ARTICLE IN PRESS

Mechanical Systems and Signal Processing ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Development of a real-time scour monitoring system for bridge safety evaluation

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ARTICLE INFO

Article history:
Received 28 October 2014
Received in revised form
31 May 2016
Accepted 31 May 2016

Keywords:
Bridge scour
Structural health monitoring
Rigid body motion
Structural instability

ABSTRACT

The fact that hydraulic problems are major factors in bridge collapse has made bridge scour monitoring an important research topic. In view of the complex nonlinear behavior of bridge structure/soil/water interactions, the fundamental frequency of the bridge may gradually change as the height of the bed drops during scour. With an insufficient embedded depth, the bridge may collapse or sink unexpectedly without warning. As experimental investigation in past research has shown that bridge failure may be governed by rigid body motion, a real-time bridge scour monitoring system to distinguish the influence of rigid body motion from the vibration frequency of the bridge is proposed. The signal measured from the superstructure of the bridge is decomposed into a structural vibration set controlling the fundamental frequency change and a rigid body motion set controlling the rigid body motion, and an instability index to examine the safety condition of the bridge is further proposed. Following a successful preliminary single-pile scour experiment, the method is applied to a series of full-bridge testing. According to analysis result, the instability index deviated considerably from its original range before the bridge piles began tilting significantly, allowing an early warning alert for bridge safety evaluation.

1. Introduction

Structures may encounter various kinds of external forces during the course of their life cycles. To prevent damage to structures, engineers must make judgments concerning the locations of potential problems without degrading the functionality of the structures, and must address aspects including remaining life, degree of reparability, and residual bearing capacity. Structural health monitoring (SHM) was first developed in the 1980s to facilitate structural safety. According to Rytter (1993) [1], structural health monitoring can be divided into four levels: (1) determination of damage existence, (2) determination of damage location, (3) judgment of degree of damage, and (4) forecasting of remaining usable life and capacity. In general, a SHM system must possess one or more of the attributes of versatility, immediacy, generalizability, and economy while a real-time early warning system must be able to rapidly determine the healthy state of a structure. Some relevant studies include the extraction of dynamic characteristics from structures by Lu and Cai [2], system realization using an information matrix (SRIM) based on linear system theory proposed by Juang, et al. [3], and the application of SRIM to

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http://dx.doi.org/10.1016/j.ymssp.2016.05.040
0888-3270/© 2016 Published by Elsevier Ltd.

derive the individual structural frequency, damping ratio, and vibration mode for the story damage estimation before and after an earthquake [4]. Moreover, inter-story drift mode shape (IDMS) has been used by Yao and Tsai to construct a structural diagnostic program[5], and the Hilbert-Huang transform (HHT) was also applied by Lin et al. to identify the mode shape and damping ratio of the structure [6]. The structural condition can then be updated from the responses under different damping parameters.

Bridge scour involves complex dynamic behavior reflecting factors such as water depth, water flow angle and strength, the shapes and width of the bridge, and attributes of sediments [7,8]. When sediment removal from the riverbed at a bridge site is greater than input, the embedded depth of the bridge will decrease. The scour degree D_{scour} in the bed height at a bridge site can be expressed as

$$D_{scour} = Q_{out(sand)} - Q_{in(sand)} \tag{1}$$

where $Q_{out(sand)}$ is the scour quantity of the river bed; $Q_{in(sand)}$ is the siltation quantity of the river bed.

When $Q_{in(sand)}$ is less than $Q_{out(sand)}$, the influence of scour will cause the bed to fall steadily.

Theoretically, three types of scour may influence bridge safety, namely, degradational scour, local scour, and contraction scour [9]. As the bearing ability of the soil decreases with an increase in the unsupported length of a bridge foundation, failure due to insufficient bearing ability may occur, and a bridge may also collapse by the hollowing -out of pier foundations.

In recent years, accompanying with the focus on hydraulic issues in bridge safety, many studies of scour monitoring have been carried out. For instance, five parameters including depth, average flow velocity, critical flow velocity, sand and column diameters were successfully applied to Bayesian neural networks for the prediction on scour depth [10]. A back-propagation neural network based method was proposed by Lee et al. to replace the traditional empirical equation for bridge scour prediction [11]. Moreover, use of vibration-based measurements to monitor the structural health of bridges was proposed [12]. The fractal theory has also been applied to analyze the instability of bridge columns [13], and a bridge health monitoring algorithm was developed based on the regression between the fundamental frequency of bridge column and the scoured depth [14]. The study from Chen et al. shows that the scour depth at a pier can be estimated by utilizing the two sensitive frequencies of local pier modes [15].

Over the last two decades, Hilbert Huang Transform (HHT) has been successfully applied in the field of SHM [16,17]. For its advantageous adaptability to nonlinear, aperiodic, nonstationary data, HHT is employed as a good candidate for signal analysis in a real-time bridge scour monitoring system in this study. By utilizing the concept of HHT, a real-time evaluation process for bridge safely is proposed. The remainder of this paper is organized as follows. The proposed method used in this study is first introduced in Section 2. By introducing an instability index as a diagnostic indicator, the safety condition of a bridge can be rapidly evaluated. To illustrate proposed process, a preliminary scour experiment involving a reduced-scale single-pier bridge was used as an example in Section 3. After verifying the feasibility of the proposed method, a series of reduced-scale full-bridge scour experiment was then performed in Section 4. Two types of commonly-used bridge piers, caisson-type pier and pile-group foundation, were employed, and the performance of the proposed bridge scour monitoring system was verified. Finally, a summary is given and conclusions are drawn.

2. The proposed scour monitoring algorithm

In 1998, the HHT was proposed on the basis of Hilbert transform and the empirical mode decomposition (EMD) method [18]. The HHT is widely used to analyze signals that are nonlinear, nonstationary, and time-variable. For an arbitrary time series $X(t)$, the analytic signal $Z(t)$ for the instantaneous frequency analysis can be expressed as

$$Z(t) = X(t) + iY(t) = a(t)e^{i\theta(t)} \tag{2}$$

$$\omega(t) = \frac{d\theta(t)}{dt} \tag{3}$$

where $Y(t)$ is the Hilbert transform of $X(t)$; $\omega(t)$ is the instantaneous frequency function

The variable amplitude and the instantaneous frequency have enabled the HHT to accommodate nonlinear and non-stationary data. This frequency-time distribution of the amplitude is designated as the Hilbert amplitude spectrum, $H(\omega, t)$, and the marginal spectrum $h(\omega)$ can be expressed as

$$\mathrm{h}(\omega) = \int_0^T H(\omega, t)dt \tag{4}$$

where $H(\omega, t)$ is the Hilbert amplitude spectrum.

The frequency in either $H(\omega, t)$ or $h(\omega)$ has a totally different meaning from the traditional Fourier spectral analysis. The Hilbert amplitude spectrum is a weighted non-normalized joint amplitude-frequency-time distribution. Consequently, the exact occurrence time of that oscillation is given in the full Hilbert spectrum while the frequency in the marginal spectrum

Please cite this article as: T.-K. Lin, Y.-S. Chang, Development of a real-time scour monitoring system for bridge safety evaluation, Mech. Syst. Signal Process. (2016), http://dx.doi.org/10.1016/j.ymssp.2016.05.040