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Assessing Foundation Scour Using the Dynamic Features of the Bridge Superstructure

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ABSTRACT: Extreme hydro-meteorological events are a major cause of concern in coastal regions, particularly with respect to the resilience of critical civil infrastructure. 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 to 2000. Hence, the ability to rapidly quantify the effect of scour, immediately following an event, on the residual strength or endurance of critical life-line bridge infrastructure is of paramount importance. To this end, the primary focus of this research is the development and evaluation of vibration-based damage detection technique capable of rapidly identifying and possibly quantifying the extent of scour at submerged piers without underwater instrumentation. The outcomes of this research will ensure resilience to disasters by enhancing preparedness, ensuring effective emergency response, and facilitating rapid recovery.

1 INTRODUCTION

As of August 2009, the National Bridge Inventory [FHWA, 2009] revealed that 603,168 bridges exist in the United States. The Federal Highway Administration (FHWA) rated 12% of these bridges as “structurally deficient” and 13% as “functionally obsolete”. In 2003, a research [Wardhana, 2003] was performed on the bridge failures that occurred from 1989 to 2000 in the United States. It was concluded that the leading causes of bridge failures are flood/scour (48%), collision (12%), and overload (9%). The FHWA defines scour as erosion or removal of streambed or bank material from bridge foundations due to flowing water, usually considered as long-term bed degradation, contraction and local scour.

Robertson et. al (2007) studied the performance of the engineered structures, including coastal bridges, when subjected to Hurricane Katrina storm surge. They observed extensive scour around abutments and piers, building foundations, and highway pavement structures along the affected areas of the Gulf Coast. This scour contributed to the partial or complete collapse of a number of coastal structures. According to the Technical Lifelines Council for Earthquake Engineering [TCLEE, 2006], the overall cost to repair or replace the bridges damaged during Hurricane Katrina, including emergency repairs, is estimated at over one billion dollars based on damage inspection reports and bid estimates.

Scour failures tends to occur suddenly and without prior warning or signs of distress to the structures. Further, the measurement of local scour at submerged piers is not simple. 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. Moreover, 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.

To this end, the primary objective of this research is to develop and evaluate a vibration-based scour detection technique following an extreme hydro-meteorological event without underwater instrumentation.

2 NUMERICAL SIMULATION

A numerical simulation was carried out on an idealized steel bridge to study the effect of scour on the dynamic response of a bridge. This structure was investigated previously [Catbas et al., 2008] to investigate the applicability of two different damage features for damage detection. A schematic of the test specimen is shown in Figure 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 S3x5.7 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 [Catbas et. al, 2008]. In addition, the structure is doubly symmetric. The steel grid is supported on six steel piles with W12x26 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 shell 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 the experimental results for the first five mode shapes did not exceed 8% [Elsaid, 2012].

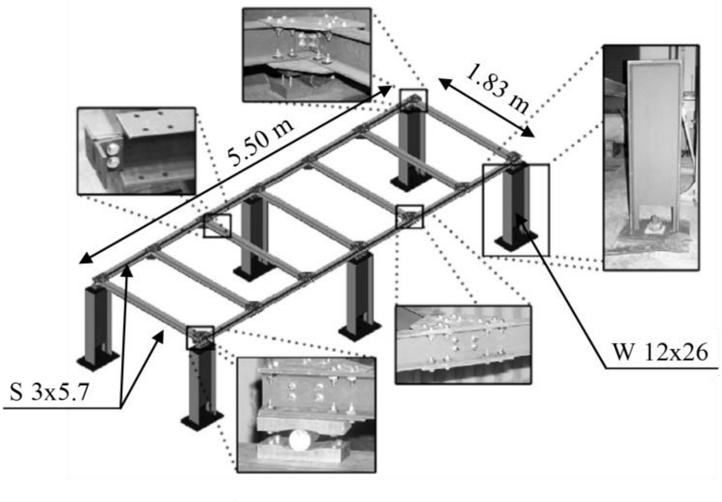

Figure 1. Schematic of the test specimen [Catbas et al., 2008]

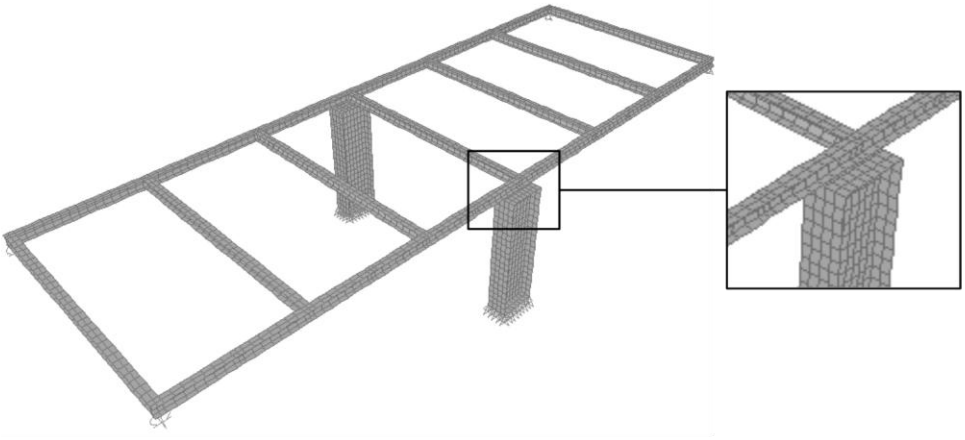

Figure 2. Finite element model of idealized bridge

After verification, the model was modified to simulate an idealized coastal bridge, where the intermediate piles were modeled as shown in Figure 2. The rotation of the steel grid was allowed over the intermediate piles. The abutments at both ends were idealized with simple pin and roller supports. Four FE models were created. The first model represented the reference (unscoured) case and the other three models simulated three different levels of scour. Scour was modeled as an increase in the unsupported height of the intermediate piles as recommended by previous researchers [Hughes et. al., 2007]. The height of the unscoured pile case is 1.1 m (42 in) [Catbas et. al., 2008] while the heights of the scoured pile cases are 1.3, 1.5 and 1.7 m (50, 58 and 66 in). It should be mentioned that the maximum scour level under study was 0.6 m, which is equivalent to 55% of the original pile height. This value represents a realistic extreme scour case [Robertson et. al, 2007].

2.1 *Finite Element Results*

The results of the modal analysis were categorized according to: 1) vertically-displaced mode shapes; and 2) horizontally-displaced mode shapes. The natural frequencies for different scour levels are summarized in Table 1. It was observed that there are no visible changes in the first five vertical mode shapes for different scour levels. Consequently, the dynamic characteristics of the vertically-displaced mode shapes are insensitive to scour which could be attributed to the small effect of the reduction in the axial stiffness of the piles on the dynamic response of the superstructure in the vertical direction. Therefore, the dynamic characteristics of the vertically-displaced mode shapes may be used to assess damages in the superstructure, such as fatigue cracking, as investigated by previous researchers [Doebling et. al, 1996]. This result might also explain the simulation of scour by previous researchers as the complete loss of the intermediate support [Catbas et. al, 2008] since they focused only on the vertically-displaced mode shapes. Conversely, the dynamic characteristics of the horizontally-displaced mode shapes showed significant changes due to scour. Figure 3 shows the schematics for the first five horizontally-displaced mode shapes. From Table 1, it can be concluded that as the pile height increases, the flexural stiffness of the intermediate piles decreases and the natural frequencies of the horizontally-displaced mode shapes decrease which suggests that the natural frequencies may be used to quantify the level of scour. Further, the second and fourth horizontal mode shapes were insensitive to scour (insignificant modes). This is due to the presence of the intermediate pile at a stationary node. It should be mentioned that it is not possible to locate damages at all locations using only one mode shape [Abdelwahab and De Roeck, 1999].

3 EXPERIMENTAL WORK

The idealized structure, analyzed in the previous section, was fabricated and tested at the Constructed Facilities Laboratory, North Carolina State University, to verify the proposed technique. The idealized structure setup is shown in Figure 4, where the superstructure was supported on two intermediate steel piles. The two end abutments were idealized by two stiff laboratory reaction frames. Roller bars were used between the steel grid and the supports (including the intermediate piles and the reaction frames). To provide the horizontal reaction, steel angles were welded to the supports against the steel grid.

Table 1. Natural frequencies (Hz) of the idealized bridge from FE simulation

Scour (m)	Vertically-displaced mode shapes					Horizontally-displaced mode shapes				
	1st	2nd	3rd	4th	5th	1st	2nd	3rd	4th	5th
0	21.47	27.23	32.27	41.96	59.49	21.10	18.65	44.37	47.64	65.83
0.2	21.47	27.23	32.26	41.96	59.45	19.92	18.64	38.43	47.64	61.20
0.4	21.47	27.23	32.26	41.96	59.42	18.35	18.64	34.14	47.64	59.38
0.6	21.46	27.23	32.26	41.96	59.42	16.58	18.64	31.52	47.48	58.45

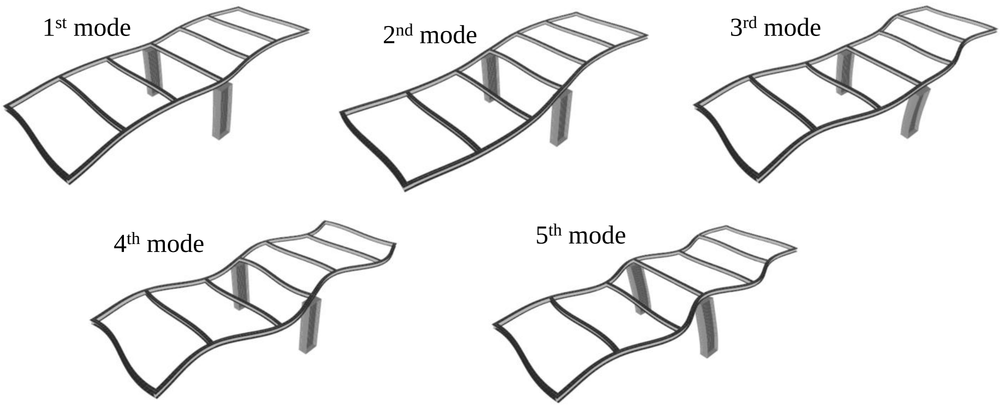

Figure 3. Schematic for the first five horizontally-displaced mode shapes

Unidirectional IEPE accelerometers were used to record the dynamic behavior of the steel grid under various scour levels. Shanon's idea of mutual information [Gallager, 1968] was used to find the optimal distance between sensors so that information is neither lost nor duplicated between two adjacent accelerometers. This optimal distance will in fact be the distance that makes information between adjacent sensors independent. From this analysis, it was chosen to use a spacing of 0.46 m (18 in) [Elsaid, 2012]. Consequently, a total of 11 uniformly distributed accelerometers were used to measure the vibration responses of the specimen in the horizontal direction. Further, four additional accelerometers, one at each connection, were mounted vertically to track the vertical dynamic behavior of the specimen. Impact loading was applied using a PCB modally tuned impact hammer to excite the bridge at different locations [Elsaid, 2012].

Figure 4. Idealized bridge test setup

The specimen was excited at the superstructure in the vertical and the horizontal directions. At each impact location, at least five tests were performed to reduce the uncertainties in the recorded signals. Five successive impacts were performed at each test. This leads to longer recorded signal and suggests that satisfactory confidence can be achieved in spectral estimates of the frequency response acquired [Duron et. al, 2005].

3.1 Experimental Results

Figure 5 shows the first five vertically-displaced and the first five horizontally-displaced mode shapes, respectively. It can be observed that the horizontally-displaced mode shapes are sensitive to scour which confirms the numerical simulation outcomes. The averaged natural frequencies for different scour levels are summarized in Table 2. The natural frequencies extracted from the experimental results are different from those predicted by numerical simulation. This is due to the simulation of the bottom end of the piles as fixed in the FE models, which is practically very difficult to achieve for such a small base plate in the laboratory. The actual connection could be assumed to be partially fixed which reduces the stiffness of the piles from the assumed fixed connection. As expected, the natural frequencies for the vertically-displaced mode shapes at various scour levels did not significantly deviate from the unscoured case, where the maximum change was approximately 3%. On the other hand, the natural frequencies for the horizontally-displaced modes decrease as the scour level increases which can be used to identify the presence of scour.

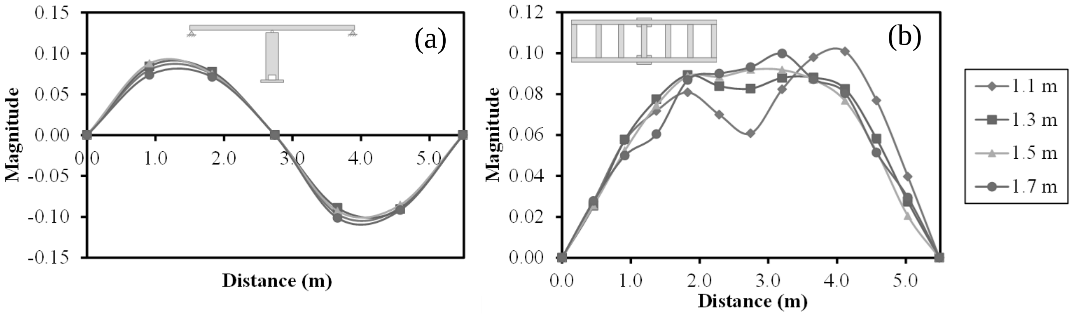

Figure 5. First five (a) vertically-displaced and (b) horizontally-displaced mode shapes.

Table 2. Natural frequencies (Hz) of the idealized bridge from experimental testing

Scour (m)	Vertically-displaced mode shapes					Horizontally-displaced mode shapes				
	1st	2nd	3rd	4th	5th	1st	2nd	3rd	4th	5th
0	23.45	28.93	33.69	42.76	64.10	18.71	20.64	34.99	52.07	63.32
0.2	23.83	29.51	33.94	43.73	63.80	16.45	20.88	32.54	51.92	63.44
0.4	23.25	28.55	34.47	42.97	63.53	14.89	20.86	31.55	52.67	62.79
0.6	24.05	29.73	34.76	43.98	63.67	14.47	20.96	31.32	52.37	62.40

4 DAMAGE FEATURES

The area of Structural Health Monitoring (SHM) that receives the most attention in the technical literature is feature extraction. Feature extraction is the process of identifying damage-sensitive properties, derived from the measured dynamic response, which allows one to distinguish between the undamaged and damaged structure [Sohn et. al, 2003]. After modal parameters (i.e. natural frequencies and mass-normalized mode shapes) were obtained experimentally, modal flexibility based deflections were investigated for damage detection.

4.1 Flexibility-Based Deflection

The dynamically measured flexibility matrix represents a damage identification method to estimate changes in the static behavior of the structure. The flexibility matrix is defined as the inverse of the stiffness matrix. It reflects the relationship between the applied static force and the resulting structural displacement. In the flexibility matrix, each column represents a set of nodal displacements of the structure due to a unit force applied at one of the DOF. The measured flexibility matrix [G] can be estimated from the mass-normalized measured mode shapes [Φ] and frequencies as follows [Doebling et. al, 1996]:

$$[G] \approx [\Phi].[\Lambda]^{-1}.[\Phi]^{T} \tag{1}$$

where, $[\Lambda]^{-1}$ is a diagonal matrix containing the reciprocal of the square of the natural frequencies in ascending order. It should be mentioned that the formulation of the flexibility matrix in Equation 1 is approximate due to the fact that only the first few modes of the structure are measured. However, this approximation in calculating the flexibility matrix is acceptable due to the inverse relation between the flexibility matrix and the square of the modal frequencies. This relation makes the flexibility matrix converge rapidly with the increasing values of frequency.

After obtaining the scaled dynamic flexibilities, the deflections under static loading can be calculated by multiplying the dynamic flexibility matrix by any given load vector. In this study, the flexibility matrix was multiplied by a unit load vector to detect the deflected shape due to a uniform horizontal unit load. The deflections calculated using the first five horizontally-displaced mode shapes for various levels of scour are shown in Figure 6. It can be concluded that as scour level increases, the horizontal deflection of the longitudinal girder increases. This is attributed to the decrease in the flexural stiffness of the pile as their height increases.

From the pre- and post-damage flexibility values, a measure of the deflection change caused by damage can be obtained from the difference of the deflection vectors. The change in the flexibility-based deflections of various scour levels from the unscoured case is shown in Figure 7. It was found that the location of scour coincides with the peak of the change in the flexibility-based deflections. Further, as the scour level increases, the magnitude of change in the flexibility-based deflection from the unscoured case increases. This leads to the hypothesis that the change in the flexibility-based deflection may be used to quantify the amount of scour as well as the location of scour.

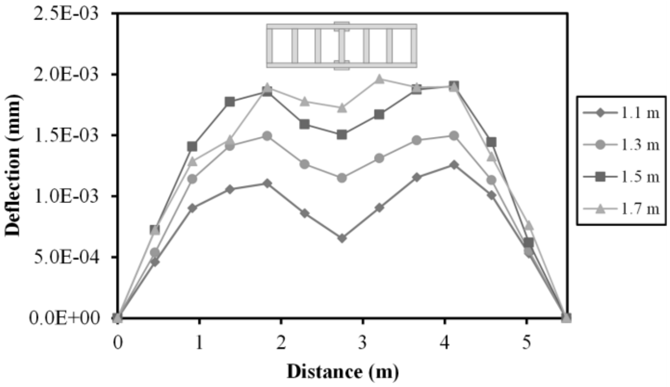

Figure 6. Horizontal deflection calculated from the experimentally calculated dynamic flexibility

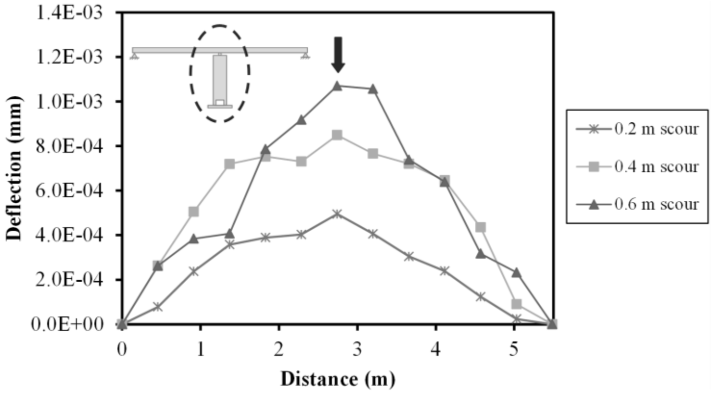

Figure 7. Absolute change in experimentally calculated flexibility-based deflection for various levels of scour

5 CONCLUSIONS

Based on the findings of the current study, the following outcomes may be drawn:

1. Flood and scour represent the main cause of bridge failure in the United States.
2. The dynamic characteristics of bridges can be categorized according to: (1) vertically-displaced mode shapes and (2) horizontally-displaced mode shapes.
3. The vertically-displaced mode shapes are not sensitive to scour; however, they could be used to detect damages of the superstructure.
4. The natural frequencies of significant horizontally-displaced mode shapes decrease as the magnitude of scour increases.
5. The change in the flexibility-based deflection from the unscoured case can be used to detect the location of scour where the location of scour coincides with the peak of the change in the flexibility-based deflections.

6. The magnitude of change in the flexibility-based deflection increases as the scour level increases which makes them applicable for identifying the extent of scour.

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