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Critical insights for advanced bridge scour detection using the natural frequency

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A B S T R A C T

Scour around bridge foundations is regarded as one of the predominant causes of bridge failures. The concept of vibration-based real-time bridge scour detection has been explored in recent years by investigating the change in the natural frequency spectrum of a bridge or a bridge component with respect to the scour depth. Despite the progress, significant issues still remain unsolved in the application of this concept. This paper investigates three unsolved issues in the current framework of scour detection using the natural frequency spectrum: the physical meaning of the measured predominant natural frequency, the location of sensor installation, and the influence of the shape of scour holes, which are easily neglected but critical to the further implementations of the natural frequency spectrum-based bridge scour detection. Firstly, in-depth discussions of these three major issues were made separately by numerically modeling the scour progression of a typical and documented laboratory test. Laboratory tests were then performed to validate the conclusions made in the discussions. It was found that for an eigenproblem of the system with soil-structure interaction, the physical meaning of the natural frequency obtained from modal analysis can be understood by comparing the modal natural frequency with the natural frequency calculated from the dynamic response of the test component in that system. The results also verified that the obtained predominant natural frequency of the pier body greatly varies with the location of the pier body where a sensor is mounted for signal pickup. The shape of the scour hole affects the predominant natural frequency of the pier, causing difficulties in practical measurements. To address such a

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problem, a new criterion was proposed to identify the depth of unsymmetrical scour holes for the first time, which is of practical significance to advance the natural frequency spectrum-based scour detection framework.

1. Introduction

Scour around bridge foundations is regarded as one of the predominant factors in inducing bridge failures [1], which seriously threats the bridge safety as scour weakens bridge foundations by removing soils around them. To avoid this threat, numerous investigations have been made to predict scour severity. The most straightforward way is to estimate scour situations using empirical equations. Factors such as construction methods, scour models, and site conditions can be included in the empirical equations [2,3]. Stochastic approaches were also proposed to evaluate scour severity considering small errors and correlation coefficients [4,5]. As a result, the predicted results using these stochastic methods are more satisfactory than those using the empirical equations [4].

Numerical simulations, laboratory modeling, and in situ monitoring have also been used to evaluate bridge scour. The complicated scour process involving soil-fluid-structure interaction has been simulated using numerical models [6,7]; while the real situations affected by the water flow and soil interaction have been modeled in laboratory tests [8,9]. Results from both of these numerical simulations and laboratory tests can be utilized to better understand the effect of different factors on the scour development. Another direct and effective way is to use sensors and instruments in situ to detect scour progression. Sensors and instruments such as Fiber-Bragg Grating sensors and buried driven rods were applied for long term scour evolution monitoring [10,11].

A novel method based upon vibration to detect scour severity has been gaining momentum in recent years. The main advantage of this method is that it only requires a simple sensor such as an accelerometer to be installed at a bridge pier rather than expensive underwater instrument installation [12]. Previous underwater instruments such as float-out devices and Time Domain Reflectometry (TDR) sensors need to be positioned in the soil near a bridge pier before monitoring [13,14]. Also, TDRs are susceptible to environmental conditions such as temperature and radiation [14]. Instruments such as Ground Penetrating Radars cannot be used for continuous scour monitoring due to the limitations [15]. However, vibration-based bridge scour detection can address such limitations by investigating the variation of the natural frequency spectrum with respect to scour severity, which possibly provides a more effective way to detect bridge scour progression.

Many investigations have explored this novel scour detection concept based on the hypothesis that scour has an effect on the natural frequency spectrum of a bridge component such as a pier. One typical approach is to install a sensor at a bridge pier, either in the laboratory or in situ, to record its dynamic response generated by forced vibration. The change in the Predominant Natural Frequency (PNF), which is the main target for scour evaluation, is obtained by transferring the dynamic data from the time domain into the frequency domain using the Fast Fourier Transform (FFT) [12,16]. The other approach is to obtain the PNF by numerically modeling simplified lab-scale or full-scale bridges. The change in the PNF can then be obtained directly from simulations using modal analysis [17,18]. Despite the progress, unsolved issues still remain in both theoretical and practical aspects of vibration-based bridge scour detection.

To advance the topic, this paper discusses three easily neglected but critical issues in the current framework of implementing bridge scour detection using the natural frequency spectrum. 1. For an eigenproblem of a system with soil-structure interaction, the natural frequency obtained from the modal analysis in the designated direction (e.g., flow direction) was considered as the PNF of the bridge or the bridge pier of that system in that direction for scour detection [18]. It is unclear whether this PNF belongs to a bridge component such as a pier, to soils, or to the whole computational domain. 2. The dynamic response is obtained by sensors at some points at bridge components such as a pier or a deck for practical scour measurements [12,19]. However, little attention has been paid to the question, “Where is the best location of sensor installation?” 3. Previous simulations considered the change in the PNF with the development of symmetrical scour holes [12,20]. However, there has been no discussion on the effect of the unsymmetrical shape of scour holes on the PNF. In this paper, these three unsolved issues were discussed separately with numerical studies, which were validated against a documented laboratory test before the discussions. Then, laboratory tests were performed to validate the conclusions obtained in the discussions based on the numerical simulations.

2. A numerical model and its validation

The natural frequency spectrum of a bridge pier is affected by its boundary conditions. As scour changes the boundary conditions by removing the soil around the pier, bridge scour can be detected by observing the change in the natural frequency spectrum. In this section, a theoretical model is presented to simulate an existing scour laboratory test with assistance of a finite element program, ABAQUS. The accuracy of the numerical model was validated by comparing the simulation results with documented experimental results.

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