Development of Pedestrian and Structural Safety Monitoring System for Cable-Supported Pedestrian Bridges

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ABSTRACT

A number of cable-supported pedestrian bridges have recently been constructed or are planned in Korea, primarily by local governments. These structures include cable-stayed and suspension bridges, with or without pylons. Some are intentionally designed to sway. However, the structural behavior of these bridges is not fully understood, and monitoring system have not been implemented, unlike for other road and railway bridges.

This ongoing research involves the development and application of various sensors and monitoring systems to assess pedestrian and structural safety on a representative pedestrian bridge. Long-term monitoring data are being collected to investigate structural behavior and performance.

To measure displacement and movement, a GNSS (Global Navigation Satellite System) was installed at the midspan and anchorage blocks. Using latitude, longitude, and altitude data with RTK (Real-Time Kinematic) correction, sag as well as static and dynamic displacements are calculated in both horizontal and vertical directions. Three-axis acceleration data are used to determine vibration frequencies and damping ratios, revealing the bridge's dynamic characteristics. Additional parameters—such as deck and anchorage inclination, cable temperature, and wind direction and speed—are also monitored to ensure structural safety.

For pedestrian monitoring, camera-based AI technologies are employed to estimate pedestrian loads and detect abnormal behaviors of pedestrians. Object recognition and tracking algorithms estimate the number and locations of pedestrians, while pose estimation combined with LSTM (Long Short-Term Memory) networks detect behaviors such as intentional cable shaking or leaning over railings. All monitoring components are integrated into an IoT system equipped with an embedded AI computing platform.

The results of this research are expected to provide a practical remote monitoring system for pedestrian bridges and serve as a basis for establishing design and evaluation criteria for cable-supported pedestrian bridges.

INTRODUCTION

Several cable-supported pedestrian bridges have been recently constructed or are planned in Korea, primarily by local governments. These structures include cable-stayed and suspension bridges with or without pylons [1]. Some bridges are built to be shaken intentionally. However, the structural behavior of these bridges is not yet fully understood, and the design and evaluation criteria have not been verified [2,3]. Furthermore, monitoring systems for pedestrian and structural safety have not yet been implemented, unlike for other road and railway bridges. This ongoing research develops and applies monitoring systems with various sensors for both pedestrian and structural safety. These are deployed on a representative pedestrian bridge. Then long-term monitoring data are collected to investigate the behavior and performance of the bridge.

For structure monitoring system, to find the displacement and location movements, IoT system equipped with GNSS (Global Navigation Satellite System) were developed and installed on midspan and anchorage block. From the latitude, longitude and altitude data with RTK (Real-Time Kinematic) calibration, sag as well as static and dynamic displacements can be calculated in both horizontal and vertical direction. Acceleration data have been collected in three directions and used to calculate the vibration frequencies and damping ratios revealing the dynamic characteristics of the bridges. Additional parameters such as inclination of the deck and anchorage, cable temperature, wind direction and speed are also collected to be used for structural safety monitoring.

For pedestrian monitoring, camera-based AI technologies are used to estimate pedestrian load and detect abnormal behaviors of pedestrians. Object recognition and tracking algorithms estimate the numbers and locations of pedestrians. Pose estimation with LSTM (Long Short-Term Memory) algorithms are used to detect abnormal behaviors such as intentional shaking of the cable, leaning over the railings and so on.

TYPES OF CABLE-SUPPORTED PEDESTRIAN BRIDGES

Cable-supported pedestrian bridges can be broadly categorized into two types: cable-stayed bridge and suspension bridges [1]. Suspension bridges can be further classified into two subtypes: those with pylons and those without, as shown in Figure 1. The type with pylons resembles conventional suspension bridges used for roads or railways. In contrast, suspension bridges without pylons often have segmented deck frames with minimal longitudinal stiffness. This configuration can lead to significant swaying motions, characterized by vertical and lateral vibrations induced by pedestrians. When designing or evaluating swaying pedestrian bridges, several structural characteristics must be considered, including sag, static and dynamic displacement (both vertical and lateral), deck acceleration, natural frequencies, damping ratios, anchorage movement or inclination, as well as environmental factors such as wind and temperature.

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PROPOSED MONOTORING SYSTEM FOR CABLE-SUPPORTED PEDESTRIAN BRIDGES

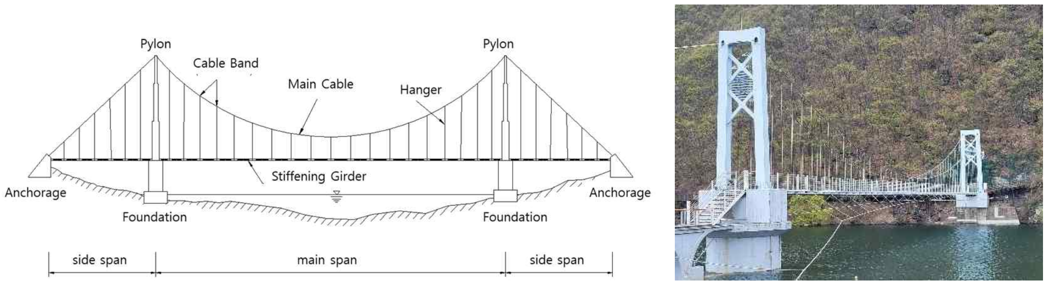
Large-scale monitoring systems are typically installed on long-span cable-supported road and railway bridges, involving high-end sensors, real-time monitoring and on-site maintenance office. However, swaying pedestrian bridges are generally simpler in structure and smaller in scale. Their low construction and maintenance budget make large-scale systems impractical. Additionally, space constraints on these structures limit the installation of sensors and related equipment.

Therefore, a low-cost, lightweight, and wireless monitoring solution is more appropriate for small-scale cable-supported pedestrian bridges. Due to the swaying motion of the bridge, pedestrian safety is another concern to the owner. In this study, separate systems for pedestrian and structure monitoring are developed and integrated into a single IoT-based platform.

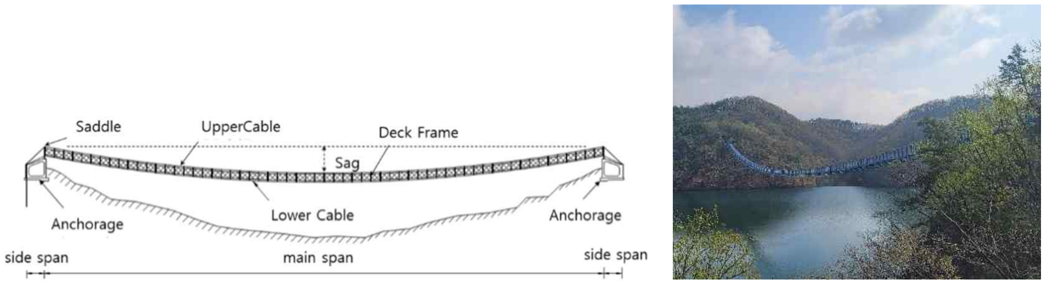
Pedestrian Monitoring System

Pedestrian monitoring system utilizes camera-based AI technologies and performs three main functions. (1) pedestrian counting using object tracking, (2) spatial localization for pedestrian load estimation, and (3) detection of abnormal behaviors using pose estimation and LSTM network.

For real-time pedestrian tracking, the pedestrian monitoring system integrates YOLO (You Only Look Once) [4] and SORT (Simple Online and Realtime Tracking) algorithms. YOLO is a single neural network-based method that divides an input image into a fixed number of grids and simultaneously predicts the object presence, bounding



(a) Suspended cable bridge with pylons



(b) Suspended cable bridge without pylons

Figure 1. Types of suspended cable pedestrian bridges

box coordinates, and class probabilities. SORT is a lightweight algorithm for real-time multiple object tracking. It predicts the state of detected objects using a Kalman Filter and optimizes frame-to-frame object matching through the Hungarian Algorithm. By combining these two algorithms, a unique ID is assigned to each pedestrian, enabling the tracking of the same object across consecutive frames (Figure 2). When an object crosses a predefined virtual line in the video, it is classified as an in or out event, enabling the system to monitor both the total number of pedestrians and the real-time occupancy on each zone of the bridge. Moreover, ID-based tracking prevents duplicate counting of in/out events.

Identification of pedestrian location is also performed using YOLO. By aggregating the center points of detected bounding boxes, the number of pedestrians per bridge zone is estimated. Temporal movement analysis enables estimation of pedestrian walking speed and direction. Special attention is given to bounding boxes near zone boundaries to avoid misclassification.

Abnormal pedestrian behavior detection uses pose estimation and LSTM networks [5]. Pose Estimation extracts key joint coordinates to reconstruct body posture, while the LSTM network models temporal joint sequences to classify actions. Detected behaviors include abnormal behaviors, including running, jumping, intentional cable shaking and leaning over the bridge structure (Figure 3).

Structure Monitoring System

To monitor structural behavior, multiple sensors are integrated into an IoT-based system. GNSS sensors measure displacement, including sag and both static and dynamic displacements, at the midspan and anchorage blocks. Accelerometers capture vibrations in three axes, allowing for the calculation of natural frequencies and damping ratios. External sensors record cable temperatures and wind velocity and direction.

Figure 2. Pedestrian counting scheme using YOLO and SORT.

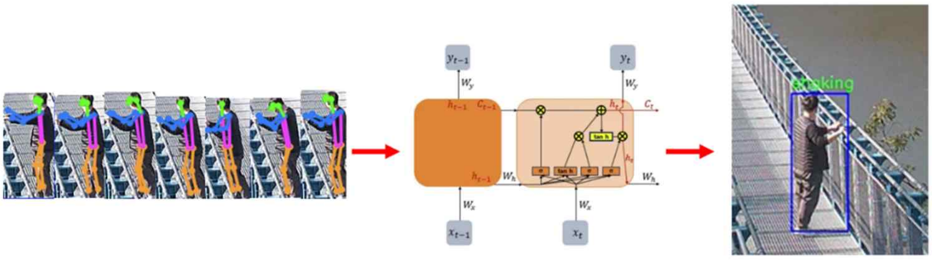


Figure 3. Detection of pedestrian abnormal behavior using pose estimation and LSTM.

The IoT system enables wireless data transmission by Wi-Fi or LTE and supports both wired and solar power supply options. Figure 4 illustrates the full monitoring setup. Two IoT units are installed: one at midspan to measure displacements and accelerations and another at the anchorage to monitor inclination and movement. Pedestrian monitoring system includes three CCTV cameras, a network video recorder (NVR), and an embedded AI computing platform, with each camera monitoring a separate deck zone.

ANALYSIS OF MONITORING DATA

The proposed monitoring system was installed on the Mir309 suspended cable pedestrian bridge in North Chungcheong Province in Korea, as shown in Figure 1(b). Although still in development, preliminary structural performance data have been recorded and partially analyzed to evaluate system effectiveness.

Sag and Vertical Displacement

Sag is defined as the vertical distance between the cable's lowest point and the horizontal line connecting the saddle points at each end. Design document [6] specify a sag of 16.787 m at 20°C. However, initial sag just after the completion of the bridge construction was not recorded. Figure 5 shows sag variation on May 4, 2025, indicating fluctuation during daytime hours due to pedestrian loads and nighttime variation due to temperature and wind. The bridge is open to public from 9 AM to 6 PM. Figure 6 presents 10-minute maxima, minima, and average sag and cable temperature from May 1 to May 7, showing clear correlation. This suggests sag variation may serve as a useful structural health indicator.

Vertical displacement due to pedestrian loading includes both static and dynamic components. Figure 7 depicts vertical displacement and its moving average (representing static displacement) over a one-minute period.

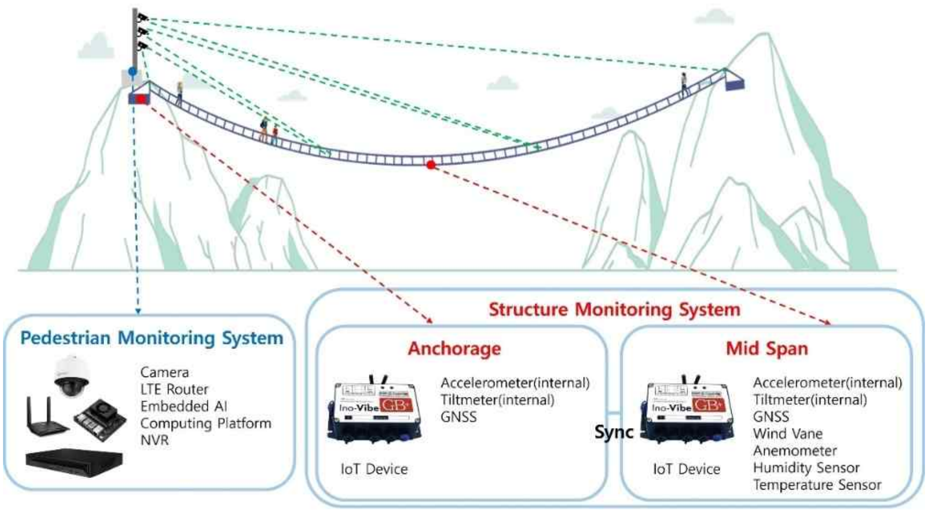


Figure 4. Schematic drawing of pedestrian and structure monitoring system installed on cable-supported pedestrian bridge.

Lateral Displacement

Lateral displacement results from pedestrian movement and wind. Using GNSS latitude and longitude data processed via Vincenty's inverse formula, lateral displacement was calculated. For wind-only effects, comparisons were made between high and low wind conditions during pedestrian-free periods from May 1 to 7. Figure 9 presents lateral displacements in the north-south and east-west directions under varying wind conditions. This data is key to investigating lateral synchronization or lock-in effects.

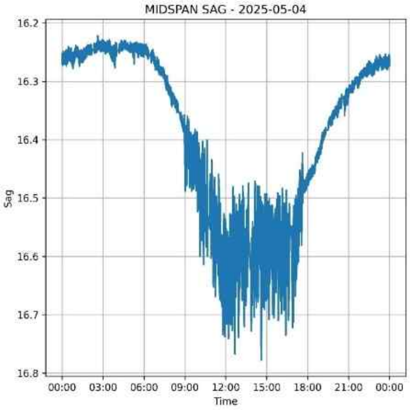


Figure 5. Daily variation of sag on May 4th, 2025.

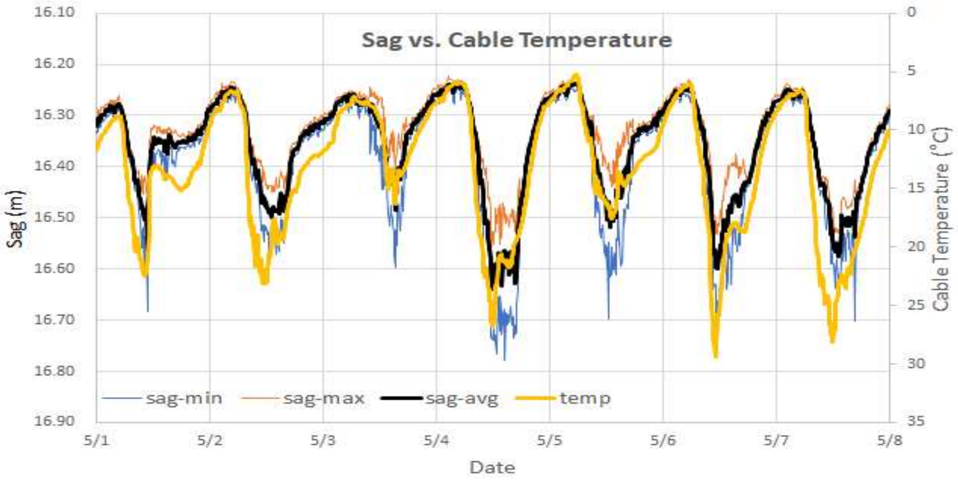


Figure 6. Weekly variation of 10-min min, max, average sag and cable temperature from May 1st to May 7th, 2025.

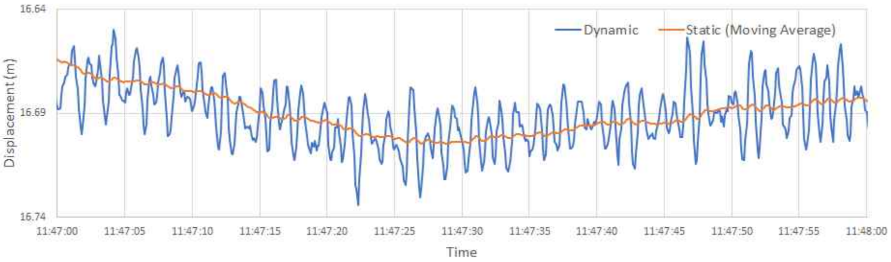
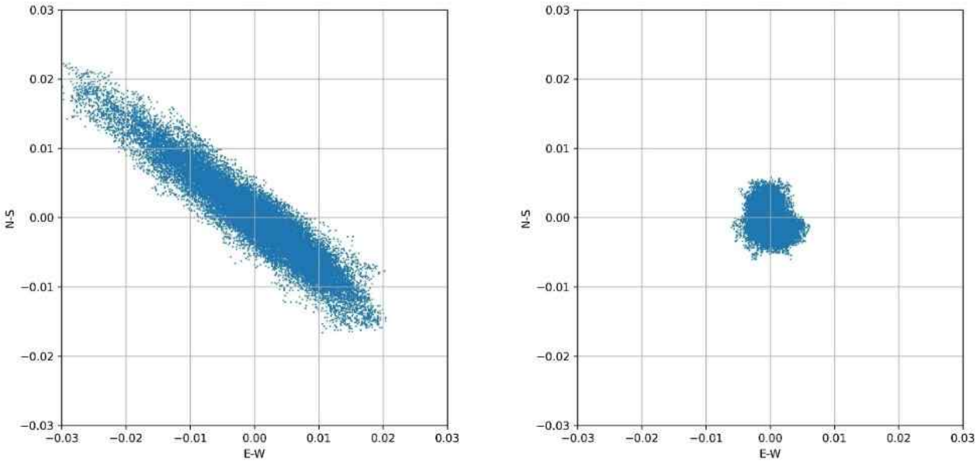


Figure 7. Dynamic and static displacement (moving average) during 1 minute.



$V_h = $ 4.043 m/s $V_h = $ 0.074 m/s

Figure 9. Effect of wind speed on lateral displacement in case of no pedestrians.

Acceleration and Natural Frequencies

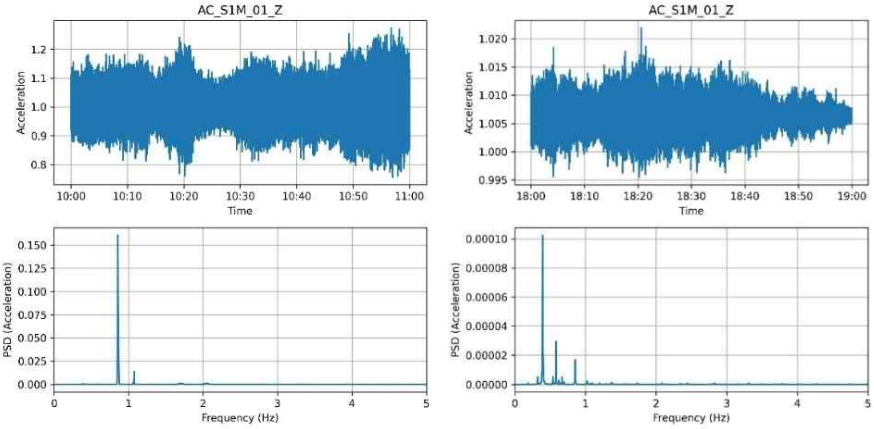
Figure 10 shows vertical acceleration and FFT (Fast Fourier Transform) results under four conditions: (1) high wind with pedestrians, (2) high wind without pedestrians, (3) low wind with pedestrians, and (4) low wind without pedestrians. Pedestrian presence consistently yielded a 0.86 Hz peak frequency, likely representing walking frequency. Under no pedestrian condition, natural frequencies of 0.186 Hz, 0.394 Hz, 0.583 Hz, and 0.854 Hz were observed, closely matching design documents [6].

CONCLUSIONS AND FURTHER STUDY

This study developed and implemented integrated monitoring systems for both pedestrian behavior and structural performance on a suspended cable pedestrian bridge. Long-term monitoring data are collected to investigate the behavior and performance of the bridge. Based on the initial results, the following conclusions can be drawn:

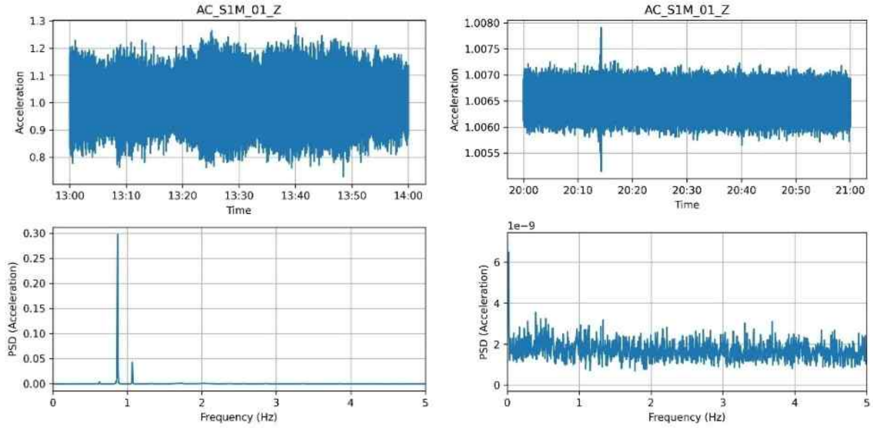
- Sag is a critical indicator of structural integrity and can be effectively monitored with temperature compensation using the proposed GNSS-based system.
- Vertical and lateral displacement, as well as acceleration, are accurately captured, enabling analysis of natural frequencies and dynamic response characteristics.
- The pedestrian monitoring system, currently under field testing, shows strong potential for estimating pedestrian loads and identifying abnormal behaviors in real-time.

As the proposed system remains under development, only partial results are presented in this paper. Continued monitoring and comprehensive data analysis are required to further validate system performance and to establish standardized design and safety evaluation criteria for swaying pedestrian bridges.



Case 1 (2025-5-1 10~11 AM)

Case 2 (2025-5-3 6~7 PM)



Case 3 (2025-5-5 1~2 PM)

Case 4 (2025-5-4 8~9 PM)

Figure 10. Acceleration records and FFT plots.

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