International Journal of GEOMATE, July., 2021, Vol.21, Issue 83, pp.-166-173
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2021.83.j2140
Geotechnique, Construction Materials and Environment

APPLICATION THE ACOUSTIC EMISSION TECHNOLOGY FOR SHM SYSTEM OF CONCRETE CABLE-STAYED BRIDGE IN VIETNAM

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*Corresponding Author, Received: 16 Mar. 2021, Revised: 15 Apr. 2021, Accepted: 25 Apr. 2021

ABSTRACT: Since My Thuan Bridge, the first concrete cable-stayed bridge in Vietnam, had begun construction in 1997 and was put into operation in 2000. After that, another concrete cable-stayed bridge had been constructed like Kien Bridge (2003), Bai Chay Bridge (2006), Rach Mieu Bridge (2009), Phu My Bridge (2009), Can Tho Bridge (2010), and three new bridges will be put into use at the end of 2018 as Cao Lanh Bridge, Vam Cong Bridge, and Bach Dang Bridge. Therefore, the SHM system is gradually being designed and installed for cable-stayed bridges to ensure economic exploitation and safety. The management unit began to pay more attention to the new cable bridges, which have already included the early stages' monitoring system. The existing SHM system installed on the bridges has many mistakes and problems in the SHM systems, which already exist in Vietnam. This paper describes the application an acoustic emission technology for the SHM system of a concrete cable-stayed bridge. The new SHM system with acoustic emission (AE) technology allows monitoring and tracking the processes that occur over a structure's entire volume. The structure is independent of strain and stress and depends mainly on the integrity of the structure that is of utmost importance for the bridge's service life and safe operation.

Keywords: SHM System, Damage, Cracks, Acoustic Emission,

1. INTRODUCTION

My Thuan (Mỹ Thuận) Bridge was the first concrete cable-stayed bridge in Vietnam (Fig.1), had begun construction in 1997 and was put into operation in 2000. After that, there are many concrete cable-stayed bridges had been built and under construction (Table 1). On April 10, 2012, the Ministry of Transport had sent Official Letter No. 2727 /BGTVT-KCHT to the Directorate of Roads of Vietnam, which regulates the suspension bridge, the cable-stayed bridge shall be installed SHM system. According to this regulation, special bridge construction (the maximum span length > 150 m high or> 50 m high) is required to have a monitoring system. The SHM system for bridges has recently been considered for installation on a few cable-stayed bridges in Vietnam due to their sensitivity to the environmental impact and live load [1].

The SHM systems installed in Vietnam are quite diverse and currently, there are no common regulations, requirements for them from the regulatory authorities. SHM systems are implemented by many different vendors with devices from various suppliers with a different number of sensors, quality, and cost. The purposes of system design are not consistent. During the exploitation phase of each bridge, the operating unit develops maintenance manual regulations on data, however, the reporting regime is still unclear, lacks unity and the maintenance requirements are not detailed which leads to difficulties in the usage and operation of these new systems.

Fig.1 General view of My Thuan Bridge (2000)

2. RESEARCH SIGNIFICANCE

In this paper the author has analyzed and evaluated the advantages and disadvantages of the SHM systems installed in the cable-stayed bridges in Vietnam, thereby proposing the application of the NDT method using the Acoustic Emission technology (AE) in monitoring entire these bridges. To minimize the operational and operational costs of the bridge, at the same time allows continuous monitoring of the bridges without complicated tests.

Also, there is no need to close the bridge to do the above operation.

3. CONDITION OF CONCRETE CABLE-STAYED BRIDGES IN VIETNAM

3.1. The Current Condition of Concrete Cable-Stayed Bridges in Vietnam

As Table 1, all concrete cable-stayed bridges in Vietnam are quite new, the oldest one is the My Thuan Bridge from 2000. For example, after 20 years in operation, the My Thuan bridge is generally in good condition. Every 5 years a thorough review of the entire bridge is conducted to assess the state of the bridge construction. As we know the biggest problem of those concrete bridges is the large number of cracks that appear on the bridge, especially at the cable to plate fixing area, on the connection between the crossbeam and deck slab, on the pylon near the crossbeam, and on the deck slab (Fig. 2) [1,3].

Table 1. The concrete cable-stayed bridges in Vietnam

Bridge	Year opened	Total length	Longest span
My Thuan	2000	1.535 m	350 m
Kien	2003	1.186m	200 m
Bai Chay	2006	903 m	435 m
Rach Mieu	2009	2.860 m	270 m
Phu My	2009	2.031 m	380 m
Can Tho [2]	2010	2.750 m	550 m
Cao Lanh	2018	2.015 m	350 m
Vam Cong	2019	2.970 m	450 m

Fig. 2 A lot of cracks were found on the My Thuan bridge: a - the cable to plate fixing area, b - a connection between the crossbeam and deck slab, c - on the pylon near the crossbeam

3.2. Overall Assessment on Current SHM Systems in Vietnam

SHM systems designed and installed in Vietnam are quite diversified. They were provided by various consultants and came with different quality and cost from many vendors. The determination of the purpose and system building method, analysis and evaluation, and use of data are not regulated and specifically guided by state management agencies, so, the comparison and evaluation are relatively complicated. Almost all SHM systems have an ambiguous purpose and the level of monitoring to be achieved has not been determined. The fact that the SHM system, which has been designed and installed in Vietnam, often includes a wide range of categories and various measurement sensors, at a very high cost, maybe at the maximum price. While to ensure economic and technical efficiency, it is also necessary to determine the appropriate minimum level for each type of bridge according to the decentralization of the project and the current status of the project towards the achievement of a higher level of monitoring (Fig. 3, Fig. 4, Fig. 5). Those systems surveyed are only at level 1, which means, only some basic raw information is provided with some additional warning messages, but warning thresholds are not accurately and defined. But up to now, the targets set for these monitoring systems have not been fully defined. The selection of monitoring system components is relatively diverse, depending on the design unit as there are no general regulations [3].

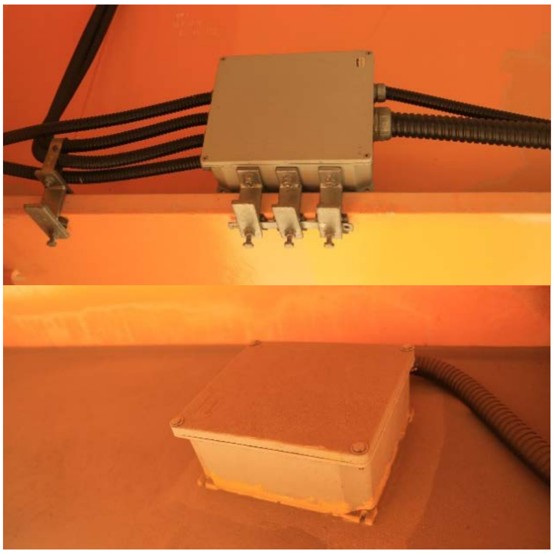

Fig. 3 Only a few sensors had been installed, an accelerator installation on the main girder of Binh Bridge

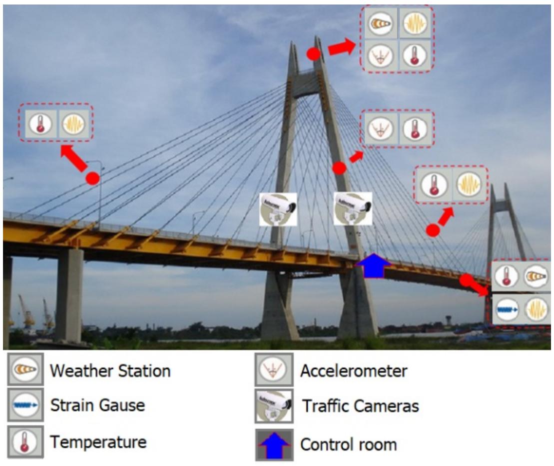

Fig. 4 The location of the sensors installed on the Binh Bridge

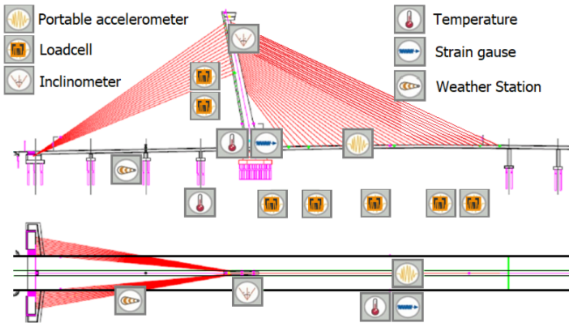

Fig.5 The location of the sensors installed on the Tran Thi Ly Bridge.

Table 2. Condition of few installed SHM system

Bridge	SHM System	Monitoring level
Bai Chay	In operation stage by ADVITAM (2014)	Basic (Level 1)
Rach Mieu	In operation stage by VSL	Basic (Level 1)
Can Tho	In the operation stage by NTT DATA (2013)	Basic (Level 1)
Binh	In the operation stage by VSL and VITEC (2012)	Basic (Level 1)
Rao II	In the construction and operation stage by SAVCOR (2012)	Basic (Level 1)
Nhat Tan	In the construction and operation stage	Level 1

The ability to provide information on the SHM system installed is also very diverse. The accuracy of the equipment is also a matter of periodic inspection and calibration. Analysis ability of the current software limits the processing capabilities and further analysis. Many of the data are provided in crude form, especially GPS, oscillation data. Management staff do not have an in-depth knowledge of data analysis and assessment, so the daily reports are mostly just the current status of the operation of the equipment. Initial assessment of the ability to provide information on structural behavior at five levels [4-5], of monitoring of the few bridges with installed SHM system (Table 2).

Disadvantages of the SHM system are:

Bai Chay Bridge – SHM system is only installed on tower P3 (half of the bridge). All system modifications must be made by ADVITAM - this is a restriction that leads to a lack of flexibility of the system. Also, there is no analysis of the data reported.

Rach Mieu Bridge - software analysis could not analyze the oscillation frequency, and the management staff does not know how to analyze and process data.

Can Tho Bridge - The SHM system sends daily reports about its status, but doesn't have a detailed analysis of the data due to the incapable of the management unit to analyze and evaluate the data. High frequency of data collection leads to memory overflows and the system automatically erases old data, leading to the loss of essential information.

The Binh Bridge - SHM system is very simple with fewer sensors to provide some basic warning on tension in the longest cable, girder oscillation, traffic, weather, etc., which do not help in the assessment of the current status of the structures.

The Rao II Bridge - This is a relatively complete system and if integrated with proper analytical software can help assess the structural status. But at the time of the survey, the system was not active, awaiting repair.

The Nhat Tan Bridge - the entire system has been shut down because of a failure by a lightning strike in 2016 [6].

4. THE "TRADITIONAL" SHM SYSTEM OF EXISTING BRIDGES IN VIETNAM

4.1. General Guidelines of The SHM System for The Cable-Stayed Bridge in Vietnam

The general main functions SHM system for the cable-stayed bridge is monitoring the influence of weather and climate on the object and determining the actual state of the object during exploitation. Measurement and monitoring equipment must be modern and durable; existing equipment (if still useful) must be included in the newly built SHM system (sensors, data collection system, and data acquisition system, the connection between these components, control, and reporting software). The SHM system should consist of the following three components [3,7]:

- Structural observation system;

- Meteorological monitoring system;
- Image monitoring system.

There are two main target function groups of the bridge SHM system:

- Maintenance and rehabilitation work, which:
  - Provide data to detect and evaluate deformation as well as degradation of structures,
  - Provide data to develop appropriate and timely maintenance and maintenance plans.
- Management of the safety of communication, which uses the monitoring data for bridge traffic management to ensure vehicles safety on the bridge.

4.2. Typical Design of SHM System for Concrete Cable-Stayed Bridges

Therefore, the design of the bridge SHM system for the concrete cable-stayed bridge, that enables it to work properly and optimally, is essential. The SHM system should be designed based on the technical and design features of the bridge, as well as the need to identify the main physical quantities of measurement and monitoring function. The selection of monitoring equipment for this system should consider the following factors [2] (Figure 6):

- The design features, the structure of the bridge, natural surroundings,
- Components to be monitored, quantities to be monitored,
- Economic efficiency,
- Accuracy and durability of the sensors.

The entire complete SHM system should have the following capabilities:

The ability to provision bridge traffic information - the CCTV cameras are one of the most effective items in the monitoring of traffic flow, accident handling, bridge protection, with enough numbers that can scan throughout the bridge. It is necessary to supplement monitoring radar and traffic count equipment to measurement number, type of vehicles and speed, etc., and combine with WIM (Weight in Motion) system that can weigh and determine the load, to restrict overload vehicles.

The ability to the provision of information on weather, environmental condition - Information on temperature, humidity, wind direction, and wind speed are fully provided. However, the association of these parameters with structural behavior analysis due to the influence of ambient temperature has not been fully conducted [3].

Warning ability - SHM system installed in Vietnam has set up operational warning systems. However, the determination of values beyond the threshold (warning value) is difficult and in fact, these thresholds are not working effectively. It is possible to apply measurement results obtained during bridge load testing in conjunction with theoretical calculations on the model to establish the required thresholds.

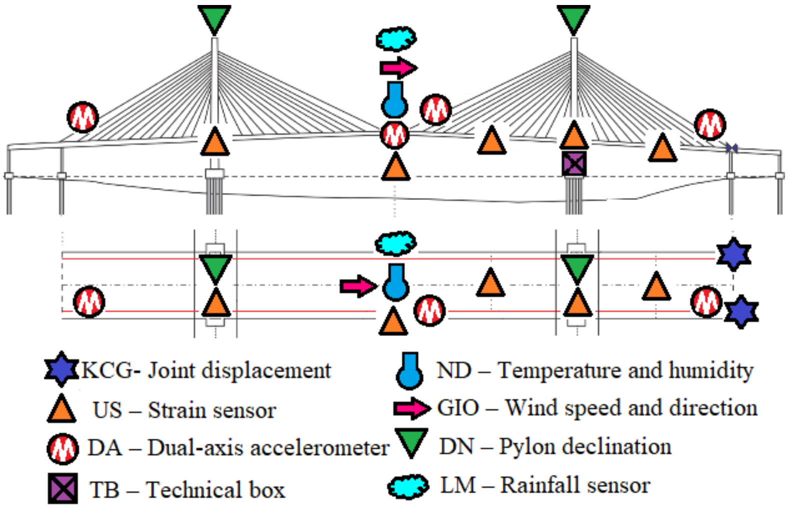

Fig 6. Typical location of sensors on the cable-stayed bridge

The ability of standardization of structural model - This is the third level that the SHM system can reach. Besides, the data collection process needs to be long enough (about 3 to 5 years) and in association with experienced experts.

The ability to the determination of damaged location, the abnormal status of work - This is the highest range of level 4 (state control) and 5 (defect detection) that the SHM system can achieve. Achievement of state control is necessary and should set a goal for the cable-stayed bridge monitoring system. Other applications such as

Acoustic Emission (AE) should be applied in detecting damages and damaged locations, especially for reinforced concrete bridges [4].

The ability to forecast, assess structure age - This is the highest threshold that the monitoring system can achieve. The system can forecast the working life of the work and many algorithms are now under development in the world to reach this level to:

- Support to determine the remaining life of the structure
- Forecast damage, abnormal status.
- Support to make timely maintenance or preservation.

The ability to combine with other maintenance works - The installed SHM system has initially supported maintenance work. It even reduced many maintenance costs, removed periodical inspection work in many bridge works. However, it should be noted that the SHM system cannot replace the maintenance work, and should be combined with other inspection work to fully assess the current status of the work.

Durability and working life of the system - Sensors have a relatively good working life span (over 5 years), but problems often occur with data transfer connections that result in system malfunction. This is noteworthy as it will affect the continuity and accuracy of the data. The sensors located in concrete have a high risk because they cannot be replaced. Particularly, in Rao II Bridge, after 2 years of operation, the system has stopped waiting for repair.

Economic criteria - Currently, according to the world's statistics, the current SHM system cost is about 0.3% - l.5% of total investment cost. The cost of the SHM system in Vietnam is very high. SHM system of Can Tho bridge has a big number of sensors, especially GPS, and the cost of this system can be up to 1 million USD (total investment cost is more than 200 million USD) [2].

4.3. The Main Disadvantages of The SHM System in Vietnam

There are three main disadvantages in the designed SHM system for this kind of bridge:

- The bridge symmetry often used to design SHM system and the system is practically installed on one half of the bridge, which does not objectively express the overall behavior of the bridge, especially with the non-symmetrical loads;
- The concrete structure of the bridge was experiencing a lot of cracks during the operation phase; therefore, it should have taken into account the possibility of monitoring the behavior of these cracks in the future;
- There is no bridge condition at the first phase of the operation – phase "zero". Therefore, to determine exactly the positions of the sensors for the entire SHM system, a FEM model should be developed to analyze the behavior of the bridge.

5. THE HYBRID SHM SYSTEM WITH ACOUSTIC EMISSION TECHNOLOGY

The concrete cable-stayed bridge is a large construction from reinforced concrete. Over time, the main beam and the pylons and anchorage sites started to experience large shrinkages and creeping changes, which are the characteristic phenomena for concrete and reinforced concrete structures with a large cubature. The aforementioned construction elements have suffered some displacement and deformation during their service time. Therefore, measuring and controlling the stresses, deformation, displacement, and temperature changes of the bridge components during operation is very essential. Besides, the bridge is also heavily influenced by weather and climate, especially from strong wind and tropical storms.

The size and current conditions of those bridge (with a lot of cracks) require that the following factors must be accounted for while developing an objective for the new SHM system [4]

- The need to locate damage over the entire structure or at least in its major parts,
- Difficulties in defining real load acting on the structure, far divergent from the results of the load tests. For example, dynamic loads on a bridge, resulting from convergent travel of several lorries with loads and at speeds far exceeding permissible values, that induce excessive loads on its elements,
- Difficulties in defining interaction between various defects; a detailed spatial location of these defects is necessary, as well as the knowledge about the loads,
- Difficulties in defining the degree to which the detected defect affects the capacity for a load of the entire structure, which is, determining whether a given defect is active (developing) or passive (static). In many cases, serious-looking cracks are just remnants of initial deformations which have resulted in the redistribution of stresses leading to fault propagation in a different region,
- Defining real operating conditions of the structure, such as temperature, rainfall, wind load, that have a noticeable effect on the development of deterioration. The diagnostic and monitoring

system has to take into account all these conditions to be able to provide objective and unequivocal information.

The system is based on the measurements of acoustic emission generated by active (growing) destructive processes. By tracking their dynamics, it is possible to assess their influence on the condition of the structure and potential risks. Identifying destructive processes with crack widths allows assessing their effect on the safety of structures by monitoring and observation of the structure's current condition and predicting service life changes in particular in building structures. The risk assessment criteria and codes are summarized in Table 3. Active monitoring and process registration are possible owing to the proper distribution of acoustic sensors to enable the exploration of the entire volume of the structure under test [7-8].

Table 3. Characteristic classes of signals, assigned symbols, and Codes [7]

Symbol	Class	Risk code	Description
	No.1	5	Crack formation in the cement paste
	No.2	4	Crack formation at the paste/aggregate boundary
	No.3	3	Crack formation in the tensile zone
	No.4	2	Crack propagation
	No.5	1	Loss of adhesion near the crack
	No.6	0	Compression/Lateral buckling of struts/rebar/ compression crushing of concrete/bar rupture

5.1. Application of the FEM method to structural analysis

In 2016, a My Thuan bridge deformation was measured with the support of Freyssinet under the bridge maintenance program. At the same time, the FEM model was developed to analyze the bridge behavior. The bridge maintenance program measurement results were just slightly different from the FEM model values [9-10] The FEM method is used to model the deformation behavior of the bridge structure. In particular, the two main girders and horizontal girders are modeled by a two-node linear element. The bridge deck is modeled by four-node plate elements.

The H-beam tower is modeled with a two-node linear element and the connection between the bridge girder and the bridge tower at the crossbar position was also simulated to ensure freedom relative to the fixed and movable pillars of the two vertical beams. The cable systems are modeled using cable elements, which can be used to calculate wire tension and nonlinear geometry analysis (Fig 7).

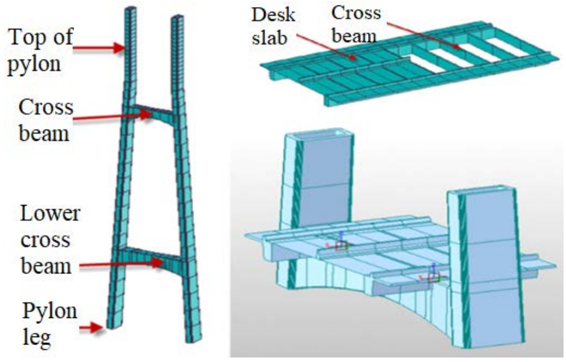

Fig. 7 FEM model for My Thuan Bridge to analyze the behavior of bridge [10].

The results show that the analysis model and experimental results are quite appropriate. The basic mode of vibration identification and its characteristics have relatively small differences between the experiment results and the experimental model values (Fig. 8).

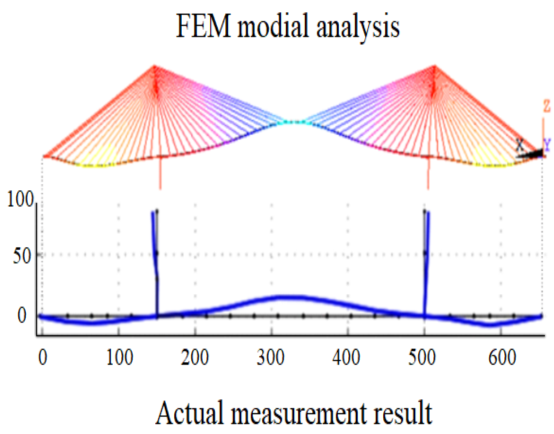

Fig. 8. Comparison of deformation of My Thuan Bridge between FEM model analysis and measurement during bridge review [10].

However, the results of the analysis also show that there is a difference between the experimental and analytical models. In the analysis model, an unknown vibration mode was found in the experimental results. This difference can be explained by the fact that the parameters in the model cannot be simulated in the real-life behavior of the bridge during bridge review by the management unit [9-10] (Table 4).

Table 4. Comparison of the vertical oscillation frequency of My Thuan Bridge (Hz) between FEM model analysis values and measurement result [9-10].

Mode	Measured result	FEM model analysis	Δ %
Mode 1 - 2	0,299	0,289	3,2%
Mode 2 - 3	0,387	0,368	4,9%
Mode 3 - 8	0,588	0,598	-1,8%
Mode 4 - 10	0,653	0,659	-0,8%
Mode 5 - 12	0,708	0,723	-2,1%

Based on these results, we can conclude, that using the FEM model for bridge behavior analysis is useful and should be included in the development of the SHM system for bridge and it could be a very useful tool for analyzing future bridge behavior [1, 10-11].

5.2. Bridge SHM System with Acoustic Emission Solution

To monitoring effectively entire bridge, there is one more component that needs to be added to the „traditional" system [7, 12]. Using the acoustic sensor to measure the AE signals, generated in the spans and pylons by excitations induced by wind (monsoon zone and strong winds), rainfall and service loads, and to diagnose the structural condition and long-term changes occurring in the structure of the spans and pylons. The main task of this component will be a short-term and long-term measurement of the AE signals generated by destructive processes [13-14]. AE sensors have to mount on several points of the structure, selected based on statistical FEM analysis results, which indicate the most critical points from the strategic point of view. There shall be 9 to 16 measurement points in the optimal configuration. The measurement points should be in the centers of spans, in the span above pylons, and each pylon leg [5] (Fig. 9).

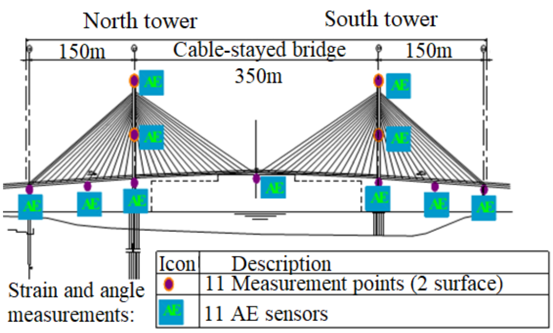

Fig. 9 Typical location of AE sensor to cracks monitoring of concrete cable-stayed bridge [5].

6. CONCLUSION

The concrete cable-stayed bridge structure is complicated. Its behavior, dependent on frequent and random loads and effects, is very difficult to verify. So, it is more difficult to control by conventional measurement works. In some cases, the design, construction, quality control work, etc. fully comply with legal documents, technical regulations, relevant standards, etc. but in construction, operation, exploitation process, etc., technical problems, even collapse of works still occurs.

Therefore, the installation of the SHM system is necessary to solve the above problems. However, the SHM system in Vietnam still has many problems and is not managed consistently. The installation of the SHM system has been individually and spontaneously carried out in some projects, largely dependent on the capital source and subjective opinions of consultants and contractors.

The owner and management unit do not have much experience in this sector. The management, analysis, processing, and storage of data and parameters collected from monitoring systems in the exploitation process in many works is perplexed, not effective and the number of experts is limited.

Based on the experience of the concrete structure and large bridges, some changes to the current system have been proposed. The proposed SHM system of global evaluation and monitoring of concrete structures, based on the measurement of acoustic emission (AE) accompanying destructive processes, covers the entire volume of the element under test or its selected part and allows locating and identifying active destructive processes and their dynamics under real service loads. The data collected can be the basis for the determination of the structural condition of the construction and risk potential.

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