

# Advancing Geotechnical Resilience with the Smart Surface Drainage Monitoring System

Raymond P. H. LAW, Jeffrey C. F. WONG

*Geotechnical Engineering Office, Civil Engineering and Development Department, HKSAR Government*

C. H. CHENG, H. LAM

*Logistics and Supply Chain MultiTech R&D Centre*

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## ABSTRACT

The Smart Surface Drainage Monitoring System (SSDMS) is a pilot project developed by the Geotechnical Engineering Office (GEO) of the Civil Engineering and Development Department (CEDD) in collaboration with the Logistics and Supply Chain MultiTech R&D Centre (LSCM). Initiated in early 2023, with site trials commencing in mid-2023, the SSDMS aims to enhance surface drainage maintenance and improve the management of landslide risks associated with extreme rainfall events. During Hong Kong's record-breaking rainstorm in September 2023, the SSDMS successfully detected drainage blockages at one of the trial sites, effectively demonstrating its capability in supporting slope safety management. This system integrates ultrasonic sensors, laser sensors, water-triggering sensors, and verification cameras to provide continuous, real-time monitoring of drainage conditions. Collected data is transmitted via the Government Wide IoT Network (GWIN) or Narrowband Internet of Things (NB-IoT), enabling rapid maintenance responses through a dedicated web application and API. Ongoing enhancements include refining sensor detection algorithms, incorporating artificial intelligence (AI) to further reduce false alarms, and optimizing hardware designs to facilitate easier installation and improved reliability.

## 1 BACKGROUND

Hong Kong is characterized by its complex topography, dense urban development, and subtropical climate, which together pose unique geotechnical challenges. Over the past several decades, the GEO of the CEDD has successfully established and continuously enhanced a robust slope safety system. This comprehensive system includes stringent geotechnical controls, rigorous engineering standards, and regular preventative maintenance programs, all of which have significantly reduced the risk of slope failures. As a result, Hong Kong is widely recognized internationally for its proactive and effective slope management strategies.

One critical element of Hong Kong's slope safety management strategy is its extensive surface drainage infrastructure, including U-channels, surface channels, and other drainage provisions. These drainage systems play a crucial role in intercepting and diverting surface runoff away from slopes, minimizing infiltration into the soil and reducing potential landslide hazards. For government slopes, regular inspections and maintenance operations are conducted by government maintenance teams, systematically clearing debris and ensuring that drainage channels maintain their designed functions.

However, ongoing global climate trends indicate a potentially increasing frequency and intensity of extreme weather events, with rainfall patterns becoming more intense and less predictable. One example is the record-



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breaking rainstorm in Hong Kong in September 2023. During this severe weather event, extreme rainfall intensity resulted in significant runoff that rapidly mobilized substantial quantities of vegetation and debris. Under such unforeseeable and exceptional storm conditions, drainage channels may experience rapid accumulation of debris, potentially leading to blockages that are difficult to detect and manage through periodic manual inspections alone. Such challenges highlight the importance of real-time monitoring solutions, as demonstrated by recent IoT-based drainage monitoring initiatives (Gawali et al., 2024).

Recognizing these evolving challenges, GEO proactively initiated the SSDMS project in early 2023. Jointly developed with the LSCM, the primary objective of this project is to complement current practices for inspecting and maintaining surface channels, ensuring that Hong Kong's slope management strategies remain future-proof and capable of addressing emerging threats posed by climate change. The SSDMS leverages state-of-the-art IoT technology, integrating specialized sensors capable of continuous, real-time monitoring of critical drainage systems. This innovative approach enables rapid detection and notification of drainage blockages and related issues, which allows for proactive and targeted maintenance interventions, a method increasingly adopted internationally to enhance drainage management (Diamse et al., 2023).

## 2 INTRODUCTION OF THE SSDMS

The pilot SSDMS integrates multiple sensing technologies, including water-triggering sensors, ultrasonic depth sensors, laser obstruction sensors, and verification cameras. Each sensor type serves a distinct purpose: water-triggering sensors activate the monitoring system upon initial water detection, ultrasonic sensors provide accurate measurements of water depth within drainage channels, laser sensors detect physical blockages, and verification cameras offer visual confirmation to reduce false alarms. Sensor data is transmitted wirelessly through the GWIN or NB-IoT, as well as LTE network for camera images, which facilitates rapid response from relevant maintenance teams. This multi-sensor integration aligns with recent research advocating sensor-based methods for drainage blockage detection (Narayana et al., 2023).

### 2.1. Water-triggering sensors

These sensors operate using a dual-float mechanism. As water levels rise within the drainage channel, the first float is lifted, triggering an initial response. If the water level continues to increase and reaches a critical threshold, the second float is activated, triggering the sensor. This activation enhances the system's measurement frequency and prompts image capture, which ensures timely and effective detection of potential drainage issues.



Plate 1 Water Triggering Sensor

### 2.2. Ultrasonic depth sensors

Ultrasonic sensors measure water depth by emitting high-frequency sound pulses toward the water surface within the drainage channel or catchpit. When these sound waves encounter the water surface, they reflect back to the sensor's receiver. By calculating the time interval between pulse emission and echo reception, and using the known speed of sound in air, the sensor accurately determines the distance to the water surface. The ultrasonic sensors used in SSDMS have an operational range of up to 7 meters. By comparing these measurements with the known dimensions of the channel or catchpit, the system can precisely assess water levels, enabling early detection of abnormal increases that may indicate downstream blockages.

Performance During Extreme Weather:

During the extreme rainstorm in September 2023, the ultrasonic sensors consistently delivered reliable performance despite the challenging conditions. While minor acoustic interference was observed, primarily caused by heavy splashing and turbulent flow, these effects only led to brief fluctuations in depth readings. Importantly, these anomalies did not result in any false alarms or incorrect system triggers.



Plate 2 Ultrasonic Depth Sensor

2.3. Laser obstruction sensors

Laser obstruction sensors installed within the SSDMS utilize infrared laser beams projected sub-horizontally along the length of drainage channels. Under normal, unobstructed conditions, these beams reflect from the channel structure to a receiving photodiode, enabling real-time distance measurement.

When obstructions such as debris, vegetation, or sediment accumulate, the laser reflects from the nearer obstacle, resulting in a shortened measured distance. By comparing these measurements against baseline values, the SSDMS rapidly identifies and locates potential blockages.

Performance During Extreme Weather:

Laser sensors were observed to be more susceptible to signal interference during periods of intense rainfall and fog, primarily due to attenuation and scattering of the laser beam. While these fluctuations fortunately did not trigger any false alerts during the trial period, the possibility of false positives under similar extreme conditions cannot be entirely ruled out. To address this, the project team is actively developing algorithmic filtering and data smoothing techniques to minimize the impact of adverse weather on sensor performance and ensure more reliable blockage detection.



Plate 3 Laser Obstruction Sensor

#### 2.4. Verification cameras

The SSDMS is equipped with digital cameras integrated with night vision capabilities and a solar power system. Upon receiving alerts from other sensors (i.e. water-triggering, ultrasonic, or laser sensors), the camera automatically activates and captures images of the monitored area. These images are transmitted wirelessly via the LTE network to the monitoring platform, allowing operators to visually confirm or dismiss alerts as necessary. This visual verification process significantly reduces false alarms, enhances decision-making accuracy, and assists maintenance teams in preparing targeted and effective clearance actions, consistent with findings from recent studies on automated visual blockage classification (Iqbal et al., 2021).



Plate 4 Verification Camera

#### 2.5. Data processing and alert system

When sensors detect a potential blockage event, the measurement period for the sensors is increased, and the gathered sensor and camera data are continuously transmitted to a designated cloud server, where specialized algorithms analyze the information in real-time. These algorithms evaluate incoming sensor readings against predefined thresholds or patterns to identify potential drainage blockages or other abnormal conditions, similar to automated alert systems described by recent IoT monitoring research (Gawali et al., 2024; Suhail et al., 2023). When sensor data indicates an issue, the SSDMS immediately transmits an alert to GEO's dedicated web application for an initial false alarm verification. If the alert is determined to be valid, the system forwards the information to relevant maintenance teams for further review and necessary action. This streamlined process ensures that only genuine issues are escalated, minimizing unnecessary interventions while maintaining an efficient response system.

### 3 SITE TRIALS

Following the completion of the initial system development in mid-2023, the first-generation SSDMS prototypes were installed at selected trial sites across Hong Kong, marking the beginning of the site trial phase. This phase aimed to evaluate the system’s performance and feasibility under real-world conditions. The selection of trial sites was guided by two general considerations. First, comprehensive GWIN coverage was preferred to ensure reliable wireless data transmission and real-time monitoring capabilities. Second, sites were strategically chosen based on assessments indicating potential susceptibility to blockage risks.

Currently, SSDMS prototypes have been installed at several selected locations, including slopes above Lung Cheung Road, Shek O Road, Sui Wo Road, and a slope at Ho Man Tin. In addition to monitoring traditional U-channel drains, the system has also been deployed at one catchwater location. This trial deployment on catchwater aims to enhance monitoring of overflow conditions, particularly given recent experiences indicating that catchwater overflow during extreme rainfall events can lead to increased landslide risks. Accordingly, SSDMS units have been strategically installed at catchwater overflow weirs to evaluate their effectiveness in detecting overflow conditions and potential blockage issues under varying weather scenarios.

The SSDMS prototypes have now been operational at these trial sites for over a year and continuously collecting monitoring data across different weather conditions and seasons. Notably, during this trial period, the SSDMS was subjected to a real and significant test: the record-breaking extreme rainfall event that impacted Hong Kong in early September 2023 (the sensors installed above Shek O Road and the catchwater above Yiu Hing Road were installed after the rainstorm and were not part of this particular test.). At one of the trial sites (Fo Tan), the SSDMS successfully detected an actual blockage event within a monitored U-channel and the collected data is presented in Plate 5. The blockage, caused by a substantial accumulation of vegetation and sediment mobilized during the intense rainfall, was promptly identified through real-time sensor data and visually verified by the integrated verification camera. This demonstration provided valuable validation of the SSDMS’s effectiveness and communication reliability under extreme storm conditions.

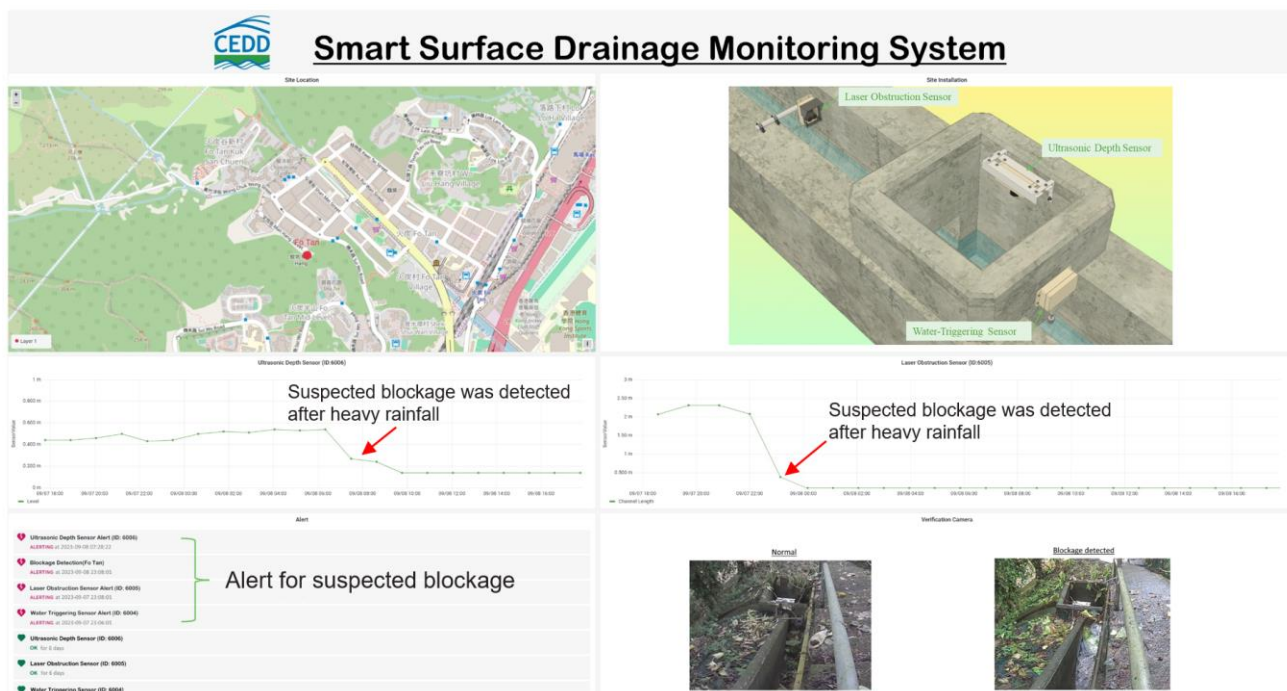


Plate 5 Monitoring platform showing actual blockage detected at U-Channel



Plate 6 Image Captured by the Verification Camera

#### Performance Summary During Trial:

##### Wireless Data Transmission:

During the testing site selection process, it was observed that obstructions commonly found in densely populated urban areas present a significant challenge to wireless communication. High-rise buildings and other physical barriers can interfere with signal transmission, reducing coverage and compromising communication reliability. Additionally, severe weather conditions such as heavy rainfall further exacerbate these challenges. During the trial period, several data packet losses were recorded during periods of intense rain, indicating that wireless communication between sensors and the server was affected. These findings highlight the need for ongoing development of weather-resilient and high penetrating communication solutions to further enhance the performance.

##### Power Management:

The SSDMS sensors are powered by non-rechargeable batteries, offering a cost-effective solution for IoT system deployments. While each battery can support up to two years of standard operation, battery replacement becomes a time-consuming and labor-intensive process when the system is deployed at scale. To mitigate this limitation, improvements in power management strategies should be prioritized to extend sensor lifespan and minimize maintenance requirements.

## 4 ONGOING ENHANCEMENTS

##### Sensor Miniaturization:

Drawing from valuable practical experience and insights accumulated during the ongoing site trials, the SSDMS is currently undergoing continuous enhancements to further improve its effectiveness, adaptability, and resilience. One primary area of enhancement involves the miniaturization and adaptation of sensors specifically tailored for constrained drainage environments. By reducing sensor dimensions and refining their physical profiles, the enhanced SSDMS will be better suited for installation in narrower or more space-restricted drainage channels.



Plate 7 Miniaturized Laser Obstruction Sensor

**Power Management Improvement:**

Another critical area of ongoing enhancement is optimizing power supply configurations to improve overall energy efficiency. This involves integrating solar energy harvesting technologies along with rechargeable battery modules that feature an automatic power detector and switch within the system design. The switch will manage the power source, alternating between a high-capacity non-rechargeable battery and a solar battery. Such enhancements will significantly extend battery life and reduce maintenance frequency, making the system suitable for remote locations or areas where frequent manual servicing is challenging.



Plate 8 Solar Powered Sensors

In addition, considerable effort is being invested in refining sensor detection algorithms. By analyzing extensive data collected during the trials, the project team aims to enhance the precision of detection algorithms, thereby substantially reducing the frequency of false alarms.

**AI-driven Feature for Verification Camera:**

The verification camera system is also being upgraded to address practical challenges identified during field trials. Improvements include enhanced camera housing designs for increased durability in harsh environmental conditions. Furthermore, AI capabilities are being integrated into the camera system to assist in automated false alarm verification with pattern and feature detection. This AI-driven feature will help reduce the need for manual intervention, particularly during extreme weather conditions, thereby streamlining the monitoring process.



Plate 9 Captured Image with AI for alarm verification during daytime and nighttime

**Enhanced Wireless Communication:**

To address the challenges of wireless communication during severe weather conditions, such as heavy rainfall, a private network utilizing low-frequency signals with high penetration capability will be developed and piloted at several test sites. This low-frequency approach is specifically selected to offer extended coverage and improved reliability, particularly in densely built urban environments and under adverse weather conditions.

## 5 CONCLUSIONS

The SSDMS leverages advanced IoT sensor technologies to deliver real-time, proactive monitoring of slope drainage conditions. By providing continuous and remote assessment capabilities, the SSDMS enhances Hong Kong's slope safety management, especially for slopes adjacent to critical access roads. The system's successful detection and timely reporting of a drainage blockage during the extreme rainfall event in September 2023 validated its practical utility. Ongoing refinements, including sensor miniaturization, robust power management, AI-driven verification, and low frequency communication will further improve its reliability, efficiency, and adaptability. This initiative represents a forward-looking, data-driven approach to geotechnical resilience in the face of climate-related challenges.

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