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Assessment of structural integrity of bridges under extreme scour conditions

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ABSTRACT

Scour has been reported as the cause of approximately half of bridge failures in the United States. It alters static and dynamic characteristics of bridges and may lead to excessive deflections and increased maximum actions induced in structural members. To estimate the response of bridges under scour conditions, comprehensive models of representative bridges that overpass waterways are developed in this study. The bridge models account for the nonlinear soil–pile–structure interactions, the nonlinear response of the abutments and columns, as well as the predominantly linear contribution of the superstructure. Different types of scour, including local scour, general scour, and aggradation/degradation are investigated and their effects on the bridge structural system are quantified. The lateral response of the structure is studied as it varies dependent on the composition of the supporting soil profile and the magnitude of the scour depth. In addition, a set of scour scenarios is introduced to represent varying scour intensities that a bridge may experience during its service life. The effects of scour on the lateral performance of a case study bridge/soil profile have been evaluated using the developed analysis procedure. The outcome of this study is an efficient approach that can be used for the design and assessment of bridges under extreme scour conditions.

1. Introduction

Scour is the leading cause of bridge failure in the United States. Between 1950 and 1991, 60% of failures were induced by hydraulic causes, including scour and channel instability [39]. Between 1989 and 2000, 16% of failures were caused by scour and 33% were caused by flood (and the majority of the failures attributed to flood were scour-related) [42]. As of 2003, 26,472 bridges over waterways were scour-critical in the United States [15]. Same failure cases have been reported in other parts of the world [13,24]. These facts call for the development of an integrated analysis procedure that can help bridge owners and Departments of Transportation to evaluate the capacity, stability, and integrity of scoured bridges so that timely management strategies can be undertaken to prevent the failure of bridges under critical flood/scour conditions.

Many research studies have been conducted to develop an integrated scour-analysis procedure. Avent and Alawady [7] studied the effect of scouring on the buckling capacity of the group piles. Hughes et al. [18] investigated the buckling and pushover behavior of scoured bridges. Lin et al. [25] studied the importance of considering the stress-history of sands surrounding bridge piles when modeling the effects of scour on the lateral response of bridges. Foti and Sabia [16] used in-field measurements to predict the effects of scour on the dynamic response of a case-study bridge. Lin et al. [26] developed an integrated model to analyze the performance of pile-supported bridges with scouring conditions. McConnell and Cann [31] used the monitoring data collected from the Indian River Inlet Bridge to inspect the effect of scour on pushover capacity of bridges. Tanasić et al. [40] used the existing data to estimate the scour vulnerability of bridges in the road network in southeastern Serbia. Prendergast et al. [36] estimated the changes in the natural frequency of the piles affected by scouring. Klinga and Alipour [22] studied the lateral response of deep foundations in layered soils. Alipour et al. [4] evaluated the probability of failure of reinforced concrete bridges supported on pile shafts under the combined effects of scour and earthquake.

Previous research has been conducted primarily with a focus on either the bridge superstructure or substructure, rather than on the full structural and soil response. Furthermore, the effect of site conditions on the performance of the scoured bridges has not been thoroughly covered, and many of the studies have used simplifying assumptions to model the effect of soil–pile interaction. The current study emphasizes on the interaction between water, soil, pile, abutment, possible debris, and superstructure, and provides

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engineers with accurate analysis guidelines capable of considering each of these contributing components. The analysis steps given in this paper provide engineers with a fast and accurate tool to analyze scour-critical bridges and to determine their integrity following possible flood events.

This paper focusses on scour's effects on the response of bridges supported on pile-group foundations (while also including pile-shaft models to compare their response). The soil–pile interaction is modeled by converting soil profile information to '*p*–*y*', '*t*–*z*', and '*q*–*z*' spring stiffness curves, and applying soil springs in the *x*-, *y*-, and *z*-directions along the length of each pile. A comprehensive study on different types of scour and the procedure to calculate them is provided. To model the effects of scour, several scour states are simulated varying in severity from no scour to extreme-flood-induced scour depths expected for a representative river. The lateral response of the structure is studied as it varies dependent on the composition of the supporting soil profile and the magnitude of the scour depth. The shear forces and bending moments generated throughout the length of columns and pile groups are estimated, as well as the forces in abutment springs. This information will be useful for the analysis of existing scour-critical structures, and will also serve as a helpful tool for design purposes.

It should be noted that in designing for the concurrence of scour and another loading/hazard condition, probabilistic analysis should be conducted to evaluate the likelihood of their concurrence, and the calculated probabilities should be incorporated into the design methods. Additionally, in the design for concurrent extreme events, the importance of the structure for the transportation system should be considered. For example, a bridge that serves as the only point connecting an island to mainland might require a more robust design compared to a bridge in a dense transportation system with ample alternate routes [3,5].

In addition to aiding in design considerations, the results of this study will be useful in evaluating existing bridges. Data from in-place scour monitoring systems [12], which provide estimates of scour depths, can be used in combination with the analytical framework developed by this study to estimate the performance capabilities of scoured bridges [14]. Steps could then be taken either to replace or retrofit bridges found to be structurally deficient. However, in developing retrofit designs, it should be noted that increasing the volume of flow-obstructing elements should be avoided as increased obstruction leads to increased scour depth [7].

The objective of this study is to provide a comprehensive procedure that considers the soil–pile–structure interaction to measure the susceptibility of the bridges under design flood conditions. The uniquely comprehensive framework developed here can be readily applied by bridge engineers in the design and evaluation of existing bridges, as it is especially capable of accurately capturing the soil–pile–structure interaction by considering substructure, superstructure, and fluid dynamic component in union. The proposed procedure implements: (i) a detailed procedure to calculate scour depth considering different types of scour (Section 2), (ii) nonlinear soil–pile–structure interaction which models each pile's soil response individually (Section 3), (iii) a detailed model of the bridge structure including the deck, abutments, columns, and pile groups/pile shafts incorporating a nonlinear abutment model (Section 4), and (iv) guidelines for pushover, buckling, and modal analysis (Section 5).

2. Estimation of scour depth

To calculate the scour depth, AASHTO [1] refers engineers to the guidelines provided in HEC-18 [17]. These guidelines are used to determine the design scour depth for planned bridge projects and also to evaluate the scour risk of existing bridges. There are three major types of scour: (1) Aggradation/degradation account for the long term changes in streambed elevation which occur whether or not a bridge is present. Aggradation is the rise of the streambed due to a surplus of sediment upstream, while degradation is the fall of the streambed due to a deficit of sediment upstream. General scour is the decrease in the elevation of the streambed due to the contraction of the flow caused by the bridge structure, and the resulting increased velocity. (2) General scour is different from degradation in that it can progress rapidly and that it only occurs around the bridge site. (3) Local scour is the decrease in elevation of the streambed immediately next to the bridge piers and abutments due to the increase in velocity and the formation of vortices as flow bends around these elements.

The models introduced by HEC-18 [17] estimate the effects of the three types of scour based on river flow conditions, soil composition, and riverbed and bridge geometries. The aggradation/degradation scour is estimated by studying the geology, hydrology, and geomorphology of the site, evaluating any trends of aggradation and degradation in the gaging station records for the waterway being considered, investigating the bridge inspection reports for bridges along the same waterway, and using this information along with engineering judgment to estimate the maximum aggradation or degradation which might occur over the next 100 years. If degradation is predicted, this degraded elevation is used as the starting elevation for further scour calculations, whereas if aggregation is predicted, the current streambed elevation is used.

General scour is dependent on whether the flow is live-bed (Eq. (1)) or clear-water (Eq. (2)). Live-bed flow is defined as having sufficient strength to suspend the bed material, whereas clear-water flow is defined as not having sufficient strength to suspend the bed material.

$$\frac{y_2}{y_1} = \left(\frac{Q_2}{Q_1}\right)^{6/7}\left(\frac{W_1}{W_2}\right)^{k_1} \tag{1}$$

$$y_2 = \left(\frac{K_{u2}Q_2^2}{D_m^{2/3}W_2^2}\right)^{3/7} \tag{2}$$

where y_1 is the average depth of the upstream streambed after degradation, y_2 is the average depth of the streambed beneath the bridge after degradation and general scour (Fig. 1), Q_1 is the flow rate before the bridge, Q_2 is the flow rate beneath the bridge, W_1 is the bottom width of the streambed before the bridge, and W_2 is the bottom width of the streambed beneath the bridge minus the widths of the bridge supports which obstruct the flow, k_1 is the bed material transport mode coefficient (ranging between 0.59 and 0.69), K_{u2} is the clear-water coefficient (0.025), D_m is the diameter of the smallest non-transportable particle in the bed material (=1.25D_{50}), and D_{50} is the median diameter of bed soil particles from the upper 0.3 m of the streambed. It should be noted that for all equations in this paper, units of meters should be used for length, and m^3/s should be used for flow.

The local scour around a single pier is determined using Eq. (3):

$$y_3 = y_2\left[1 - 2.0K_1K_2K_3K_4\left(\frac{a}{y_2}\right)^{0.65}Fr^{0.43}\right] \tag{3}$$

where y_3 is the average depth of streambed around piers after degradation, general scour, and local scour (Fig. 1), K_1 is the pier shape coefficient (=1.0 for circular piers), K_2 is the flow angle coefficient (=1.0 for a zero angle between the flow and the length of the pier), K_3 is the bed geometry coefficient (ranging from 1.1 for clear water scour, anti-dune flow, and/or small-dunes to 1.3 for large dunes), K_4 is the bed-armoring coefficient (ranging from 0.4 to 1.0 based on D_{50} and D_{95}, with larger diameters yielding smaller K_4 values), a is