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IMPLEMENTATION OF SMART SITE SAFETY SYSTEM AND 5G/IOT IN TUNNEL CONSTRUCTION IN HONG KONG – SOLUTION FOR SAFETY CONSTRUCTION

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Abstract: To enhance safety management, the Hong Kong Government issued a technical circular in 2023, promulgating the adoption of smart site Safety System (4S) in public works projects with a contract sum exceeding $30 million. Confined space (such as a tunnel, a cavern, etc.,) is considered as one of the most dangerous environments for construction, and is therefore specially listed in 4S plan as a separate item. This paper begins by summarizing common risks in tunnel construction and introduces the corresponding elements of 4S in confined space management, including confined space access control, worker health monitoring, equipment management, air quality monitoring, AI CCTV, electronic locking systems, and their integration into a Central Management Platform (CMP). For each functional component, the paper elaborates on targeted problem-solving approaches through 4S implementation, as well as the corresponding actions to be taken by administrators and safety officers in response to various alerts and notifications. Additionally, the paper highlights specific challenges that may arise during the application of 4S in confined space projects and proposes practical solutions. Furthermore, the paper discusses the application of 5G/IoT technologies during tunnel construction, which supports 4S functionalities and internet-based communication. The adoption of smart site systems represents an emerging trend in engineering project practices. It is hoped that the experiences summarized in this study will assist industry peers in strengthening confined space project management and fostering a safer working environment.

Keywords: Tunnel Construction; Smart Site Safety System (4S); 5G/IoT implementation; AI Safety Monitoring; Centralized Management Platform

1. INTRODUCTION

Tunnel construction is widely recognized as one of the most hazardous activities in the construction industry due to the confined and dynamic nature of the working environment. According to the “Code of Practice for Safety and Health at Work in Confined Spaces” (Labour Department, HKSARG, 2024), the major hazards in a confined space include five main situations, namely: (1) flammable, explosive or oxygen enriched atmosphere; (2) excessive environmental heat; (3) toxic / harmful gases or oxygen deficient atmosphere; (4) in-rush of liquid; or (5) in-rush of free flowing solids.

The risks associated with tunnel construction necessitate the adoption of safety management systems. Thus, in “Guidance Notes on Safety and Health of Hand-dug Tunnelling Work” of Occupation Safety and Health Branch (Labour Department, HKSARG, 2017), project teams should establish safe systems and safety precautions for construction, which mainly includes risk assessment and permit-to-work system, tunnel tag in / out system, air monitoring, electricity management, monitoring devices etc.

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In recent years, the integration of high-tech solutions has revolutionized safety management in tunnel construction. In February 2023, the Hong Kong Government issued a technical circular, promulgating the adoption of smart site Safety System (4S) in public works projects with a contract sum exceeding $30 million (Development Bureau, HKSARG, 2023), aiming to enhance safety management in construction stage. Projects are divided into 16 categories with different recommendations and options of 4S products. For tunnelling, the recommended items are: centralized management platform (CMP), digitalized permit-to-work system, hazardous areas access control by electronic lock and key system, unsafe acts / dangerous situation alert for mobile plant operation, smart monitoring devices for workers and frontline site personnel and confined space monitoring system. Other optional items are also listed in the circular.

2. CURRENT 4S IMPLEMENTATION STATUS IN HONG KONG

A preliminary study (Chan et al., 2024a) after the issuing of the 4S technical circular interviewed four groups of stakeholders, including government engineer, supplier, site safety officer and safety trainer, to figure out the thoughts and doubts about the implementation and training of 4S in projects from different perspectives. As the study was carried out before the actual implementation of 4S, problems such as integration of the system, power supply of products were raised out by stakeholders, which later became true problems for the industry. The following study about the design and implementation of 4S (Chan et al., 2024b) reports two existing sites implementing 4S. It is found that the responsibility of 4S management was unclear, leading to many uncertainties in follow-up of incidents and maintenance of components; Meanwhile, trainings should be provided in different themes for different site personnel from different backgrounds. The method of developing a training course on 4S was also discussed in another study (Chan et al., 2025).

Although the technical circular of 4S has been put into effect for more than three years, there are still a large number of public projects had commenced before the issuing of the circular. Most clients / employers / project managers from these projects issued instructions to contractors for partly / fully implementing 4S. However, the release of tunnel projects in is not as expected, only few tunnel projects are currently on the market. As of April 2025, 523 projects with different scales were granted with the 4S Labelling in Hong Kong, of which there are only 6 tunnel construction projects (https://www.cic.hk/content/4s-labelling/en/project-list).

Lacking experience and references makes the project / research team encountered a lot of problems, and considering optimization plan for 4S. As a mature contractor who has its own smart construction industry, while had constructed and is constructing major tunnel projects in Hong Kong, this project / research team have carried out on-site researches about the implementation of 4S in tunnel projects for over two years, and has its own understanding of the development and use of 4S components.

3. 4S COMPONENTS AND NETWORK SUPPORT FOR TUNNEL CONSTRUCTION

As listed in the 4S Technical Circular (Development Bureau, 2023), 4S components and relevant solutions implemented for tunnel construction can be summarized in Table 1.

Table 1. *Recommended 4S Products for "Tunnelling" Package in 4S Technical Circular and solutions implemented.*

Recommended 4S Products	Solutions
Centralized management platform (CMP)	CMP for website and mobile devices
Digitalized permit-to-work system for high-risk activities (e-permit)	E-permit including confined space, lifting, hot work, ladder use etc.
Hazardous areas access control by electronic lock and key system	E-lock with QR code, can unlock by card or mobile apps
Unsafe acts / dangerous situation alert for mobile plant operation danger zone	Machinery 360-degree AI camera system
Smart monitoring devices for workers and frontline site personnel	Smart watches or smart helmets for locating and health detection
Safety monitoring system using Artificial Intelligence	CCTV with AI implanted or real-time AI post processing

Confined space monitoring system	Tag in / out system for entry counting and control; Air monitoring system for air quality inside tunnel

Understandings and optimizations from the project / research team of 4S components related for tunnel construction use are proposed in the following sections.

3.1. 4S Components for Tunnel Construction

3.1.1. Centralized Monitoring Platform (CMP)

The Centralized Management Platform (CMP) should be a web-based with access control intelligent and intuitive platform to manage and collect all signals received from 4S. CMP should also centralize construction data, including BIM, site progress, intelligent alerts and early warnings, apps data, IoT sensor data, and weather information, etc. for better demonstration. It should provide the site staff and stakeholders with a more transparent and accurate up-to-date overview anytime, anywhere (Figure 1).

CMP should be placed in the control center, access available through any device with internet access and browser. Details of computer hardware and software and associated furniture refer to contract. The contractor should have its own control center be in its site office.

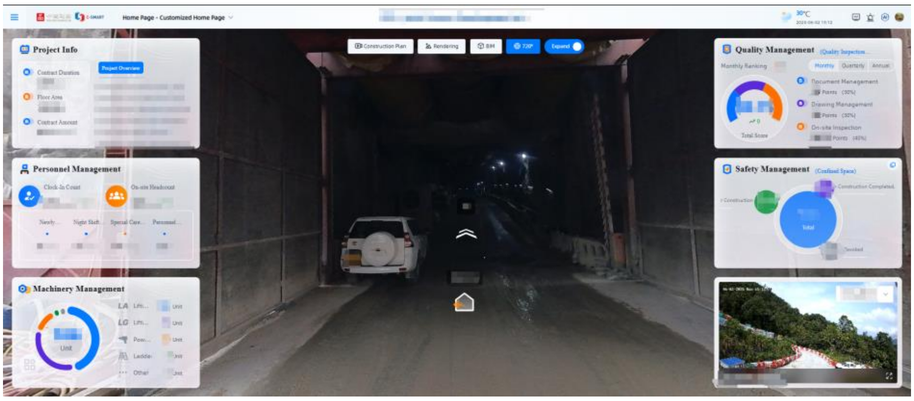

Figure 1. *Dashboard of CMP.*

For a tunnel project, alert center is a necessary part of CMP. The alert center should be able to display notifications from products, especially confined space air monitoring, confined space worker status, AI CCTV, LALG, e-permits, machinery 360-degree AI Cameras, etc. As a confined space always generates important air quality alerts and worker status alerts, it is recommended to divide alerts into different levels (2 to 3 levels) to reduce unnecessary interferes. Details of the levels should be negotiated with the client / employer / project manager, and liaise with supplier for customization.

Taking 3-level alert system customized for the project / research team as an example, notifications are recommended to be marked with different colors such as red, orange and blue separately to reflect different importance. For a red situation, the alert will pop-up in CMP immediately and push to relevant personnel via mobile app simultaneously; for an orange situation, the alert will pop-up in CMP without app notification; for a blue situation, the alert will pop-up in backstage instead of dashboard, avoiding bunches of unnecessary notifications.

Only authorized personnel (e.g. safety officers) can eliminate the alerts after issues are solved and conditions turn back to normal. Frontlines who do not have the accesses to CMP, may call relevant authorized personnel to deal with the alerts after making sure everything working normally (Figure 2).

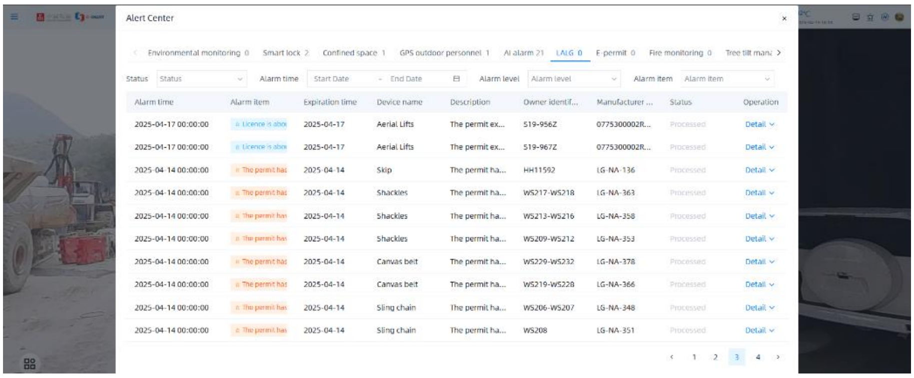

Figure 2. *Different Levels of Alerts.*

3.1.2. Digitalized Permit-to-Work System for High-Risk Activities (e-permit)

A permit-to-work system is a mean to ensure safety and health of the workers who enter and work in a construction space, enhancing management and control, and encouraging higher transparency for operation.

As stated in the code (Labour Department, 2024), a confined space e-permit is required before entering a tunnel after any change of conditions (Figure 3). The permit should be displayed conspicuously at the entrance of the confined space, and the Labour Department will conduct spot checks. However, according to the present 4S technical circular, e-permit of confined space is required, and this requirement is written in the project contract so that the contractor is to follow.

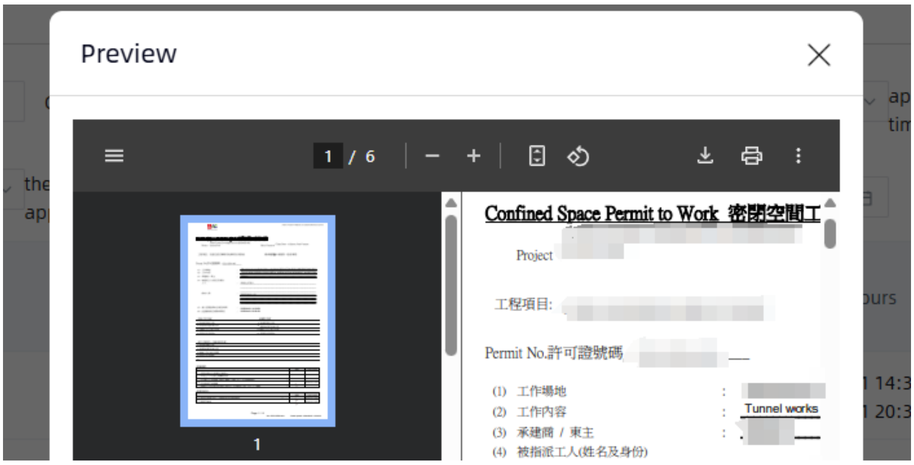

Figure 3. *Preview of Confined Space E-permit.*

To make sure the safety construction environment and enhance management, it is suggested to set a display system at the tally room (tunnel access control points) for display of confined space e-permit. This system can not only display the e-permit, but also the air monitoring dashboard, entering counting etc. (Figure 4).

In practice, although e-permit is in use, the Labour Department also checks the paper permit. Two regulations should be unified.

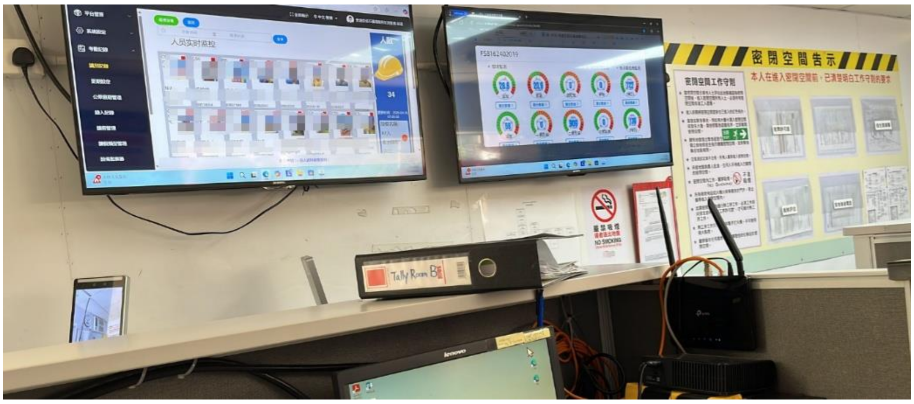

Figure 4. *Arrangements in Tally Room.*

3.1.3. Smart Monitoring Device for Workers and Frontline Site Personnel

Smart monitoring devices, which detect the location, health conditions (body temperature, heart beat etc.) and standstill, including but not limited to smart wristband and/or smart helmet, should be provided to every worker and frontline site personnel.

As the cost of a monitoring device is relatively high, service life and reusability which may affect the total cost should be taken into consideration. Thus, smart watches are the most recommended gears for tunnel workers as they are easy for collecting back and reuse. Watches are usually distributed to personnel for daily wear and keep; or distributed in the tally room (tunnel access control points) after tag in for registration, and collected back after personnel exiting tunnel.

Watches can be classified by the locating method, including GPS, LoRa, or Bluetooth. Due to the inability to receive GPS signals inside the tunnel, Lora watches were initially used in one of the projects. Zoners needed to be installed inside tunnel for locating watches, which need uninterrupted power supply, making it inconvenient for use.

In the latest practice, GPS watches with Bluetooth were introduced to another tunnel project, which only required installation of Bluetooth beacons. The beacons would be installed every 25-50 meters inside tunnels for locating watches, and are equipped with batteries, which can last over 1 year. Instead of demolishing the whole LoRa zoners for maintenance, users only need to replace Bluetooth beacons by a new one and reconnected to the CMP, saving a lot of time and cost (Figure 5).

Figure 5. *Zoner of LoRa Watches and Beacon of Bluetooth Watches.*

As requested by the Mines Division, Geotechnical Engineering Office of Civil Engineering Development Department of HKSAR, mobile phones and other communication devices are prohibited within 15 m of the explosives. Thus, blast engineers, shotfirers, miners and other staff related to blast works are not allowed to wear watches. This has resulted in a place where the regulations violate each other. In practice, for safety reasons, relevant site staff are not distributed with watches while carrying our blast works.

3.1.4. Confined Space Monitoring System – Tag in /out System

The purpose of tag in / out system is to prevent staff from randomly entering or exiting the confined space area, which may affect daily blast works as evacuations with people counting are required.

Site staff with Certificate of Certified Worker under Section 4(1) of the Factories and Industrial Undertakings (Confined Spaces) Regulation (HKSAR Government, 1999) or other regulations such as the Safety Supervision of Work in Confined Space (Drainage Services Department, HKSARG, 2021), are given tunnel tags for punching. In practice, information such as the expiration of certificate and photo of site staff should be input to the card, preventing unqualified staff from entering the tunnel area (Figure 6).

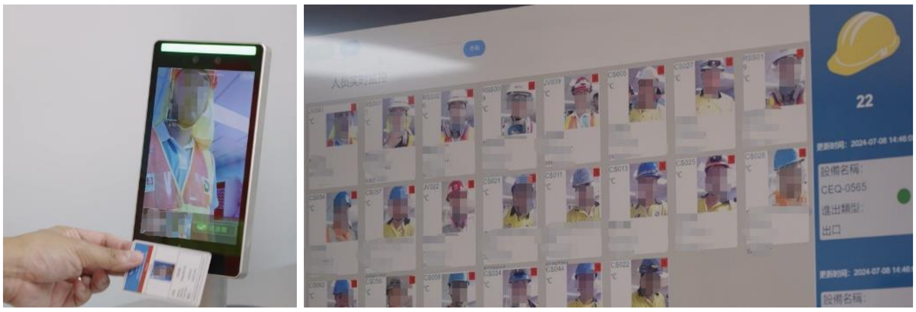

Figure 6. *Tag in /out System at Tally Room.*

3.1.5. Confined Space Monitoring System – Air Monitoring System

Air monitoring system detects oxygen, carbon monoxide, carbon dioxide, hydrogen sulfide, methane, combustible gas, temperature, humidity etc. As this system highly relies on sensors, regular maintenance should be arranged to retain the accuracy. As the sensors are quite expansive and installed in tunnel at fixed locations, protections such as metal cases should be installed to prevent the sensors from being damaged from flying rocks generated by blasting (Figure 7).

In practice, as the air monitoring system are not installed close to blast faces, manual air tests are still vital for the renew of confined space permit. The air monitoring system may only be a reference at current stage.

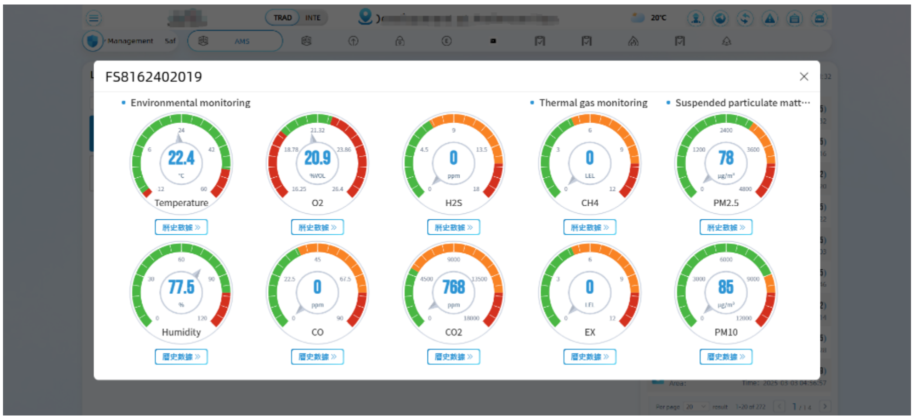

Figure 7. *Air Monitoring System Dashboard.*

3.2. 5G, Wi-Fi and IoT for Tunnel under Construction

As excavation progresses deeper, network connectivity within the underground space deteriorates significantly. Many projects encounter this issue, yet due to cost considerations, dedicated network infrastructure is often not deployed.

To facilitate communication between the tunnel interior and exterior, provide network connectivity for smart devices, and establish an IoT (Internet of Things) system for interconnected equipment, the project / research team progressively installs 5G/Wi-Fi base stations in alignment with tunnel blasting progress in two tunnel projects. This approach aims to achieve near-complete coverage of the under-construction tunnel space. These two tunnel projects are also the first two projects applying 5G/IoT inside tunnel during construction (Figure 8).

Once the base stations are operational, on-site personnel can maintain uninterrupted internet access and communicate with external colleagues via voice calls. Additionally, network-dependent devices within the tunnel (such as e-locks, watches, air monitoring system, etc.) can establish real-time connections to the central control platform and transmit alarm signals when necessary.

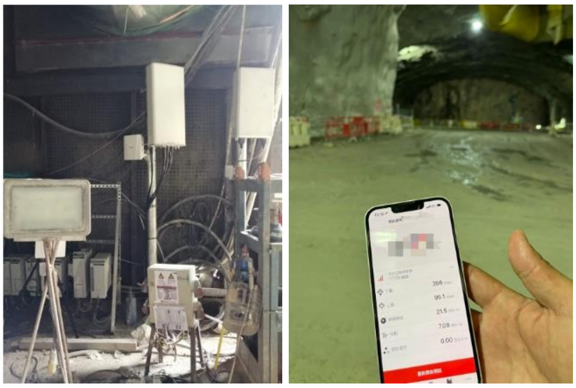

Figure 8. *5G / Wi-Fi Stations and Test.*

4. RESPONSIBILITIES AND ACTIONS BY SITE STAFF

As mentioned in Section 2 of this paper, former study had found that the responsibility of 4S management tended to be unclear and confusing. To enhance efficiency of 4S management, project / research team develop and assign responsibility to individuals including site top management, site safety team, site engineers, site frontlines, electricians etc. to better fulfill the safety regulations and 4S contract requirements.

4.1. Responsibility

4.1.1. Site Top Management

(1) Assigning competent persons for confined space management and 4S management;
(2) Ensure and arrange all resources for 4S;
(3) Liaise with related parties on the implementation of 4S, propose to the client / employer / project manager new 4S products for possible instructions.

4.1.2. Site Safety Team

(1) Lead 4S implementation, maintain daily functions and products;
(2) Supervise 4S operation of other site staff;
(3) Enhance safety management by organizing unsafe act workshops, regular safety education etc. as per assisted by 4S information;

4.1.3. Site Competent Personnel

(1) Supervise 4S operation of subcontractors according to respective sections;
(2) Report to site safety team for instruction on any issue related to 4S;

4.1.4. Electricians

(1) Maintain 4S products including CCTV, e-locks, air monitoring system according to instructions of safety team;
(2) Only registered electricians assigned by site top management is eligible for opening e-locks.

4.2. Actions to Emergencies detected by 4S in Tunnel

4.2.1. Alerts from Workers by Watches

Alerts are automatically generated when exceeding thresholds of worker's health index, or triggered by pressing the button by a worker over 3 seconds for an SOS (Figure 9).

Site safety team receives any alert from watches immediately by notification from CMP or phone message. Site safety team will contact the worker immediately for condition checking, and contact frontline in charge to find and check the condition of the worker according to the location displayed on CMP.

Figure 9. *SOS Sending by Worker.*

4.2.2. Alerts from AI CCTV

AI CCTV are automatically triggered when personnel are detected not wearing personal protection equipment properly, entering restricted area, or being too close to a vehicle etc.

Site safety team receives any alert from AI immediately by notification from CMP or phone message. If it is a true alert, site safety team will contact the frontline in charge to remind relevant persons, site safety team may also contact the person directly if recognized. No matter which situation, name of the person involved will be recorded for further education (Figure 10). If it is a false alert (usually appears when the helmet is block from the camera by umbrella, or fail to recognize the reflective tape on shirt), site safety team will mark the alert as "false alert" on CMP.

Figure 10. *Unsafe Act Detected by AI CCTV and Further Safety Education.*

4.2.3. Alerts from Air Monitoring System

Air monitoring systems are automatically triggered when related gas are detected exceeding thresholds.

Site safety team receives any alert from AI immediately by notification from CMP or phone message, and contacts the frontline in charge to remeasure gas inside tunnel using CP/CW handheld gas meter (Figure 11). Frontline in charge will reply to site safety team if the alert is true or false warning. If the alert is true, evacuation is to be conducted until the condition turns back to normal; if false, site safety team will mark the warning as "false alert".

Figure 11. *Site Safety Team Reminding Frontline for Manuel Check in Tunnel*.

5. CHALLENGES ENCOUNTERED DURING TUNNEL 4S IMPLEMENTATION

In the process of promoting the implementation of 4S, challenges arise from various aspects, primarily including human factors, environmental factors, and management factors.

5.1. Human Factors

Human factors constitute the most significant influencing elements to implementation, primarily include usage willingness, enforcement compliance, and work convenience.

5.1.1. Usage Willingness

Most site staff (whether from main contractor or sub-contractors) initially experience a period of adaptation when the 4S system is first implemented. Research/project team summarized from two main tunnel projects (one commenced for three years and the other for one and a half years) that it is particularly evident in the use of health monitoring watches—over 70% of the workers fail to develop the habit of wearing watches during work (Figure 12); Meanwhile, while watches can be distributed and collected at tally rooms (tunnel access control points), monitoring workers operating outside the tunnel area remains challenging. This presents a natural disadvantage compared to building projects, where work zones are more easily controlled.

Figure 12. *Low Wear Rate of Watches.*

Additionally, the use of AI Machinery 360° Cameras, equipped with audible-visual alarms (triggering 100-decibel alerts to warn nearby personnel), leads to mental fatigue for operators due to repeated alarm exposure. Consequently, many operators deliberately deactivate the devices (Figure 13).

Figure 13. *Unplugged Devices by Plant Operators.*

5.1.2. Enforcement Compliance

Full implementation can generally be ensured within the main contractor’s internal workforce. However, since the mandatory adoption of 4S in Hong Kong is relatively recent, many subcontract contracts lack explicit clauses on 4S compliance, resulting in enforcement difficulties. Currently, this research/project team primarily rely on positive reinforcement, such as monthly "Safety Star" awards for workers with high device usage rates.

5.1.3. Work Convenience

Certain tasks—such as those performed by registered shotfirers and blasting engineers (who handle explosives and must avoid electromagnetic interference)—prohibit the use of wearable devices. Moreover, trades like shotcrete operators, rebar tiers, and form workers require extensive wrist movement, making smartwatch wear highly impractical during operations.

5.2. Environmental Factors

Environmental factors are the most critical determinants affecting product durability and cost control, including operational environments and maintenance environments.

5.2.1. Operational Environments

A representative case involves AI Machinery 360° Camera. Plants (especially excavators) are particularly prone to collisions during rotational movements, often resulting in detached or lost AI cameras and audible-visual alarms (Figure 14). These incidents lead to unpredictable replacement costs, compelling management to develop enhanced protective measures.

Figure 14. *Damage of Cameras Caused by Operation.*

Another case happens with health monitoring watches. The research/project team identified a significantly higher watch damage rate among shotcrete operators compared to other trades, with device lifespans rarely exceeding two months of continuous use. Post-failure analysis revealed that all damaged watches were fully encrusted with concrete slurry, and internal inspection confirmed moisture ingress—a finding consistent with the humid, slurry-intensive working conditions characteristic of applying shot concrete. This phenomenon poses substantial challenges for cost management and equipment sustainability.

5.2.2. Maintenance Environments

Tunnel blasts generate flying debris while producing substantial hazardous gases and dust. This necessitates robust external casing for air monitoring instruments to protect internal electronic components, along with frequent filter replacements. However, the exact quantities of replacements are difficult to predict due to the unpredictable nature of blasting damage. Consequently, accurately estimating these costs during the bidding phase remains challenging. In practice, this research/project team make close coordination with Clients and Project Managers to optimize equipment placement—ensuring data validity while minimizing damage risks.

5.3. Management Factors

Management factors may contribute to false alarms, escalated management costs and damaged devices.

5.3.1. False Aerts

The AI CCTV for restricted area monitoring requires precise demarcation of restricted zones at the post-processing layer. However, as construction progresses, CCTV cameras frequently require realignment or relocation. When restricted zone parameters are not updated timely, false alarms will be tremendously generated, which have a significant increase in security team workload, and deterioration of clients / employers / project managers relations.

5.3.2. Management Cost

The implementation of the 4S system in tunnel construction generates substantial daily alerts across multiple monitoring domains, including gas detection, AI detection, and personnel monitoring, all of which necessitate prompt response and resolution. As the principal oversight entity, the Safety Department is tasked with dual responsibilities: (1) acquiring operational proficiency of 4S, and (2) maintaining continuous system monitoring through dedicated full-time personnel who serve as the primary liaison with Clients and Project Managers. From a cost perspective, the employment of a full-time Assistant Safety Officer (typical monthly remuneration: HKD 18,000 – 22,000) represents a significant long−term financial commitment. For a 5−year tunnel project, this position contributes over HKD 1 million in additional labor expenditures. Contractors must incorporate these anticipated costs during the project planning and budgeting phases to ensure adequate resource allocation.

5.3.3. Damaged Devices

During the use of Smart Locks, regular charging is required to maintain functionality. However, due to the extensive area of the tunnel project, inspection oversights occasionally occur, leading to situations where electronic locks are completely drained and rendered inoperable.

A critical incident arose when a circuit breaker inside tunnel tripped, and the Smart Lock securing the electrical cabinet had depleted its battery, preventing access. This occurred during an urgent situation requiring immediate power restoration for scheduled blasting operations. Without notifying the project / research team, the subcontractor resorted to cutting the electronic lock using hydraulic shears to expedite repairs (Figure 15). This ad-hoc intervention resulted in financial losses and subsequent disputes between the involved parties.

Figure 15. *Damaged E-locks by Workers for Power Repair.*

6. CONCLUSION

This paper introduces the implementation of 4S in Hong Kong tunnel engineering based on two major tunnel projects under construction. Requirements for tunnel engineering and 4S in tunnel engineering were firstly summarized according to the government's regulations, and the practices of this project / research team in actual projects were introduced.

This paper then summarizes the corresponding product selection based on the 4S functions that need to be met, combined with the actual situation of two tunnel projects under construction. Understandings of the required implementation functions and related configurations for some tunnel specific functions and products (CMP, worker health monitoring, tag in / out system, and air monitoring device, etc.) are proposed, and elaborate on the ways to cover 5G / Wi-Fi network communication and IoT in the tunnel under construction to ensure the smooth use of 4S products in the tunnel.

To make clear of the responsibility of different staff in the operation of 4S, this paper described the work distribute based on actual project management, and standardizes the measures that different site staff shall take when different alerts occur, in order to improve relevant management efficiency.

At last, the project / research team summarizes the main problems encountered in actual management from three aspects: human factors, environmental factors, and management factors:

(1) For human factors, suitable and effective solutions for enhancing the use rate of 4S products are not yet found and applied, as they are the most complex factors and greatly affect the outcome of implementation. Design of the products may focus more on the experiences of users, and management methods should be negotiated and agreed upon with subcontractors from the beginning for effective management.

(2) For environment and management factors, contractors may focus more on the potential extra cost and make reasonable estimation on the tendering stage, to avoid unexpected situations of insufficient management manpower and budget.

7. ACKNOWLEDGMENTS

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