836. Bridge scour evaluation based on ambient vibration

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Abstract. The vulnerability of bridges to hazards such as earthquakes, wind and floods necessitates special structural characteristics. To guarantee the stability of bridge structures, the precise evaluation of the scour depth of bridge foundation has recently become an important issue, as most of the unexpected damage to or collapse of bridges has been attributed to hydraulic issues. In this paper, a vibration-based bridge health monitoring system that utilizes only the response of superstructure to rapidly evaluate the embedded depth of a bridge column is proposed. To clarify the complex fluid-solid coupling phenomenon, the effects of embedded depth and water level were first verified through a series of static experiments. A confined finite element model simulated by soil spring effects was then established to illustrate the relationship between the fundamental frequency and the embedded depth. Using the proposed algorithm, the health of the bridge is able to be inferred by processing the ambient vibration response of the superstructure. To implement the proposed algorithm, a SHM prototype system monitoring environmental factors such as temperature, water level, and inclination was developed to support on-line processing. The performance of the proposed system was verified by a series of dynamic bridge scour experiments conducted in a laboratory flume and compared with readings from a water-proof camera. The results showed that using the proposed vibration-based bridge health monitoring system, the embedded depth of bridge column during complex scour processes is able to be reliably calculated.

Keywords: bridge scour, structure health monitoring, short-time Fourier transform.

Introduction

Structural Health Monitoring (SHM), an interdisciplinary concept originated from aerospace engineering, has been widely applied into different research fields. Due to natural disasters such as earthquake or flooding and the inevitable aging problem, structures are found to collapse without any warning. As the economy and society may be stricken seriously by this kind of catastrophe, SHM has become an important issue all around the world. Generally, the stretegy of SHM is divided inot four leverls [1]. Verification of damage existance or not should be achieved in level I, and the damage location should be presented in level II. The damage condition are then confirmed in level III while the residual life of the structure, whcih is the final goal of the SHM system, can be evaluated in level IV. Based on the real-time monitoring result, pre-warning signals can be sent out to aviod the possible loss on property and human life. Over the last decades, the concept of SHM is mostly implemented by extracting the dynamic characteristic of structures including mode shape, fundamental frequency, and damping to reflect the variation of structural stiffness [2, 3]. For example, the stiffness and damping ratio of a full-scale structure was identified by analyzing the ambient vibration signal with the Hilbert-Huang Transform (HHT) [4]. Methods based on Bayesian inference to detect the damage location of strucutres were also proposed [5] while some long-term SHM systems have been applied practically on strucutres [6].

For the special structural characteristic, bridges are prone to suffer from multiple hazards such as earthquake, wind, or floods among all the structures. Recently, as most of the unexpected damage or collapse of bridges are caused by scour phenomenon, bridge scour monitoring has been widely concerned. As a result, development of accurate and reliable bridge scour monitoring system has become an increasingly crucial challenge nowadays. Different than traditional SHM cases, bridge scour is a dynamic phenomenon affected by many factors such as water depth, flow speed, substructure geometry, and material property of the sediment [7]. As the loss of structural stiffness is mainly reflected on the change of embedded depth and the scour flow where the integrity of the superstructure only degrades slightly during the scour process, the fundamental frequency of the bridge is highly correlated with the embedded depth. As a result, a vibration-based bridge health monitoring system is proposed to rapidly and reliably predict the embedded depth. The stability condition of the bridge structure can then be rapidly evaluated based on the embedded depth estimated.

The vibration-based system

The main objective of the vibration-based system is to convert the measured fundamental frequency into its corresponding embedded depth. Since bridge scour is a complicated solid-fluid-coupled mechanism, the effects of embedded depth and water level on fundamental frequency were first clarified. A numerical model considering the distribution of the soil spring was then established to simulate different scour conditions for the proposed algorithm. Furthermore, Short-Time Fourier transform (STFT) was also utilized to extract the fundamental frequency from the vibration signal and the corresponding embedded depth could be calculated.

The effect of embedded depth and water level

In order to clarify the dominant factors involved in scouring, a preliminary static experiment was conducted to investigate the variation in fundamental frequency with different combinations of embedded depth and water level under static conditions. As shown in Fig. 1, a total of 16 testing groups, each increasing in embedded depth and water depth in 6 cm intervals, were tested. The embedded depth is defined as the depth where the caisson foundation is embedded in sand, and the water depth indicates the height difference between the water level and the sand surface.

To precisely illustrate the fundamental behavior of the bridge pier, three high resolution velocity meters with a sampling rate of 200 Hz were deployed on the top of the bridge to measure its response in the flow, transverse, and vertical directions. The details of the experiment setup are shown in Fig. 2. The results of the static experiment indicate that the dominant frequency of the bridge is mainly affected by the embedded depth; a deeper embedded depth results in a higher structural frequency while a minor influence from the water level was observed, as shown in Fig. 3. To further verify this phenomenon, a finite element model was built by considering the confinement provided by soil.

Simulation of soil confinement by soil spring

To express the soil confinement of the bridge column, the equivalent soil spring was simulated based on the regulations of the Japanese Road Association (JRA) [8]. The soil spring constant of each direction can be expressed as:

$$k_H = 1.2 k_{H0} \left(\frac{B_H}{30} \right)^{-3/4} \tag{1}$$

$$k_V = k_{V0}\left(\frac{B_V}{30}\right)^{-3/4} \tag{2}$$

$$k_{SB} = \lambda k_V \tag{3}$$

where k_H is the horizontal soil spring coefficient representing the resistance per unit area; k_V is the vertical soil spring coefficient; k_{SB} represents the shear coefficient in the horizontal direction while k_{H0} and k_{V0} are the basis values to be modified under specific loading conditions. B_H and B_V are the equivalent loading widths in the horizontal and vertical directions, respectively, and λ, which ranges between 0.25-0.33, indicates the ratio between the shear coefficient in the horizontal direction and the vertical soil spring coefficient.

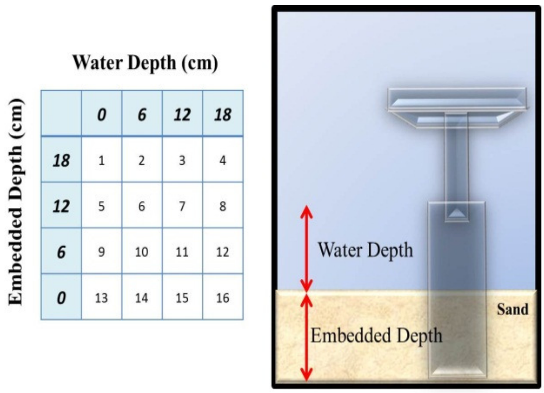

Fig. 1. Static experiment scheme

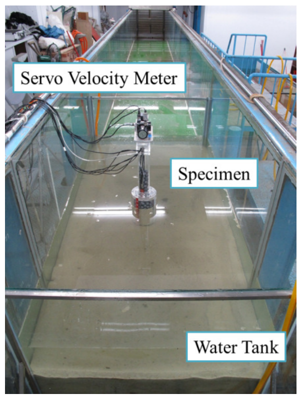

Fig. 2. Static experiment setup

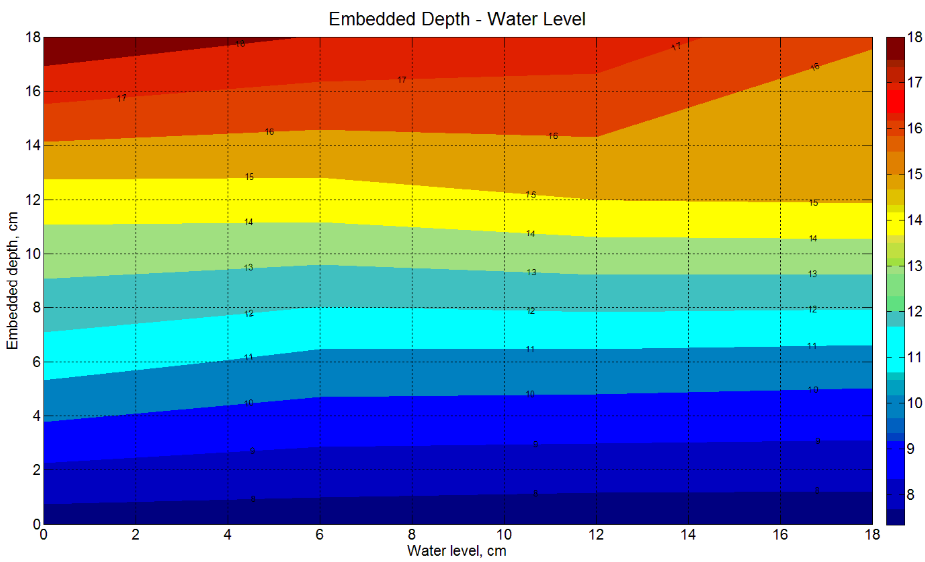

Fig. 3. Contour of static experiment

By utilizing the soil spring coefficient derived above, the total equivalent spring can be summarized by:

$K_y = 2b(0.5 \times k_H \times l) + k_{SB} \times A_B$ for top layer

$K_y = 2b(k_H \times l) + k_{SB} \times A_B$ for other layers (4)

$$K_Z = k_V \times A_B \quad (5)$$

$$K_{\theta x} = [0.33 k_H \times l^3] + k_{SB} \times A_B \times l^2 \quad (6)$$

where K_y, K_Z, $K_{\theta x}$ is the total stiffness contributed by the soil spring in the horizontal, vertical, and torsion directions, respectively; l is the thickness of each layer; A_B is the area of the foundation.

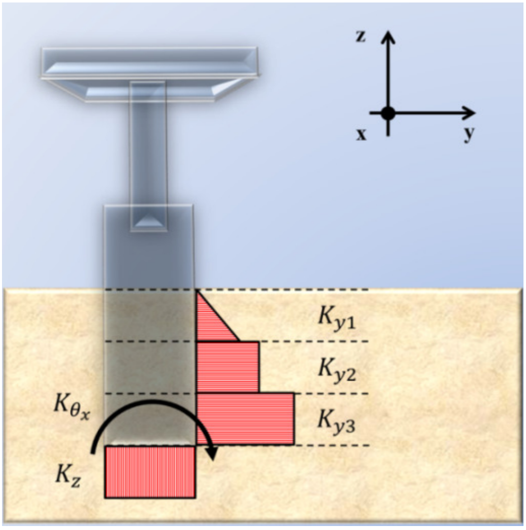

Fig. 4. Equivalent soil spring diagram

Finite element method model

The finite element model was established with the use of the soil spring model. The size and material of the bridge column was also considered. An equivalent lateral spring was arranged every 10 cm to provide the horizontal confinement. The vertical and torsion spring were located at the bottom of the bridge column. By sequentially removing the horizontal spring from the top, the scouring phenomenon was modeled. As shown in Fig. 5, the fundamental frequency gradually increased with the increase in embedded depth, and a correlation was observed between the results of the static experiment and the FEM model. The trend between the structural frequency and the embedded depth can be approximated as a quadratic function of the embedded depth.

The proposed SHM algorithm

According to a study by Srdjan Stankovi'c [9], the real-time fundamental frequency can be obtained from the measured signal by utilizing the short time Fourier transform technique (STFT). Tri-phase contours illustrating the relationship between time, frequency, and amplitude can be drawn to reflect the frequency variation.

Moreover, based on the results of the static experiment, a quadratic equation is proposed to describe the relationship between the embedded depth and the dominant frequency:

$$Frequency = a \times Depth^2 + b \times Depth + c \qquad (7)$$

where a, b and c are the coefficients to be determined.

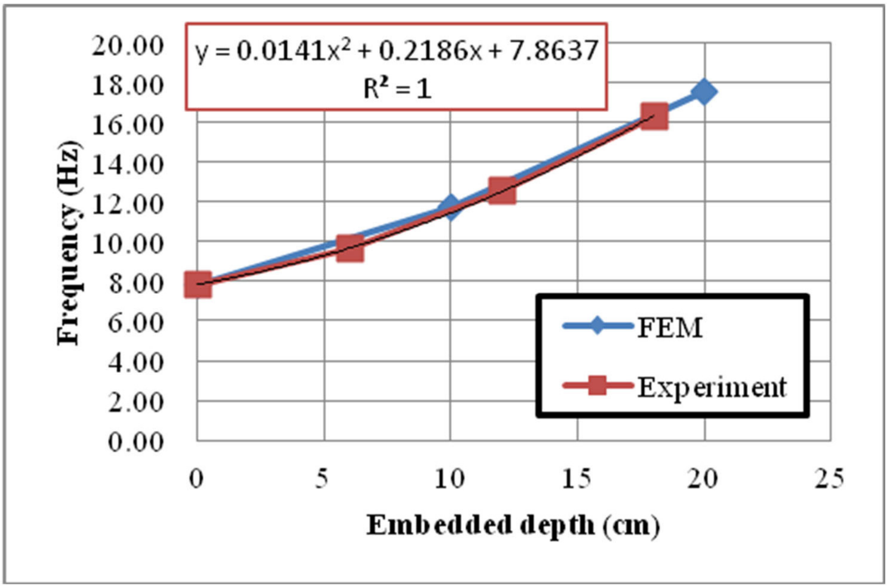

Fig. 5. FEM model vs static experiment

To obtain the three parameters a, b and c, at least 3 sets of embedded depth and structural dominant frequencies were used. Since only the first set can be obtained from ambient vibration measurements in practical applications, the second set was obtained from the finite element model with the dominant frequency that of the non-lateral soil springs, that is, the zero embedded depth frequency. Similarly, the third set was also obtained by the finite element model of the dominant frequency with a scouring depth of one half of the initial embedded depth. From the above three data sets, the quadratic relationship between dominant frequency and embedded depth can be obtained and the embedded depth can then be derived by solving the quadratic function.

Experiment verification

In order to verify the performance of the proposed algorithm, a series of scouring tests on a scaled-down single bridge column with a caisson foundation were conducted. The complex scour phenomenon and the corresponding structural response including the dynamic signal of the superstructure, environmental factors and the embedded depth were recorded through the course of the experiment in order to provide the database required by the proposed scour monitoring system.

Experiment setup

The dynamic scouring experiment was executed in an indoor water channel 37 m long, 1 m wide and 1.5 m high, as shown in Fig. 6. A 1/36 scaled down bridge model shown in Fig. 7 was designed to simulate the behavior of bridge columns during the scour process. In order to precisely record variations in the embedded depth, an acrylic specimen was deployed along with a water-proof camera on the bottom of the channel, as shown in Fig. 8.

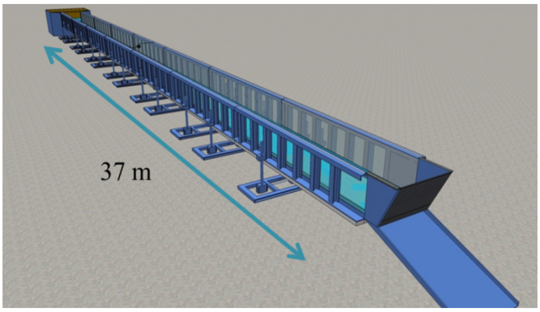

Fig. 6. Setup of the dynamic scour experiment

Fig. 7. The acrylic specimen

The proposed algorithm was embedded into a prototype monitoring system developed based on LabVIEW software and a National Instruments hardware platform with data acquisition, storage and real-time processing functionality, shown in Fig. 9.

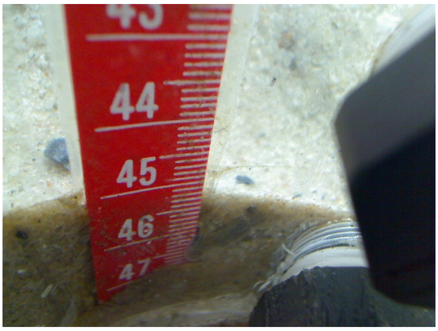

Fig. 8. The embedded depth monitored by camera

Fig. 9. The bridge health monitoring prototype

Verification

The initial embedded depth of the single bridge pier scouring test was 12 cm, and the maximum capacity was 40 cm. Similar to the static experiment, three sensors with a sampling rate of 200 Hz were placed on the top of the scaled down bridge model. In addition, a wireless inclinometer, thermometer and a water level gauge were deployed to measure the environmental factors with a sampling rate of 10 Hz, as shown in Fig. 10.

In order to verify the stability of the prototype system, the time history of the monitored environmental factors was recorded, as shown in Fig. 11, where the X and Y axes of the inclinometer represent the response in the flow direction and traffic direction, respectively. The water flow detected by the level gauge arrived at the water channel at about 100 seconds while the inclinometer decreased 1 degree in both X and Y axes. Based on the thermometer measurements, the temperature dropped 1.5°. It was observed that during the scouring experiment, the bridge column specimen remained stable with a steady water level of 10 cm. Therefore, the main factor influencing the variation in structural frequency could be inferred to be the changing of the embedded depth due to the scour effect.

As mentioned in Section 2.4, the initial embedded depth and the corresponding frequency were obtained from the experiment. The other two data sets required by the proposed algorithm, shown in Table 1, were derived from a finite element model that considered the effects of soil spring. The quadratic equation in this study was found to be:

$$Frequency. = 0.0035 \times Depth^2 + 0.2074 \times Depth + 9.2530 \quad (8)$$

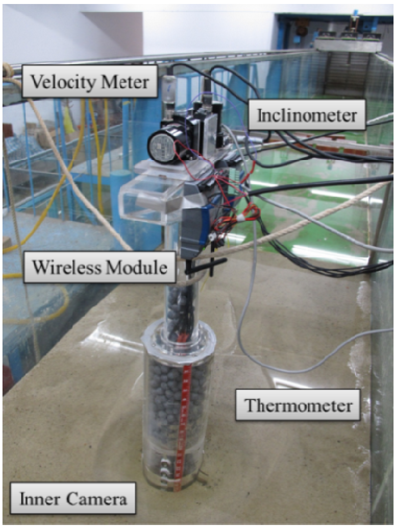

Fig. 10. Scour test setup

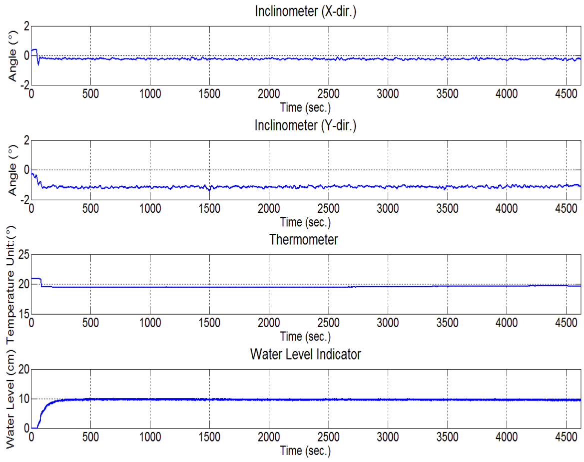

Fig. 11. Time history of environmental factors

Table 1. The embedded depth and dominant frequency

Depend on	Embedded depth (cm)	Dominant frequency (Hz)
Measured	12.0	12.2387
FEM	6.0	10.6234
FEM	0.0	9.2530

The frequency spectrum of the current direction was extracted from the measured vibration by the STFT every 2048 points, as shown in Fig. 12. The dominant frequency of the bridge column is depicted in Fig. 13.

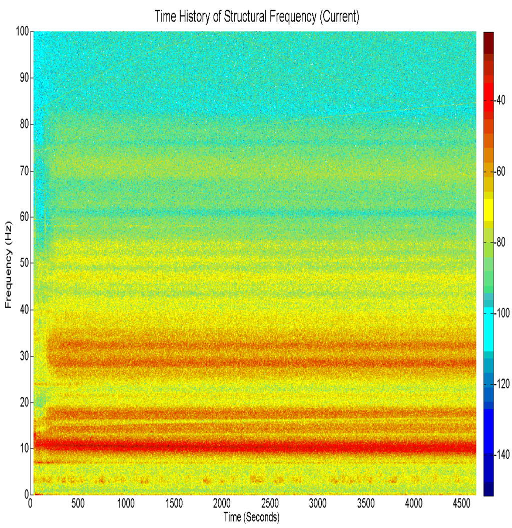

Fig. 12. STFT spectrum

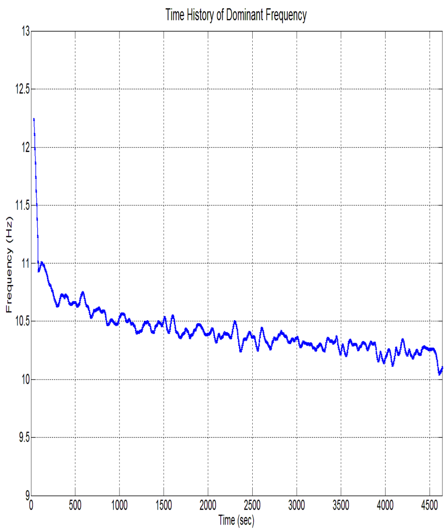

Fig. 13. Time history of dominant frequency

Based on the results, an excitation was generated by the arrival of water flow at 100 seconds and the fundamental frequency was maintained at around 12 Hz. Due to the rapid loss of embedded depth caused by the scour phenomenon, the structural frequency descended drastically and later stabilized at 500 seconds. In conjunction with the scour process, the dominant frequency continued to drop with small fluctuations of 0.1 Hz until reaching a frequency of 10 Hz. The decrease in fundamental frequency reached 2.3 Hz compared to the initial value after 4500 seconds and a scour hole 40 cm in diameter was observed, as shown in Fig. 14.

With the support of the frequency-time history, the embedded depth was able to estimate based on the proposed quadratic equation. The results are shown in Fig. 15 and compared to the time history of embedded depth recorded by the camera, which is depicted by the dashed line. The results clearly indicate that the predicted embedded depth offers a more conservative value than the actual embedded depth for the first half of the scouring process. The reason for this is discussed in the following section. As the inner camera only takes readings from the scour surface, the confinement of the soil at the beginning of bridge scour was not considered. The physical scouring conditions can be reflected by the proposed method, which estimates the embedded depth from the fundamental frequency. With the accompanying stabilization of the scouring process, the difference between the proposed algorithm and the inner camera gradually decreased to less than 1 cm after 2600 seconds, which can be treated as an acceptable measurement error. In short, a more sensitive and accurate embedded depth is able to be reflected by the proposed algorithm than using an inner camera and the structure stability is able to be evaluated accordingly.

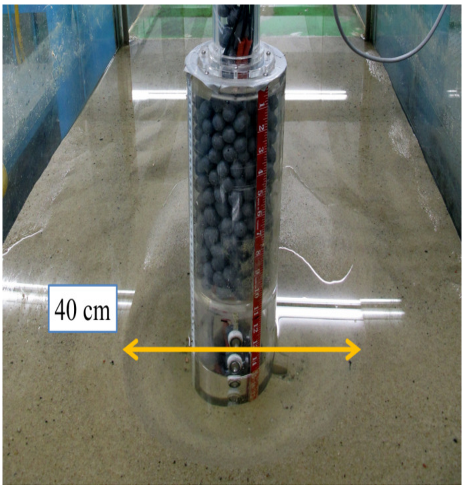

Fig. 14. Scour hole

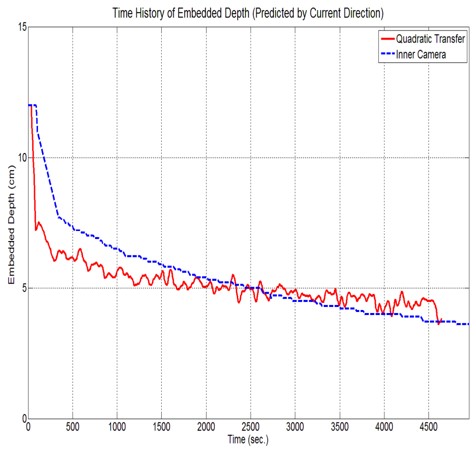

Fig. 15. Comparison of embedded depth between the proposed algorithm and inner camera

Conclusions

A vibration-based bridge health monitoring system focusing on the scouring issue in bridge columns was proposed. To analyze the complex fluid-solid coupling characteristics of bridge scouring, a preliminary static experiment was conducted. The results have clarified that the embedded depth of the bridge column is the primary governing factor of the fundamental frequency, as opposed to the water level. In order to clearly illustrate the scouring phenomenon, the confinement of the surrounding soil was simulated by a finite element model considering the soil spring. Moreover, a quadratic equation describing the relationship between the

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embedded depth and the dominant frequency was also proposed by utilizing three data sets, the first of which was obtained from experimentation and the other two from simulations. By integrating the STFT output, the real-time embedded depth of the bridge column was able to be rapidly estimated. A series of dynamic scouring experiments were then executed with the help of the developed prototype system to demonstrate the performance of the proposed system. The results have proven the reliable prediction of embedded depth by the proposed algorithm by analyzing the response from the superstructure only. This system would be a great help in saving human life and property in the near future.

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