SASBE 2025 aims to encourage the international exchange of innovative ideas between researchers from academia and industry. In addition to knowledge dissemination, the conference offers a valuable platform for professional networking, particularly benefiting university professors, graduate students, and postdoctoral researchers.

Research Article/ Review Article/ Perspective Article (Remove where relevant)

Enhancing Concrete Bridge Inspection with Preventive Maintenance and Data Fusion Techniques for User Safety

Masreta Mohd[1], Rahinah Ibrahim[2], Othman Zainon[3]

Polytechnic Ungku Omar, 31400 Ipoh, Perak, MALAYSIA 1
University Putra Malaysia, 43400 UPM Serdang, Selangor, MALAYSIA 2
University Technology Malaysia, 81310 Skudai, Johor, MALAYSIA 3
Correspondence: masbasri@puo.edu.my

Copyright: Copyright: © 2025 by the authors.

SASBE is an open-access proceedings distributed under the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0).
View this license's legal deed at https://creativecommons.org/licenses/by/4.0/

Abstract

As a critical link between the West Coast and East Coast of Peninsular Malaysia, the Banding Bridge supports thousands of vehicles daily. Persistent structural issues such as cracks and corrosion pose significant risks, endangering lives and disrupting traffic. Urgent advanced inspection and maintenance are necessary to ensure user safety. This study proposes a concrete bridge inspection system utilizing a fusion of GNSS and vibration data to enable the Malaysian road agencies to monitor bridge health. Through visual inspection analysis, the system could identify critical damage such as slab holes and corrosion. Comparing data from the system with the visual inspection data successfully demonstrated the system's effectiveness. The results show a vibration signal of up to 1.0000 m/s recorded in a dataset taken at point KB21 at span 13. A visual inspection rating of 3 indicates that the bridge needs to be improved. These results emphasize adopting advanced technology to enhance bridge health to prevent accidents, causing tragic fatalities. This study contributes to the field by illustrating data fusion as a reliable, evidence-based method for enhancing bridge structural health. The results are expected to encourage Malaysian road agencies to improve visual inspections by adding new tools to provide actionable insights. The comparative data could improve the authority's decision-making and preventive maintenance efficiency. Future research could explore real-time monitoring and predictive analytics to advance bridge maintenance practices further while addressing weaknesses proactively.

Keywords: Concrete bridge inspection, Bridge health, Data fusion technique, User safety, and Preventive maintenance.

Highlights

- Preventive maintenance reduces bridge failures through early issue detection.
- Data fusion improves accuracy in assessing bridge conditions.
- Safer bridges result from combining smart tech with regular inspections.

1 Introduction to the Concrete Bridge Inspection

Due to aging and deterioration processes, bridges must undergo extensive repair and maintenance on a large number of existing bridges that are nearing the end of their service lives. This has enormous social and economic ramifications for many countries. For a logical distribution of the available financial resources at the infrastructure scale, bridge managers and owners must set up effective management practices to prioritize maintenance and rehabilitation operations. An essential tool for bridging condition assessment processes is Bridge health monitoring (Bianchi, S., Capacci, L., Anghileri, M., Biondini, F., Rosati, G., Cazzulani, G., Barindelli, S., & Caldera, S. 2023). A significant building in Malaysia's north, the Sg. Perak Reservoir Bridge is a vital component of the transportation system connecting West and East Coast Malaysia. Given that bridges are frequently traversed by heavy vehicles, maintaining and inspecting them is crucial to extending their lifespan. Visual or manual inspection alone cannot readily identify the invisible damage that causes it. As a result, the primary method of detecting bridge damage is inspection, which is done regularly and is frequently subjective (Fernando, K. S. D. M., Dissanayake, D. M. C. D., Dharmasiri, M. A. K. M., & Dammika, A. J. 2020).

Extreme loads, aging, and rising traffic volumes are the variables influencing bridge serviceability (Xi, R., He, Q., & Meng, X. 2021]. Considering that large trucks use the bridge, inspection and maintenance are crucial to extending its lifespan. In order to measure the vibration on the Sungai Perak Reservoir bridge, the pier is inspected. Vibration is one of the primary causes of bridge damage and is increasingly acting as a causative factor. Unlike forced vibration, ambient vibration has an unregulated load function. Furthermore, it is typically brought on by inadvertent man-made or atmospheric disturbances, such as winds, floods, and passing cars (Bao, T., & Liu, Z. 2017).

Data gathered from a vehicle route census conducted by the Malaysian road agencies throughout the year 2017 provided this information. Wind gusts of up to 70 km/h were recorded during the observation. Heavy traffic loads were possible, particularly during morning and evening rush hours when tidal traffic movements were visible. Because the shoulder of the Sg. Perak Reservoir Bridge is just 1000 cm wide; pedestrians may be at grave risk due to the bridge's fairly ancient construction. Therefore, the technique of acquiring data requires very careful study. Alternative energy sources include wind, human activity, and vehicle traffic, which can cause vibrations on bridges. The strength and frequency of the energy generated determine how well the vibrational effect works. Typically, the vibration energy along the bridge is neither continuous nor continuous (Gaglione, A., Rodenas-Herraiz, D., Jia, Y., Nawaz, S., Arroyo, E., Mascolo, C., Seshia, A. A. 2018).

This study demonstrates how a data fusion strategy, which combines accelerometer and GNSS, can yield a more accurate and comprehensive picture of a bridge's status. Together, inspectors can gather and examine this information to have a better understanding of the structure's performance over time. By immediately informing inspectors of odd changes or possible concerns, a notification system added to the inspection toolset will enhance the procedure even further and enable prompt action before issues worsen. In order to avoid mishaps that could result in tragic deaths, bridge health must be improved. Most significantly, combining these technologies facilitates better decision-making and aids agencies in efficiently prioritizing maintenance requirements. The report recommends that Malaysian road agencies use more contemporary, data-driven techniques that result in safer and more effective infrastructure management, rather than relying solely on visual inspections.

2 Concrete Bridge Inspection Process

2.1 A Fieldwork

For this study, the researchers focused exclusively on the Sungai Perak Reservoir Bridge as the primary site for data collection. A series of observation points was strategically placed along the bridge, with sensors mounted on top of each pier member, as well as in central locations to capture structural responses more effectively. These placements were intended to provide a clearer picture of how the bridge behaves under varying traffic loads. Given that vehicles enter from one end of the bridge and travel to the opposite exit, the team was particularly interested in understanding how the bridge responds to continuous and directional vehicle flow. The observation points—each marked with its precise coordinate played a crucial role in gathering vibration data across the 800 meter-long span of the bridge.

Observations were carried out throughout the day, starting early in the morning and continuing until midday. At each observation point, the team recorded data over several minutes, with some sessions lasting up to fifteen minutes, to ensure accurate measurement of the traffic flow and the bridge's corresponding vibrational response. The data collected on the first day served as a reference point for determining typical vehicle frequency. Based on this preliminary dataset, the researchers identified three key observation periods: early morning, around noon, and again in the early afternoon at approximately 3:00 PM as the most representative times for continued monitoring. However, it's worth noting that high temperatures during the day posed a challenge, often limiting the amount of time researchers could safely remain on the bridge to conduct their fieldwork.

2.2 Description of the Study Area

(Figure 1) shows the Sungai Perak Reservoir Bridge, which was constructed in 1978. Between Gerik and the island of Banding, it crosses Banding Lake and has two car lanes as well as a promenade for pedestrians. Refer to (Figure 2) above, a total of 36 stations have been installed along the dual carriageway bridge route from the First Gerik Bridge on the East-West Highway. On the left side of the bridge, there are 18 stations numbered from 127A to 144A, as shown in Figure 2. Meanwhile, another 18 stations have been placed on the right side, numbered from 101A to 122A.

Figure 1. The Sungai Perak Reservoir Bridge's structure.

Figure 2. 36-point observation on Sungai Perak Reservoir Bridge's

This asymmetrical suspension bridge is 880.52 meters long overall, with 14 spans, the longest of which is 91.46 meters. The carriageway's width is 8.48 meters. Its tower is made of non-reinforced concrete (RC). Initially, area orientation is scheduled as the best time to start and finish the entire observation procedure. The two most crucial elements that must be guaranteed during the orientation are the observer's and the equipment's safety. The monument is situated in a region that can receive more than five satellites and satisfies the requirements of having a minimum satellite with a face angle of 10 degrees and the capacity to track more than five satellites, once it has been shown that the observations can be made efficiently and successfully. The study's focus on this bridge's structure is to examine how the vibration mark changes as a fundamental vibration-based detection method using the dynamic properties of the bridge's physical structure (Aasim, B. A., Sor, M., & Abdul, G. 2020).

2.3 Concrete Bridge

The requirements for gathering data were twofold. First, to gather sufficient vibration data in real-world traffic scenarios so that we can process them offline and power profile our hardware while simulating (Gaglione, A., Rodenas-Herraiz, D., Jia, Y., Nawaz, S., Arroyo, E., Mascolo, C., Seshia, A. A. 2018). The second goal of this study is to conduct an on-site inspection to locate and evaluate the damage to each bridge pier.

To gather data on the pier between the slabs that are parallel to each pier and examined simultaneously using a quick static method, three station locations were established on this bridge and designated for additional observations. Determining the typical behavior of both damaged and undamaged structures is an additional technique in the application of suitable methods for data collecting and analysis.

On October 10, 2019, the area was oriented to identify and organize logistics for conducting observations on the East-West coast Highway in Gerik, Perak, the following day. This marked the beginning of the data collection process for all the base stations. Three (3) base stations were designed, and on October 11, 2019, static method observations were carried out, with four hours of observation at each base station. The observation period lasted from 10:00 am to 3:00 pm. On October 20, 2019, Trimble Business Center software version 3.50 was used to process the base stations. For reference, station data was obtained from the Department of Survey and Mapping of Malaysia (JUPEM) server at www.rtknet3.gov.my/SpiderWeb. The Virtual Reference Station is the reference station that is utilized.

Microsoft ActiveSync is used to download the data, which is in RAW format (T02). Trimble Business Centre 3.50 is used for processing, with a set solution type and a maximum of 10 iterations as the processing criterion. Trimble Business Centre version 3.50 is used to make data adjustments, and the processed and reviewed data is then exported to the Trimble Data Exchange Format (TDEF). During the processing activity, two TDEF files were produced in total. Both are gathered and entered into the program. Three reference stations are used as reference stations in a full constraint with adjustments performed. Without altering the coordinates set in the RINEX, these coordinates have been set and inserted into the RINEX JUPEM data. The Fast Static approach is used to monitor the observed station data following the observation and processing of the control station. The observation must be completed over the course of two days. Both when the bridge is not in use (no vehicles are going over) and during the busiest times of the day, GNSS makes observations. To ensure that each observation post was roughly 250 meters from the others, they were positioned on the road shoulder across the bridge and centered on the pier. Following the modifications, the three primary coordinates of the GDM 2000 and Cassini Geocentric coordinates can generate the final coordinates.

The locations of the three (3) established reference stations, BASE 1, BASE 2, BASE 3, and VRS, are displayed in (Table 1). A Virtual Reference Station (VRS) is the name given to this station. In Malaysia, VRS is a reference station created using JUPEM SpiderWeb. The MyRTK Network Malaysia station, which is open twenty-four hours a day, powers this reference station. There were just three (3) stations used for this observation, and (Figure 3) below shows all of the stations' details.

Table 1. Coordinates of the table reference station.

Station	Latitude	Longitude	Height (m)
Base 1	5° 32' 36.78" N	101° 19' 49.09" E	262.125
Base 2	5° 32' 32.84" N	101° 20' 44.17" E	279.616
Base 3	5° 33' 05.57" N	101° 20' 51.84" E	238.836
VRS	5° 33' 06.26" N	101° 21' 09.24" E	263.536

Figure 3. These Are the CORS Malaysia Reference Stations, Bases 1, 2, and 3.

Four Reference stations, BASE 1, BASE 2, BASE 3, and VRS, were selected for this observation. These serve as Virtual Reference Stations (VRS), which are generated using JUPEM's SpiderWeb system in Malaysia. The VRS is built from data collected by the MyRTK Network, a nationwide system of continuously operating reference stations that run 24/7. This data can be accessed and downloaded from anywhere via the SpiderWeb portal at http://www.rtknet3.gov.my/SpiderWeb/frmIndex.aspx. The files are provided in RINEX format (Receiver Independent Exchange Format), making them compatible with a wide range of processing software. For this project, only four stations were used, and their full details are illustrated in (Figure 4).

Figure 4. Base station at Sungai Perak Reservoir Bridge, Gerik.

2.4 Data Fusion Description – GNSS and Accelerometer

With the use of Global Navigation Satellite System (GNSS) technology, structures and infrastructure facilities can have their three-dimensional displacements monitored for long-term observations of their behavior and damage detection, which helps to guide the planning of the best possible maintenance and management (Bianchi, S., Capacci, L., Anghileri, M., Biondini, F., Rosati, G., Cazzulani, G., Barindelli, S., & Caldera, S. 2023). Since displacement and attitude data offer vital information on the stability and condition of structures, obtaining precise data is crucial for structural health monitoring of large-span bridges. When bridge displacement and attitude are determined in conjunction with the GNSS, possible structural problems can be identified early, and a more efficient maintenance plan is created for well-informed decision-making (An, X., Meng, X., Hu, L., Xie, Y., Zhang, F., & Pan, S. 2025). Accelerometers are primarily utilized in vibration monitoring because of their high data rate. There are a few instances of effective bridge vibration monitoring using GNSS (Schönberger, C., & Lienhart, W., 2024).

To achieve the desired sub-cm accuracy, the location of the GNSS receiver must be positioned towards full-sky visibility to minimize major problems in GNSS surveillance, such as multipath errors, troposphere delays, and limited visibility to satellites. Thus, the accurate positioning of the reference station at the GNSS data acquisition location makes it possible to obtain millimeter-level position information on a short baseline (<10km) (Bazanowski, M., Szostak-Chrzanowski, A., & Chrzanowski, A., 2019). The use of GNSS techniques is widespread as it requires only minimal interaction and cost savings. The device used to conduct this observation is the Trimble R10, and this device can detect signals from various satellite sources, namely GPS, GLONASS, Galileo, QZSS, and Beidou. The observation technique used 4 VRS for each reference station, and the maximum distance between reference stations was around 30 km to 60 km. During the observations, the PDOP was less than 5.0

with more than 12 satellites. The maximum epoch is 15 seconds, and the satellite opening angle is about 10 degrees, with the misclose baseline observations being 10ppm.

Since the inherent frequencies of each bridge element were unknown beforehand, they probably have greater vibration modes (Gaglione, A., Rodenas-Herraiz, D., Jia, Y., Nawaz, S., Arroyo, E., Mascolo, C., Seshia, A. A., 2018). As a result, the Accelerometer was set to sample at 20,000 Hz. At the conclusion of the data acquisition period, the data is downloaded in bulk from the device's local storage. To identify structural elements exhibiting large-amplitude vibrations in both the time and frequency domains, locations were selected by trial and error. The accelerometer can be used for both orientation and vibration detection in systems. For every axis, the accelerometer produces an analog signal that is proportional to the acceleration force (measured in g units) parallel to that axis. The sensitivity range of the chosen accelerometer can be adjusted to provide more coarse-grained data at higher g levels or fine-grained data at lower g levels. The data logger Dewesoft attached to the accelerometer recorded and saved the resulting acceleration time history data from vibrations caused by cars crossing the bridge (Fernando, K. S. D. M., Dissanayake, D. M. C. D., Dharmasiri, M. A. K. M., & Dammika, A. J., 2020). Vibration measurement in the field: Because of the dynamic nature of the applied load, the bridge vibrated when cars passed over it. Due to the bridge's vibration readings under normal operating conditions, a wired accelerometer setup was necessary. At the same time as the GNSS observation, the accelerometer turned on and waited for the cars to cross the bridge within the allotted time.

According to (Dong, C. Z., Bas, S., & Catbas, F. N., 2020), research on the applicability of vibration is becoming more and more focused on reducing substantial or excessive vibration. This is also the case in structural engineering, where the work done is to examine the level of vibration of bridges. An object may vibrate when it oscillates or moves repeatedly around an equilibrium position with no force acting on it. The frequency, which is expressed in hertz (Hz), is the number of times a full motion cycle occurs in a second. We used one accelerometer (Shear Accelerometer Model # 393B05, Serial # 33008, Sensitivity: 10.36 V/g (1.056 V/m/s2), with a bias level of 11.6 to obtain actual traffic-induced vibration data. The vibration sensor was used to collect the data in parallel, and the Sirius Mini 4 Channel of DEWEsoft software was linked for data processing and graphics creation. The fundamental frequencies of the majority of civil constructions are below 10 Hz (Mandatory Bridge Inspection Report, 2008), and the accelerometer's sound-capturing capacity is up to 160 dB. The reference state at the end of the monitoring data, which includes accelerations from ambient and forced vibrations. In addition to discussing the uncertainties associated with robust damage detection that arise from operational and environmental variables, as well as sensor malfunctions, the possibility of damage-sensitive features to detect damage is presented (Reuland, Y., Garcia-Ramonda, L., Martakis, P., Bogoevska, S., & Chatzi, E., 2023).

3 Results and Discussion

3.1 A Vibration Reading

Everywhere we go, we experience vibrations, and these vibrations are typically unwanted (Rajeswari, K., & Lakshmi, P. 2011). For instance, passenger discomfort and eventually exhaustion might result from vibrations in a car or any other type of vehicle. Although vibration-based monitoring techniques are appropriate for tracking the structural behavior of bridges, it is debatable whether they are effective at tracking minute variations in the structural dynamic characteristics locally. Local monitoring techniques to identify subtle changes in the mechanical characteristics of bridge components are, therefore, a relatively recent trend. For bridge constructions, a thorough bridge health system utilizing modal identification and vibration-based approaches is well outlined. A few sophisticated ideas and applications about bridge safety assessment techniques, such as load-carrying capability and damage detection, are examined. When creating a bridge management database, the authority or structural owner will benefit from the first full evaluation of the advantages and disadvantages of each vibration technique. The state of the bridge structure can then be evaluated and predicted using this data for ongoing structural monitoring (Saidin, S. S., Jamadin, A., Abdul Kudus, S., Mohd Amin, N., & Anuar, M. A. 2022). Modal characteristics of the structure, including damping ratios, mode shapes, and vibration frequencies, can be gleaned from the vibration data. Any observed changes in the modal frequencies, mode shapes, or damping ratios are regarded as indicators of potential damage or deterioration of the structure since the estimated modal parameters of the structure are treated as features, and these extracted features are tracked over time (Desjardins, S., & Lau, D., 2022).

Due to the minimal and hazardous site for observations, the time permitted was spread out over the day. The GNSS and the accelerometer's observation readings should be used to collect the data simultaneously. When the observation locations' coordinate readings were taken at eight in the morning, the vibration was found to be in a modest state at 14.6 mm/s2. According to these readings, comparatively fewer autos and heavier vehicles used the bridge in the morning. When the point observations are at coordinates and the vibration reading is at its highest from 11:00 am onwards, Longitude: 101.07903, Latitude: 4.598300006. At that time, the maximum vibration reading, classified as significant damage, was 53.7 mm/s2. This subtly suggests that traffic on the route is growing quickly, particularly due to the frequent usage of large trucks. The increase in traffic and associated vibration readings not only had an impact on the bridge's structure, especially the piers, but also made it possible for the researchers and their companions to feel the vibrations directly, which raised serious concerns for user safety. Yes, the circumstances were really dangerous at the time.

The vibration at the bridge abutment observation locations was then still higher at 14:20, with a reading of 49.6 mm/s2, which falls into the category of significant damage. Despite its state of being frequently handled by cars and large vehicles, the bridge remained intact, appearing strong and sturdy due to its straightforward design. This indicates that there is a good chance that the bridge's pier will sustain damage or distort if the vibration conditions continue with values as high as 30 mm/s2 without halting. GNSS-based observation methods can be the basis of a structural monitoring system for preventative maintenance when paired with other technical tools. The structure may be monitored and its condition evaluated using GNSS data from observation stations because it shows very minor changes over time. As a result, changes in natural frequency can be used to determine traffic volumes and spot early indications of structural stress. (Figure 5) shows the spatial coordinates and displacement signals at the position of point KB21.

SPAN 13
NIL
KB21
3 (PWD RATING)

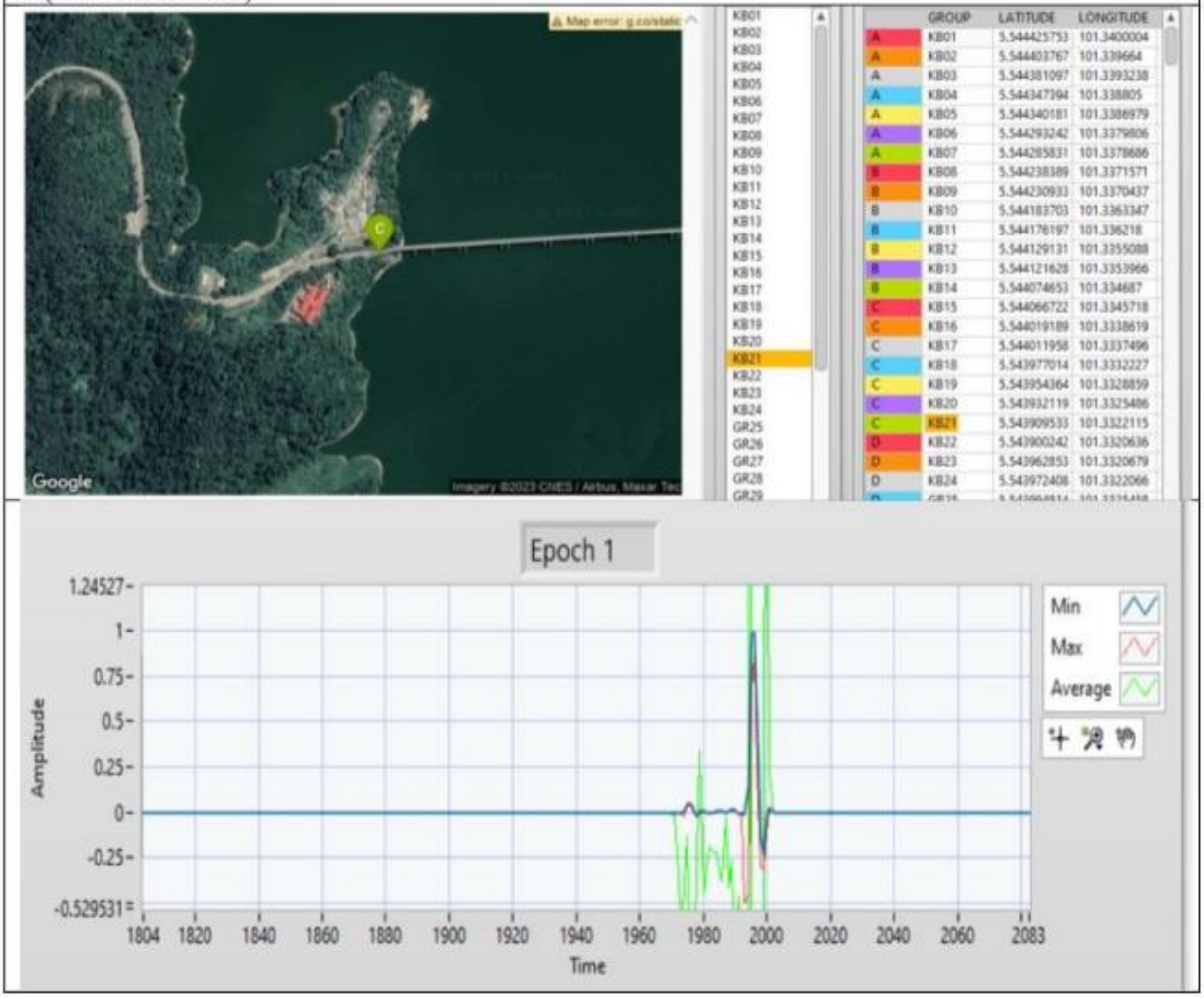

Figure 5. Spatial coordinates and displacement signals at the position known as KB21, which is next to the pier, as amplitude (m) vs. time (t).

Based on (Figure 5), displacement measurements at point KB21 (5.543909533, 101.3322115), displacement levels on span 13 not on the pier can reach up to 1.0000 m/s. The state of the surface slab/span is deemed to be subpar, and KB21 is situated on the terrestrial embankment structure. A visual evaluation gave the span structure a rating of 3, meaning it needs to be improved. Road surface problems are indicated by vibrations at KB21, which result in considerable displacement. High displacement values need to be monitored and addressed right away. Bridge stability and safety are maintained by taking immediate corrective action, as shown by a visual inspection rating of 3, referring to Table 2 below. From the results, the computed eigenfrequencies between accelerometers and GNSS data matched well for vibration monitoring. Moreover, the computed eigenfrequencies were not significantly affected by the vehicles' speed (Schönberger, C., & Lienhart, W. 2024).

Table 2. Bridge condition rating in Malaysia.

0 .	The bridge part cannot be fully inspected because of an access problem, such as a submerged structure...
3 .	Implementing regular maintenance is necessary since damage detection is only marginally critical.
5	Due to the severe and extensive damage, which may have an impact on traffic safety....

[1]Mandatory Bridge Inspection Report (2008).

To sum up, the displacement study at KB21 identifies serious problems, such as excessive displacement values and damage to the road surface at span 13. To preserve bridge performance, immediate corrective measures are required in addition to careful observation and prompt repairs. Proactive maintenance is essential, and fixing problems as soon as they are found will improve serviceability and guarantee user safety. Maintaining the bridge's structural integrity and dependability requires careful maintenance and ongoing observation. Its long-term operation will be ensured by prompt corrective action and efficient maintenance, allowing all vehicles to travel safely. The analysis's conclusions improve and prolong the lifespan of the transportation network by informing infrastructure management.

3.2 Graphical Representation of System

In the 21st century, rapid advancements in electronic information technology have transformed how we approach testing and data acquisition. Among the tools available, LabVIEW stands out as a favorite among engineers due to its powerful features, user-friendly visual programming interface, and seamless integration with other software. It allows users to easily build custom data acquisition systems tailored to real-world applications, enabling real-time monitoring and logging from a wide range of sensors and devices (Sen Hou, 2024). Data is gathered using LabVIEW software; fault data is captured and stored for a predetermined amount of time, and post-processing is carried out with the LabVIEW front end and required hardware (Kulkarni, V. V., & Channapattana, S., 2025). The results of using the accelerometer are displayed in the inspection system as readings that were displayed directly on the laptop screen after the observation data was processed using LabVIEW. The versatility and adaptability of LabVIEW are well known. LabVIEW offers a wide range of applications in integrated systems because of its adaptability in input-output systems. The one derived from the highest reading is the one that is shown in (Figure 6).

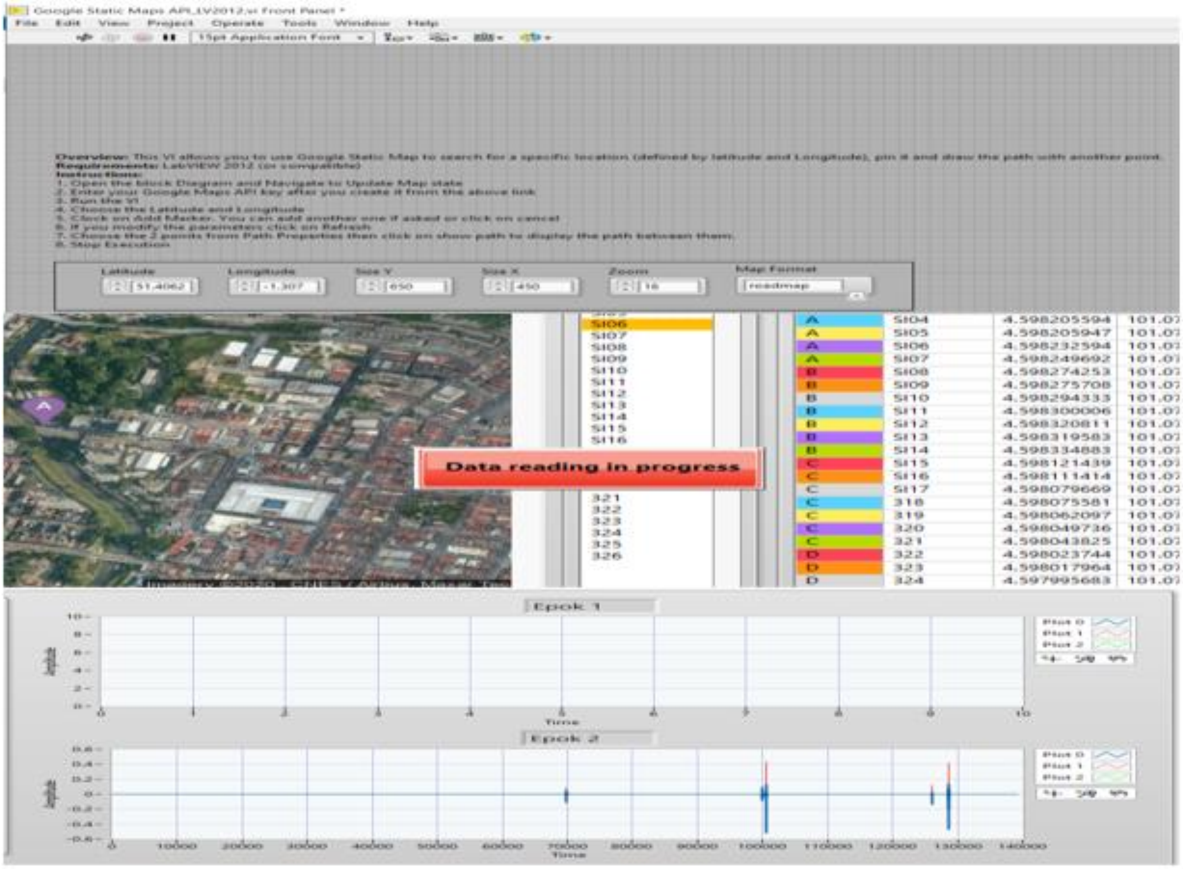

Figure 6. Front panel of the data acquisition for inspection.

The data from the bridge folder will be immediately loaded by the system, shown in (Figure 6). The User Interface will display and allow for the selection of all available data. A maximum of two epochs may be chosen by the user for comparison. From the coordinate list, the user can also choose the location of the measurement data that was captured. To display the map, an internet connection is necessary. Before showing the data on the graph, the software will load the data and compute the necessary parameters if the data for the chosen location is available. As seen in the image, the outcome will be plotted on the graph. The graph tool on the right side of the graph allows the user to zoom in or out.

4 Conclusion

Numerous factors, including vibration frequency, damping ratio, and mode shape, can result in damage or deterioration and alter the structural vibration response. Undoubtedly, the vibration will be even and the damage will be minimized if the road surface, or slab, is in good and level condition. The results of this small study are analyzed to produce the following conclusions:

i. A helpful resource for local engineers to know about when monitoring to guarantee the effective deployment of the bridge deformation monitoring system, especially for upcoming projects in Malaysia. The functioning of a system known as the BDMS, which combines accelerometer amplitude data at the same place with position (latitude, longitude). ii. Real-time bridge monitoring must be done continuously. It is recommended that this project be taken into consideration for the future because GNSS technology can offer real-time data. Moreover, monetization of research may also be considered. iii. The data from the bridge folder will be automatically loaded by the software. The User

Interface will display and allow for the selection of all available data. A maximum of two epochs may be chosen by users for comparison. From the coordinate list, users can also choose the location of the measurement data that was captured. To display the map, a strong internet connection is necessary. iv. Due to their exceptionally high sensitivity, GNSS signals may give inspectors exact coordinate information for each pier. This information is useful and can be combined using a data fusion technique to improve the accuracy of bridge inspection and allow more trustworthy evaluations of bridge health. v. Heavy vehicle movement can exacerbate vibration-related damage, increasing the danger to user safety, particularly for sensitive road users like motorcycle riders. This emphasizes how crucial it is for road authorities to continuously recognize the value of preventive maintenance in order to guarantee both public safety and structural integrity.

Since concrete bridge assets are deteriorating due to aging as they near the end of their design life, many existing bridges that have been in use for a number of years now require intervention, such as strengthening (Gkoumas, K., Gkoktsi, K., Bono, F., Galassi, M. C., & Tirelli, D. 2021). By using cutting-edge monitoring methods that provide more useful insights, the study's findings should motivate Malaysian road agencies to improve their conventional concrete bridge inspection procedures. Agencies can obtain a better understanding of the overall health of bridges by using a data fusion technique, which combines GNSS-based observations with other structural health data. This allows for quicker and more informed decision-making. By recognizing and resolving any dangers before they become more serious, this strategy not only increases the effectiveness of preventive maintenance but also fortifies the dedication to user safety. In order to facilitate a more proactive and astute approach to bridge repair nationwide, future research should investigate real-time monitoring systems and predictive analytics.

Acknowledgements

The authors would like to thank the data gathering team, particularly Norfaiza Binti Mukaram Abid and En. Adi Salihi Bin Adnan from Malaysian road agencies. Zulhasdee Zulkifli from Politechnic Ungku Omar, and Nazirah Abdullah from University Tun Hussein Onn Malaysia.

Funding

The Department of Polytechnic and Community College Education (JPPKK) from the Ministry of Higher Education, who have been actively involved in granting authorization and support for this research, have provided financial assistance for it. The Polytechnic Ungku Omar Research Grant (No. P63 050110010001).

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request and with appropriate ethics approval. This study was conducted in accordance with ethical standards and approved by the Road Agency of Malaysia. All participants provided informed consent prior to participation.

Conflicts of Interest

The authors declare no conflict of interest. This research received 100% funding for fieldwork from the Department of Polytechnic and Community College Education (JPPKK). JPPKK also holds the copyright for the developed system. The funder had no role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

References

An, X., Meng, X., Hu, L., Xie, Y., Zhang, F., & Pan, S. (2025).: GNSS integrated displacement and attitude determination for structural health monitoring of long-span bridges. *Satellite Navigation*, *6*(1), 3–10. https://doi.org/10.1186/s43020-025-00174-9

Aasim, B. A., Sor, M., & Abdul, G. (2020). Vibration-based comparison of accelerometer and microtremor sensors with numerical verification by assessing a PC bridge. MIDAS Civil, 25–28.

Bao, T., & Liu, Z.(2017). Vibration-based bridge scour detection: A review. Structural Control and Health Monitoring, 24(7). https://doi.org/10.1002/stc.1937.

Bazanowski, M., Szostak-Chrzanowski, A., & Chrzanowski, A. (2019). Determination of GPS session duration in ground deformation surveys in mining areas. Sustainability (Switzerland), 11(21). https://doi.org/10.3390/su11216127.

Bianchi, S., Capacci, L., Anghileri, M., Biondini, F., Rosati, G., Cazzulani, G., Barindelli, S., & Caldera, S. (2023). Structural health monitoring of bridges based on GNSS. *Life-Cycle of Structures and Infrastructure Systems - Proceedings of the 8th International Symposium on Life-Cycle Civil Engineering, IALCCE 2023*, 2001–2008. https://doi.org/10.1201/9781003323020-245.

Desjardins, S., & Lau, D. (2022). Advances in intelligent long-term vibration-based structural health-monitoring systems for bridges. *Advances in Structural Engineering*, *25*(7), 1413–1430. https://doi.org/10.1177/13694332221081186.

Dong, C. Z., Bas, S., & Catbas, F. N.(2020). Investigation of vibration serviceability of a footbridge using computer vision-based methods. Engineering Structures, 224(October), 111224. https://doi.org/10.1016/j.engstruct.2020.111224.

Gaglione, A., Rodenas-Herraiz, D., Jia, Y., Nawaz, S., Arroyo, E., Mascolo, C., Soga, K., & Seshia, A. A. (2018). Energy Neutral Operation of Vibration Energy-Harvesting Sensor Networks for Bridge Applications. *International Conference on Embedded Wireless Systems and Networks (EWSN)*, 1–12. https://ecc153fc-a-3b850097-s-sites.googlegroups.com/a/ewsn.org/ewsn/file-repository/ewsn-2018/001_012_gaglione.pdf?attachauth=ANoY7coy34cd6ViNLsRPJe2QuBZSuzSe8eldlHx3W7BPO7vRLTV6WQjOV3NG-cv7DVJ4FHw3XZ7OE8VlGjVyfNecK5HQaFQxv43uzXbg9Q4vj_FEM9GlEqz8belOCiAt

Sen Hou. (2024). Design and Implementation of a data acquisition system based on LabVIEW. Proc. SPIE 13171, Third International Conference on Algorithms, Microchips, and Network Application (AMNA 2024), 13171IO (8 June 2024); http://doi.org/10.1117/12.3032034.

Annual Public Work Department, Mandatory Bridge Inspection Report (2008).

Fernando, K. S. D. M., Dissanayake, D. M. C. D., Dharmasiri, M. A. K. M., & Dammika, A. J.(2020). Damage Detection and Condition Monitoring of Prestressed Concrete Bridges by using Vibration-based Health Monitoring Techniques. Engineer: Journal of the Institution of Engineers, Sri Lanka, 53(3), 91. https://doi.org/10.4038/engineer.v53i3.7422.

Gkoumas, K., Gkoktsi, K., Bono, F., Galassi, M. C., & Tirelli, D.(2021). The way forward for indirect structural health monitoring (Ishm) using connected and automated vehicles in Europe. Infrastructures, 6(3). https://doi.org/10.3390/infrastructures6030043.

Kim, S., Pakzad, S., Culler, D., Demmel, J., Fenves, G., Glaser, S., & Turon, M.(2007). Health Monitoring of Civil Infrastructures Using Wireless Sensor Networks, 254–263. https://doi.org/10.1109/ipsn.2007.4379685.

Kulkarni, V. V., & Channapattana, S.(2025). Advanced Diagnosis of Bearing Defects: A Multi-Domain Approach. *International Journal of Mechanical Engineering and Robotics Research*, *14*(4), 436–444. https://doi.org/10.18178/ijmerr.14.4.436-444.

Rajeswari, K., & Lakshmi, P.(2011). Vibration control of a mechanical suspension system using LabVIEW. *International Journal of Instrumentation Technology*, *1*(1), 60. https://doi.org/10.1504/ijit.2011.043592.

Reuland, Y., Garcia-Ramonda, L., Martakis, P., Bogoevska, S., & Chatzi, E.(2023). A full-scale case study of vibration-based structural health monitoring of bridges: prospects and open challenges. *Ce/Papers*, *6*(5), 329–336. https://doi.org/10.1002/cepa.2001.

Saidin, S. S., Jamadin, A., Abdul Kudus, S., Mohd Amin, N., & Anuar, M. A.(2022). An Overview: The Application of Vibration-Based Techniques in Bridge Structural Health Monitoring. *International Journal of Concrete Structures and Materials*, *16*(1), 1–17. https://doi.org/10.1186/s40069-022-00557-1.

Schönberger, C., & Lienhart, W.(2024). Drive-by Structural Monitoring using GNSS measurements at alpine bridges. *11th European Workshop on Structural Health Monitoring, EWSHM 2024*, *July*. https://doi.org/10.58286/29845.

Xi, R., He, Q., & Meng, X. (2021). Bridge monitoring using multi-GNSS observations with high cutoff elevations: A case study. Measurement: Journal of the International Measurement Confederation, 168(August), 108303. https://doi.org/10.1016/j.measurement.2020.108303.

Disclaimer/Publisher's Note

The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and do not reflect the views of the Architecture, Buildings, Construction and Cities (ABC2) Journal and/or its editor(s). ABC2 Journal and/or its editor(s) disclaim any responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.