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Rapid assessment of foundation scour using the dynamic features of bridge superstructure

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HIGHLIGHTS

- Flood and scour represent the main cause of bridge failure in the United States.
- The vertically-displaced mode shapes are not sensitive to scour.
- The natural frequencies of significant horizontally-displaced mode shapes decrease as the magnitude of scour increases.
- The change in the flexibility-based deflection from the unscoured case can be used to detect the location of scour.

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ABSTRACT

The ability to ensure the resiliency and to predict the future performance of coastal bridges is very dependent on identifying damages in critical components of the bridge rapidly after an event. Traditional vibration based damage detection efforts focused mainly on the detection of fatigue cracking. Although detecting fatigue cracking is important, it does not contribute significantly to the total number of bridge failures in the United States. A critical review of the up-to-date literature showed that hydraulic loading, including scour, is responsible for about 50% of the failed bridges over the period of 1989–2000. To this end, the primary focus of this research is the development and evaluation of damage detection techniques capable of rapidly identifying and possibly quantifying the extent of deterioration of critical coastal bridges due to scour at submerged piers without underwater instrumentation. This paper illustrates, for the first time, the use of horizontally-displaced mode shapes and the calculated change in the dynamic flexibility features to identify scour from the response of the bridge superstructure.

1. Introduction

As of August 2009, the National Bridge Inventory revealed that 603,168 bridges currently exist in the United States (US). The Federal Highway Administration (FHWA) [10] rated 25% of these bridges as “deficient”. AASHTO announced in their 2009 Bottom Line Report [2] that 50% of US bridges, which are in daily use, are more than 40 years old without sufficient information on their current condition. And although they represent 50% of the bridges, they are responsible for 80% of structural deficiencies.

Wardhana and Hadipriono [27] collected 503 cases of bridge failures that occurred from 1989 to 2000 in the US. The age of the failed bridges ranged from one year (under construction) to 157 years, with a mean of 53 years and a mode of 63 years. They defined failure as the incapacity of a constructed facility (in this case, a bridge) or its components to perform as specified in the design and construction requirements. They concluded that the dominant types of failed bridges are steel beam/girder and steel truss bridges, which represent 50% of the total bridge failures. Moreover, they concluded that the leading cause of bridge failures (48%) is hydraulic loading which is mainly due to flood and scour. The ASCE Technical Council on Lifeline Earthquake Engineering [26] mentioned that the overall cost to repair or replace the bridges damaged during Hurricane Katrina, including emergency repairs, is estimated at over US $1 billion based on damage inspection reports and bid estimates. In Europe too, scour represents one of the major causes of bridge failures. For example, this problem represents a heavy burden for the Italian railroads in terms of operating disruption and expenses for the restoration of damaged bridges [6].

Further, visual inspection of bridges has limited capabilities in detecting all possible damages in bridges and there is the potential to miss damage that appears between inspection intervals. Nondestructive tests such as ultrasound, magnetic field methods, radiographs, eddy-current, and thermal methods require that the

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location of the damage be known a priori and the portion of the structure being inspected be readily accessible. Based on the current condition of bridges, the need for global damage detection methods that can be applied to complex structures has led to the development of methods that examine changes in the vibration characteristics of the structure [7].

The primary objective of this research is to develop and evaluate a damage detection technique that could be used to rapidly assess bridge scour following an extreme hydro-meteorological event without underwater instrumentation. This technique relies on the effect of scour at submerged piers on the dynamic response of the bridge superstructure. It should be mentioned that the proposed technique does not require continuous long-term bridge monitoring and could be integrated to detect other forms of damage.

An idealized bridge was investigated numerically and experimentally under four different levels of scour. The numerical simulations were used to investigate the effect of scour on the dynamic characteristics of the bridge while the experimental testing was used to develop the scour detection technique. The mode shape curvature and dynamic flexibility features were evaluated for this novel application.

2. Background

Scour is the result of the erosive action of flowing water, excavating and carrying away material from the bed and banks of streams and from around the piers and abutments of bridges. Determining the magnitude of scour is complicated by the cyclic nature of the scour process. During the increasing phase of the flood, the water's height and speed increase which tends to excavate pits in front of the bridge piers/piles. At the decreasing phase of the flood, the water velocity decreases and the leading transport and the suspended sediments precipitate and partially fill the pits. The suspended sediments that fill the excavated pits do not provide good confinement for the pile since they are not as compacted as the rest of the soil. This behavior underlines how the measurements carried out immediately after the event of flood are of little significance [6,11]. It should be mentioned that most of the available methods used to detect scour are either expensive such as Radar [14,16,21,23,6,20,15,18], or based on underwater instrumentation such as Time-Domain Reflectometry (TDR) [28] and Sliding Magnetic Collar (SMC) [19]. The most accurate of these methods is the Radar that can give a correct measurement of the amount of scour and the depth of the precipitated sediments. Unfortunately, following extreme events debris typically accumulates over the excavated scour pits and consequently Radar will measure an unrealistic scour level. Therefore, there is a need for a damage detection technique that may be able to identify bridge damages at the superstructure, such as fatigue cracking, as well as scour at submerged piers.

The overall response of a bridge to static and dynamic loads is influenced by the soil-foundation-structure interaction [12]. An analysis of the dynamic behavior of a bridge and the foundation system can provide useful data for the evaluation of scour. The dynamic response of the piers is expected to be strongly affected by the presence of a scour pit, even if filled, since the precipitated sediments are not compacted and do not represent a good confinement for the scoured piles.

Catbas et al. [3] investigated the modal flexibility-based deflection and curvature for damage detection. Different damage scenarios were simulated on a large-scale laboratory structure and a three-span highway bridge for demonstration including scour/settlement. They simulated scour of the laboratory structure as the total loss of the intermediate pile. The pile loss scenario on the test structure was achieved by removing the roller support between the superstructure and the steel pile. It should be mentioned that it is not very realistic to simulate scour in this severe case as it should be detected at an earlier stage. In the real life application, a number of different damage scenarios were applied such as changes at the boundary conditions including bearing removal, cutting steel elements at different levels, and breaking of composite action between deck and steel girders progressively. Foti and Sabia [12] studied the influence of scour on the dynamic response of an existing bridge. The bridge was monitored once prior to retrofitting and then after the replacement of the scoured pier. Two different approaches for monitoring foundation scour, using traffic-induced vibrations, were evaluated to examine its applicability. The modal identification of the bridge spans (identifying the eigenvalues and eigenvectors associated with each mode of vibration) was one approach and the analysis of the dynamic response of the pier foundations was the other. It should be mentioned that the modal identification comparison did not show a significant change due to scour while the dynamic response of the foundations clearly identified the presence of scour at the damaged pier, however, underwater instrumentation would be required in the case of submerged foundations. Hence, there is a need to consider alternative methods which is the focus of the remainder of this paper.

3. Numerical simulation

For this investigation, an idealized structure representing a two-span continuous bridge was selected. This steel grid was investigated by Catbas et al. [3] as previously mentioned. A schematic of the idealized structure is shown in Fig. 1. The model has two 5.5 m (18 ft) girders in the longitudinal direction. The lateral stability is provided by 1.8 m (6 ft) transverse bracing beams at 0.9 m (3 ft) intervals. Each member of the superstructure has the same cross-section. An S3 × 5.7 beam section was found by the previous researchers to be the most desirable in terms of modal frequencies, deflections, rotations, stresses, and strains to represent a short to medium span highway bridge [3]. In addition, the structure is doubly symmetric. The steel grid is supported on six steel piles with W12 × 26 cross-section. The height of the steel piles is 1.1 m (42 in.). A finite element (FE) model using SAP 2000 was created for this specimen, where the steel grid was modeled as frame elements and the steel piles were replaced by pin and roller supports. The steel grade for the specimen under study was A992F50. An eigenvalue analysis was performed to extract the dynamic characteristics of the structure. It should be mentioned that the difference between the natural frequencies of the FE model and

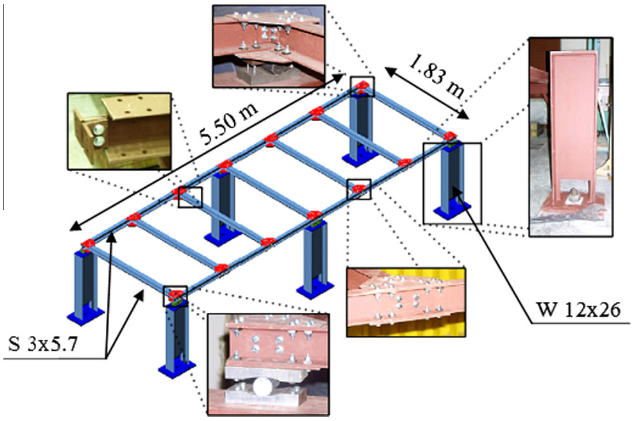

Fig. 1. Schematic of test specimen [3].