel construction.

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2.1. Wearable Device for Workers

The wearable device for workers (Gsil-B0011) is depicted in the illustration as a yellow module attached to the safety helmet, as shown in Figure 4. It weighs a mere 11.6 g and features a detachable clip design, allowing for readable attachment and removal. The short-range communication signals generated by Gsil-B0011 can reach a radius of 50 – 70 m, enabling the transmission of worker identity information to the relay stations installed within the tunnel. It is possible to restrict the recognition of only pre-registered BLE devices by the safety management system. The Gsil-B0011 is a compact and lightweight BLE tag, as shown in Figure 4, and is applied on-site. It allows for the identification of individual workers through the signals generated by the wearable device. These signals are transmitted in real-time to the server, enabling the tracking of workers' current positions.

Figure 4. Wearable device for workers.

2.2. Real-Time Worker Monitoring System

Install relay stations within the tunnel as illustrated in Figure 5. The spacing between the relay stations is determined based on actual measurements of signal range within the tunnel. Each relay station is equipped with a Bluetooth scanner (Gsil-S0011) to communicate with the wearable devices (Gsil-B0011) worn by workers, transmitting the received information from the wearables to the server, as shown in Figures 6–8. The relay stations are capable of receiving wireless signals (such as WIFI, LTE-MTC, or LORA) present within the tunnel and amplifying and relaying them to other relay stations. Moreover, they can be easily installed at desired locations during tunnel construction and reused in different sites after the completion of the project, offering cost-effectiveness. As depicted in Figure 5, the signals emitted by the wearables (Gsil-B0011) worn by workers allow for individual worker identification. This worker identification information is transmitted in real-time from the relay stations installed within the tunnel to the server, enabling real-time tracking of workers' current positions. Furthermore, essential information regarding workers' skills, age, nationality, and equipment usage status, among others, is displayed in real-time on a web-based interface. This allows for the transmission of information beyond analog radio communication and document delivery, providing a richer understanding of the site's status. Worker positioning is performed through a web-based interface, accessible on any operating system with a compatible browser. It can be monitored from worker rest areas, safety management rooms, and even within the tunnel using a mobile application to assess on-site alignment. With internet access and a compatible browser, monitoring is possible from the contractor's headquarters, client offices, and other locations, enabling real-time tracking of work progress by authorized personnel.

doi:10.20944/preprints202307.0378.v2

Figure 5. Bluetooth scanner (Gsil-S0011) for communication based on wearable devices (Gsil-B0011): (a) Installation; (b) Inner module; (c) Installed device with casing.

2.3. Sensor for Sensing Real-Time Environmental Status

As shown in Figure 6, environmental sensors capable of sensing temperature, humidity, oxygen, carbon monoxide, and carbon dioxide are integrated into the relay stations, enabling real-time transmission of environmental data to the safety management system. Additionally, as depicted in Figure 6, measurements of fine dust, temperature, humidity, and carbon dioxide within the tunnel can be taken and assessed for a safe working environment through mobile devices. As shown in Figure 6, in the event of an increase in humidity within the tunnel, it can be inferred that there is a potential risk such as tunnel leakage. Early prediction of such risks allows for timely interventions. Moreover, if the air quality within the tunnel exceeds the prescribed standards, it becomes possible to assess the working environment and implement necessary measures.

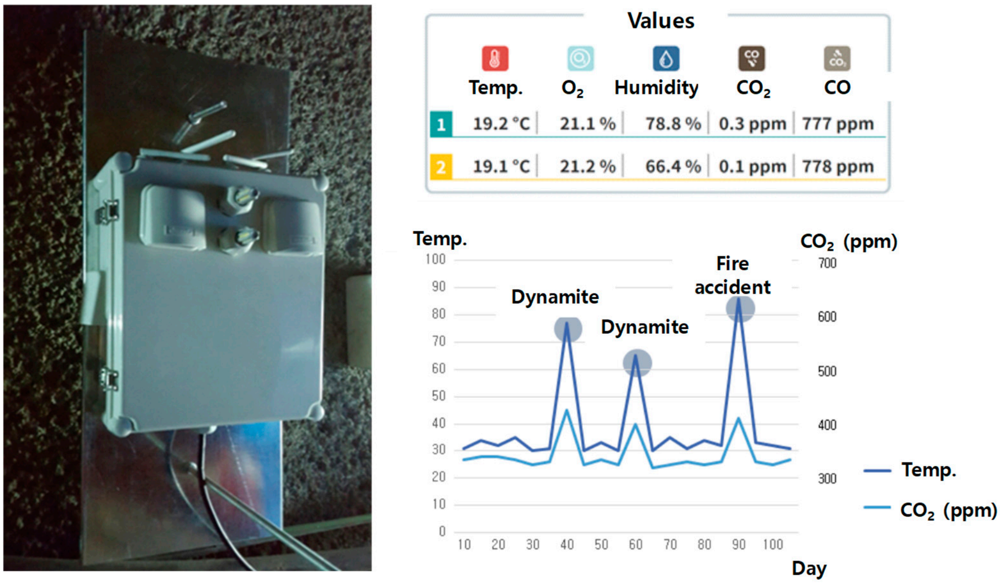

Figure 6. Environmental sensor installed on tunnel wall: sensor device (left); temperature, oxygen content, humidity, carbon dioxide content, and carbon monoxide content measured and displayed (right-top); long-term temperature and CO_2 content change with respect to time upon incident of dynamite blasts and fire accident.

2.4. Development of Real-Time Risk Prediction System

By conducting risk assessments based on the work conditions at the construction site and promptly integrating the direct safety inspection results into the server, real-time risk assessment can be achieved. This allows for dynamic control over workers' access to specific tasks or hazardous areas, adapting to the evolving circumstances (Figure 7). Additionally, system enhancements have simplified the conventional paper-based documentation process, enabling convenient mobile inspections and facilitating result sharing through web monitoring. This ensures transparency regarding inspection performers and timestamps, thereby facilitating responsibility management.

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Moreover, real-time notifications are sent to designated personnel for confirmation based on the risk level, enabling continuous monitoring of the completion of necessary checks.

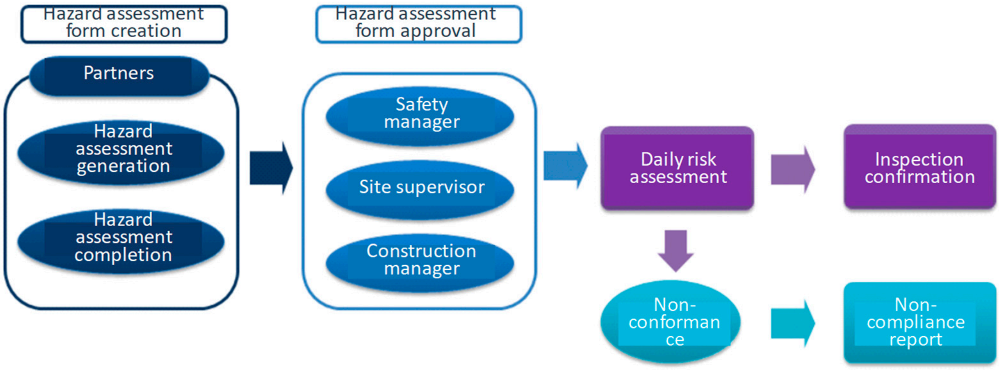

Figure 7. Hazard assessment process.

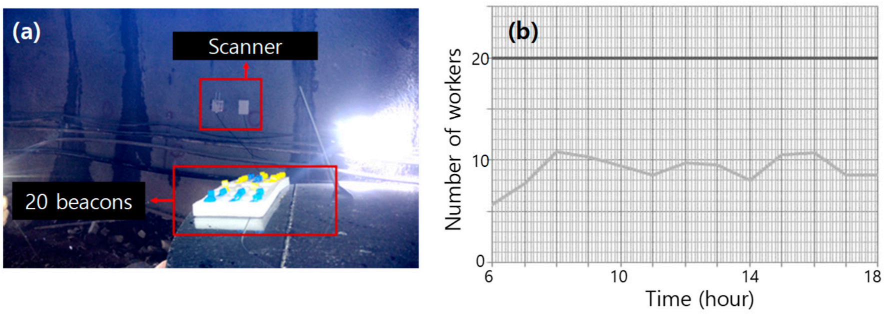

Figure 8. Communication reliability test for the worker monitoring system: (a) Real-time monitoring of on-site worker number; (b) Number of on-duty workers in tunnel with respect to time.

3. Demonstration

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn. To assess the effectiveness of the developed technology, reliability tests were conducted on the safety management aspects. The test items included real-time verification of the number of workers, verification of the scalable capacity for worker supervision per scanner (value indicating the manageable range per scanner), communication stability of the safety management system, location matching accuracy (accuracy of scanner-identified positions), and the success rate of accessing process-related safety management information. These tests aimed to evaluate the performance of the system in terms of the following aspects.

3.1. Real-Time Monitoring on-Site Worker Number

In this test, capability of the monitoring devices within the tunnel to simultaneously detect over 20 worker wearable terminals in real-time was verified using 20 beacons, as illustrated in Figure 8a. The test was conducted to estimate the maximum density of detectable personnel at a single work location in the tunnel construction process. The value of 20 was determined based on a survey conducted at the HANLA Construction Co., Ltd. on the Janghang Line 3 construction site, from October 31st, 2022, to November 6th, 2022, covering a one-week period from 06:00 to 18:00. The average number of workers entering the site during each time slot was estimated to be around 10 individuals, as depicted in Figure 8b.

3.2. Number of Controllable Workers

The number of controllable workers is determined by measuring whether the coverage range (distance) for each monitoring device within the tunnel exceeds 100 m. When the coverage range of a single device reaches 100m, the achievable distance between the terminal devices is thus equivalent to 200 m.

3.3. Communication Stability

The test setup is illustrated in Figure 9a. In this test, the signal transmission between the beacon and the gateway is evaluated by setting a distance of 50 m between them. The beacon signal is transmitted 100 times, and the number of signals detected by the gateway is measured.

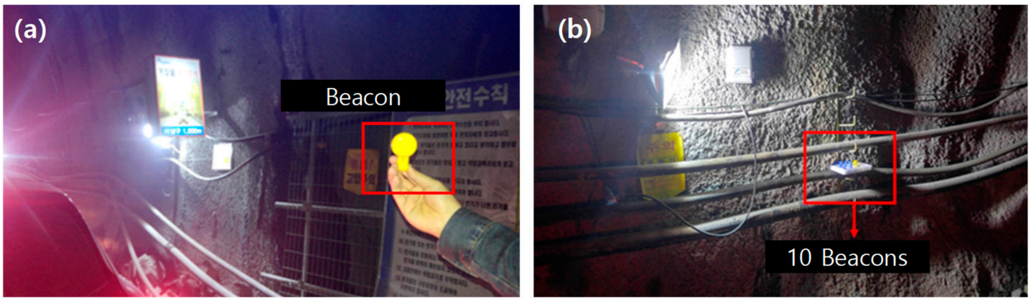

Figure 9. Tests for communication stability and accuracy: (a) Communication stability; (b) Accuracy in location monitoring.

3.4. Accuracy in Location Monitoring

The test setup is illustrated in Figure 9b. The level of accuracy in determining the location of workers within the work zones in the tunnel construction site is assessed. A single monitoring device installed in the tunnel is used to measure how accurately it can track the positions of 10 individual worker terminals worn by the workers inside the tunnel.

3.5. Success Rate of Reaching Process Safety Management Information

The performance of transmitting and receiving process information in tunnel construction is examined (Figure 10a). Using a mobile application, the blasting time is inputted from outside the tunnel, and the blasting time is then verified using the mobile application inside the tunnel.

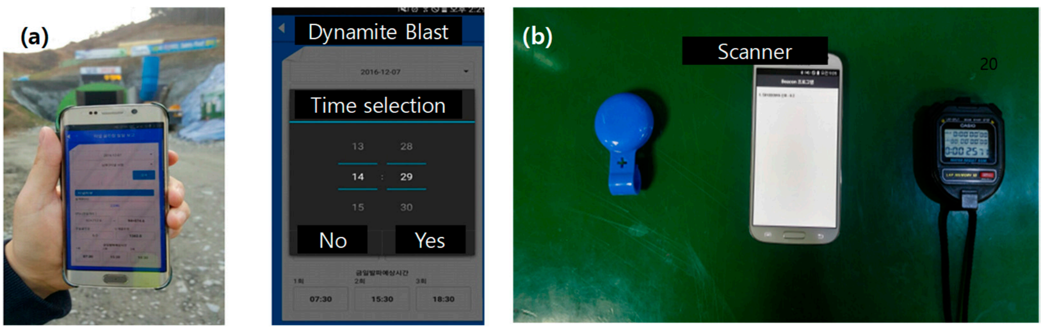

Figure 10. Tests for communication stability and accuracy: (a) Communication stability; (b) Accuracy in location monitoring.

3.6. System Durability

The convenience of system maintenance was verified through tunnel site testing. (Figure 10b). The usage period is calculated based on the daily usage of the worker's wearable device. The maintenance stability of the tunnel information relay device (Scanner Gsil-S0011) was verified. Under simulated power outage conditions, which assume the removal of the charging cable connected to the beacon via the relay device (Scanner Gsil-S0011), the duration of continuous communication with the beacon was observed. The daily power consumption of the beacon battery was measured to calculate the expected battery lifespan.

Table 1 shows the summary of test items and their results. During the testing conducted at the tunnel construction site, the following aspects were examined to ensure the safety and stability of the system. Verification of the system's ability to accurately recognize actual workers within the designated work zones, assessing the scale of worker detection; Measurement of the control range (distance) achievable per tunnel information relay device (Scanner Gsil-S0011) to confirm the extent of monitoring coverage; Assessment of the communication stability (transmission reliability) of the tunnel construction safety management system; Confirmation of the alignment accuracy of worker positions within their respective work zones, comparing it with the beacon positions detected by the tunnel information relay device; Verification of the success rate of delivering process-related safety management information, ensuring the structural stability of the safety management system during operation. Additionally, the testing results indicated that the relay devices (Scanner Gsil-S0011) can operate continuously for over 26 hours, while the beacons' batteries can last for more than 200 days after a single replacement. This demonstrates the system's resilience against power outages and electrical issues, as it can continue functioning without the need for additional measures until the situation is resolved. To summarize, based on the field testing results, it was confirmed that the system exhibits low power consumption and maintains stability, effectively preventing system failures and malfunctions caused by power interruptions. This ensures convenient system maintenance and management during tunnel construction operations.

Table 1. Reliability test items and results summary.

Classification	Test method	Result (/criteria)	Decision
Real-time monitoring of on-site worker number	Monitored with 20 beacons (workers) for the workers in the tunnel	20/20	Passed
Number of controllable workers	Check the maximum distance per one tunnel information scanner (standard: 100m)	100 m /100 m	Passed
Communication stability	Converted into a statistical percentage after 100 measurements.	100%/99%	Passed
Accuracy in location monitoring	Using one tunnel information scanner and 10 beacons, check the accuracy of positioning the beacon	100%/99%	Passed
Success rate of reaching process safety management information	Test and check transmission/reception status using 1 tunnel scanner and mobile	Communication quality	Passed
System durability	Maintenance stability of device is measured using a stop watch	26 h/24 h	Passed

4. Results and Discussions

4.1. Efficiency and Time Savings

In this study, through the application of our developed technology, the registration of personnel involved in tunnel construction is carried out on the server. Unauthorized workers can be identified and access control measures can be implemented. Additionally, the system allows verification of whether workers have completed site-specific safety training, enabling effective management of worker registration. In regard to the worker location monitoring, in the conventional approach, most workers enter the tunnel without registering their entry on the status board, making it challenging to accurately track the number of people, equipment, actual locations within the tunnel, and personal information of workers. With the implementation of our technology, real-time monitoring of all individuals entering the tunnel, including detailed access information of subcontractor employees,

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became possible. Installation of Tunnel Information Relay Devices: The relay devices receive wireless signals (such as Wi-Fi, LTE-MTC, or LORA) present within the tunnel and amplify and transmit them to other relay devices. These devices can be easily installed at desired locations during tunnel construction and can be economically and effectively reused in other sites after project completion. Wearable Devices: The wearable devices (Gsil-B0011) transmit short-range communication signals, allowing accurate transmission of worker identity information to the relay devices installed within the tunnel within a radius of 50m to 70m. Furthermore, essential information about workers, such as skill level, age, nationality, and equipment usage, is displayed in real-time on a browser-based interface. This eliminates the need for analog radios and paper-based information dissemination, providing rich situational awareness. Worker location tracking is conducted on a web-based screen, accessible on any operating system with a compatible browser. The information can be monitored from locations such as worker restrooms and safety management offices, as well as within the tunnel using a mobile app to assess on-site alignment. Reduced Blasting Process Time in Tunnel Construction: As depicted in Figures 6–20, our proposed technology facilitates real-time monitoring of workers, enabling automatic identification of their locations before and after blasting operations. This has demonstrated a reduction in the overall construction duration by approximately 20 minutes per blasting event (Figure 11).

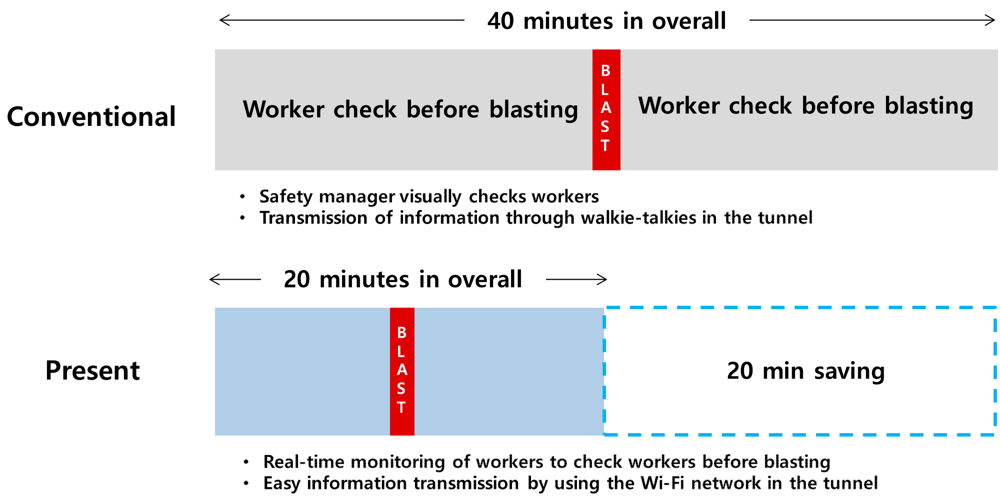

Figure 11. Schematic diagram of time saving using the worker location monitoring system of the present study: 20 minutes of time saving and worker safety enabled by excluding the visual- and walkie-talkie-based worker location monitoring process.

4.2. Enhanced Safety Effects

Real-time risk assessments were conducted by evaluating the safety conditions based on the work situation and immediately reflecting the results of direct safety inspections on the server. This allowed for real-time risk evaluation, enabling the control of workers' access to specific tasks or hazardous areas according to the dynamic situation. In terms of monitoring and automated documentation, through system enhancement, inspections were conducted easily on mobile devices, and the results were shared through web monitoring. This enabled easy tracking of inspection records, including the responsible personnel and the timing of inspections. Based on the risk level, designated individuals received real-time notifications, and monitoring was implemented to ensure confirmation of completed inspections. The system allowed for the generation of evaluation forms by selecting specific risk items, and daily tasks such as work registration and identification of risk factors could be managed through mobile devices. The integration of the identified risks into the safety management system enabled immediate instructions for corrective actions, improving the inefficiency and time delay associated with the creation and sharing of non-conformance reports.

In regard to emergency signals, even in the poor mobile communication environment within the tunnel construction site, our technology allowed for the generation of emergency signals and the provision of information to respond to disaster situations according to predefined protocols. Additionally, simplification of accident reporting processes on the construction site facilitated clear action guidelines for effective coordination among victims, nearby workers, supervisors, site managers, headquarters personnel, and emergency response teams at hospitals. In addition, measurements of fine dust levels, temperature, humidity, and carbon dioxide inside the tunnel were conducted to ensure a safe working environment. If the humidity within the tunnel exceeded normal levels, indicating potential risks such as leaks, early prediction of hazards became possible. Furthermore, if air quality exceeded the specified standards, appropriate measures could be taken to address the working environment.

4.3. Economic Benefits

The direct material cost for the proposed technology increased by KRW 13,563,760 compared to the comparative technology, while the direct labor cost decreased by KRW 18,049,025. Overall, the combined direct material and labor costs demonstrated a 13% reduction in expenses with the implementation of our developed technology, as shown in Table 2. Table 3 provides a cost analysis report comparing the developed technology and the comparative technology. Additionally, Table 3 compares the project costs using the developed technology and the comparative technology. The results indicate that while there was an increase in material costs, significant savings of approximately 13% in overall construction costs were achieved by reducing labor expenses. Furthermore, Table 3 presents the additional maintenance costs incurred after the construction phase, both on a monthly and annual basis. The table illustrates that through the use of the developed technology, monthly costs can be reduced by approximately 38% and annual costs by approximately 77%.

Table 2. Construction and maintenance costs of the present and previous studies: Construction cost (monthly-based, unit: KRW).

Classification	Present	Previous
Material cost	28,617,480	14,782,812
Labor cost	7,598,358	27,434,236
Expenses	3,539,090	5,630,319
Pure construction cost	39,754,928	47,847,367
Total	44,168,634	56,108,518

Table 3. Overall cost taking into account the maintenance cost (unit: KRW).

Classification		Present study	Conventional construction
Construction cost		**44,168,634**	**56,108,518**
Maintenance cost	**Inspection**	**408,769**	-
	Maintenance	1,117,275	17,768,190
	Subtotal	1,526,044	17,768,190
Total (monthly)		44,168,634	73,876,708
Total (annually)		62,481,162	269,326,798

4.4. Discussions

Development and application of smart construction safety technologies were examined in this section, focusing on tunnel construction as a representative case study. Tunnel construction involves various types of work such as excavation, blasting, and formwork, and due to its higher risk level compared to typical construction sites, it requires advanced safety management. Based on the smart construction safety technologies, a tunnel safety management system was developed and implemented. To accomplish this, the worker location monitoring technology and environmental measurement technology were utilized. Wearable modules for worker location measurement were developed, along with wireless signal transceivers, and environmental scanners capable of measuring tunnel conditions were utilized. The application of the technologies has demonstrated a reduction in tunnel construction costs by approximately 13%. It has also been confirmed that through the developed technologies, monthly costs can be reduced by approximately 38% and annual costs by approximately 77%. Moreover, it has been reported that a reduction of approximately 88% in maintenance costs can be achieved after five years. These findings suggest that the developed technologies will have significant industrial implications. It is important to note that this research was conducted as part of the activities of GSIL Co., Ltd., to which the researchers belong. Therefore, it is characterized as field-oriented R&D conducted directly by the researchers, involving rigorous analysis of relevant technologies and needs, as well as sophisticated system design, in line with the nature of the field.

As previously discussed, prior studies have primarily focused on investigating individual technological components and their values within the context of smart construction. However, in real-world construction sites, a comprehensive evaluation should consider various factors, such as the integration of different technological elements, feasibility, economic viability, and the perspectives of managers and workers who are adopting new technologies. In this regard, this study holds significance as it evaluates the practical ap-plicability of existing smart construction technologies by extracting and merging field-friendly elements. The proposed smart construction management system enables seamless connectivity throughout all stages of construction, including planning, design, procurement, construction, and maintenance, facilitating effective collaboration among stakeholders involved in the construction process

5. Conclusion

In this research, a novel smart construction system was proposed and demonstrated to enhance safety and cost-efficiency in tunnel construction. The system utilized worker location monitoring technology, integrating wearable beacons, strategically placed scanners, environmental sensors, and mobile devices for data collection and analysis. Through a field demonstration conducted at a Korean tunnel construction site, the effectiveness of the system was validated, showcasing real-time monitoring of workers and reliable communication capabilities, resulting in improved safety and cost-efficiency.

The implementation of the proposed system led to a significant reduction of 37% in monthly construction costs and 77% in annual construction costs compared to conventional methods. The system's application demonstrated its potential for substantial cost savings, making tunnel construction more economically feasible. Additionally, the system enhanced safety in tunnel construction through features such as real-time risk assessment, monitoring, and automated documentation. It provided the capability to assess worker access to hazardous areas and dynamically control tasks based on the evolving situation. Emergency signals could be generated, enabling effective coordination in disaster situations. Furthermore, environmental sensors allowed for continuous monitoring of temperature, humidity, air quality, and other factors, ensuring a safe working environment. The reliability tests conducted on the system's performance demonstrated its capability in real-time worker monitoring, communication stability, accurate location tracking, and successful access to process-related safety management information. The system exhibited low power consumption and durability, ensuring its operational stability even during power outages.

Overall, the research findings highlight the potential of the proposed smart construction system to enhance safety and cost-efficiency in tunnel construction. The system's implementation can lead to significant economic benefits and improved safety practices, reducing construction costs, and minimizing the risk of accidents. The research, conducted as part of GSIL Co., Ltd.'s activities, represents a field-oriented R&D effort with rigorous analysis, addressing the specific needs and challenges of tunnel construction. The developed technologies have obtained "New Technology Certification" from the Ministry of Land, Infrastructure and Transport, indicating their recognition and potential for wider industrial implications.

 doi:10.20944/preprints202307.0378.v2

Author Contributions: J Lee conducted the research himself, secured the data, and wrote the manuscript. DP Shin consulted on the study and performed the theoretical analysis necessary to obtain the data. SH Park assisted J Lee in conducting the research and securing the data. C Byon established the SCO evaluation method and wrote part of the manuscript.

Funding: This work was supported by the Industrial Technology Innovation Program (20012292, Development of effective industrial safety education services for foreign workers based on intelligent information technology) funded by the Ministry of Trade, Industry & Energy (MOTIE, Korea).

Data Availability Statement: Information relevant to the manuscript can be found in gsil.kr.

Acknowledgments: This work was supported by the Industrial Technology Innovation Program (20012292, Development of effective industrial safety education services for foreign workers based on intelligent information technology) funded by the Ministry of Trade, Industry & Energy (MOTIE, Korea).

Conflicts of Interest: The authors declare no conflict of interest.

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