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Vulnerability evaluation of scoured bridges under floods

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ABSTRACT

The erosion or removal of soil from around bridge foundations due to scour can significantly increase the vulnerability of bridges under flood conditions. It has been reported that scour at bridge foundations due to flooding is a major cause of bridge failure. While retrofitting bridge foundations with additional piles is a common approach to improve the resilience of scour-critical pile-supported bridges, its effectiveness remains to be explored. The objective of the study is to develop a rational vulnerability evaluation method for scoured pile-supported bridges under flood conditions. In addition, the effects of scour depths and foundation retrofitting work on the failure mechanism and vulnerability of bridges subjected to flood-induced loading are quantitatively investigated. The investigation is conducted using a complex nonlinear three-dimensional finite element model that accounts for the interactions between bridge structures, soils, water flow, and pile foundations. The validity of the developed vulnerability evaluation method is demonstrated using the Shuang-Yuan Bridge that collapsed during a flood event in 2009. Finally, a safety management procedure for scour-critical bridges is suggested.

1. Introduction

Scour during flood conditions can erode away the soil around the foundations of pile-supported bridges. The exposure of pile foundations reduces the stability as well as the bearing capacity of bridges. It has been reported that excessive scour is the major cause of half of the bridge failures in the United States [1]. Significant scour has also caused serious damage to numerous bridges in Taiwan since 2000 [2]. Recent research results further show that climate change has increased the probability of bridge failure due to scour [3]. It is therefore essential to identify scour-critical bridges and take necessary actions to reduce their failure probability. Although a variety of scour prediction methods have been developed to improve the scour design for bridges [4–8], only limited research has been carried out to evaluate the effect of scour on the behavior of bridges [9–16]. In addition, while the retrofitting of bridge foundations with additional piles is a common approach to enhance the flood resistance of scoured bridges, it also adversely magnifies the flood-induced loads acting on the bridge during flood conditions. Its feasibility for scoured-critical bridges requires further investigation.

The first objective of the study is to understand the mechanical behavior of scoured bridges under flood conditions. The behavior is investigated using a complex nonlinear three-dimensional finite element model. An actual reinforced concrete bridge in Taiwan that has three variations is employed for investigation purposes. The effects of scour depths and foundation retrofitting work on the failure mechanism and vulnerability of the bridge subjected to flood-induced loading are studied. The second objective of this paper is to develop a simple and reasonably accurate safety evaluation method that is capable of assessing the vulnerability of scoured bridges under flood conditions. The evaluation method allows authorities to identify scour-critical bridges prior to and during flood events.

2. The Shuang-Yuan Bridge

The Shuang-Yuan Bridge constructed in early 1970 in Taiwan is employed as the prototype bridge in the study. As illustrated in Fig. 1, the bridge is composed of 3-span continuous units with each span 30.6 m long. The total length of the bridge is 2083 m. The superstructure of the bridge consisting of I-type prestressed concrete beams is supported by single-column piers. The dimensions of the bridge columns are plotted in Fig. 1(b). Each bridge column is supported on pile foundations consisting of a pile cap and six reinforced concrete circular piles. The piles, which are 44 m in length, have different longitudinal reinforcement designs for the exterior and interior piers in each bridge unit. The design details for the pile foundations are shown in Fig. 2(a).

Due to the scour risk, the foundations of piers P5–P14, P22–P25, and P30 were retrofitted in 2003 by enlarging the pile caps and

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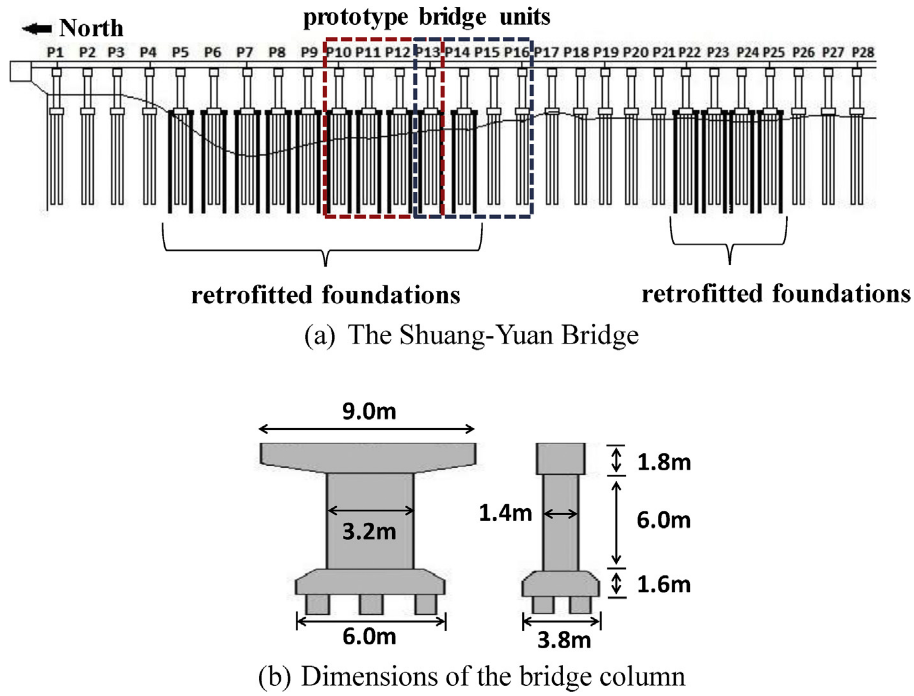

Fig. 1. The Shuang-Yuan Bridge.

installing four additional 50 m long reinforced concrete piles. Fig. 2 (b) shows the layouts and the reinforcement designs for the retrofitted foundations. Although the Shuang-Yuan Bridge had been retrofitted, piers P2–P16 collapsed in a flood event in 2009. Existing evidence [17] shows that the collapse of the bridge was mainly caused by the significant scour at the bridge foundations. The collapse of the bridge was initiated at bridge unit P10–P13 and then propagated to P2 and P16.

3. Nonlinear finite element bridge model

In order to represent the complicated inelastic behavior of scoured bridges subjected to flood-induced loads with reasonable accuracy, a complex nonlinear three-dimensional finite element bridge model is established using the finite element analysis software package LS-DYNA [18]. The modeling of the prototype bridge consists of three main tasks, i.e., the bridge structure and the pile foundations, soil reaction forces, and flow-induced loads.

For the bridge structure and pile foundations, the concrete parts are modeled using three-dimensional solid elements whereas the steel bars are represented by truss elements. The nonlinear behavior of concrete materials is represented using a constitutive relationship based on a three-invariant model with three shear failure surfaces [19]. The concrete material model was shown by Schwer and Malvar [19] to be capable of addressing the concrete behavior under multi-axial stresses. Further details about the concrete constitutive model can be found in [19]. The nonlinear behavior of steel bars is represented using a bilinear elastic-plastic model with a 5% hardening ratio. The concrete and steel material properties in the employed material models, listed in Table 1, are decided based on the available material data of the Shuang-Yuan Bridge [20].

As for the simulation of the pile-soil interaction, the well-known Winkler model is employed. Independent, translational spring elements are used to simulate the lateral reaction force of soil. Table 2 summarizes the blow counts of the standard penetration test (SPT-N values) at the bridge site (P10–P16) that were obtained from the on-site investigation [20,21]. The nonlinear behavior of the spring elements is calculated in compliance with [22,23]. When the lateral displacement, s, of the pile is less than the reference displacement, s_0, the coefficient of horizontal subgrade reaction, k_{h0}, is calculated using Eq. (1) [22]:

$$k_{h0}\ (\mathrm{kg/cm^3}) = 0.34(\alpha E_0)^{1.1} D^{-0.31} (EI)^{-0.103} \tag{1}$$

where s_0 is 1% of the pile diameter; α is the condition constant, and it is equal to 1 under normal conditions or 2 under earthquakes; E_0 (kg/cm^2) is the equivalent elastic modulus and can be approximated as 28 N, where N is the SPT-N value; D (cm) is the pile diameter; and EI (kg cm^2) is the flexural rigidity of the pile. When the lateral displacement of the pile is larger than s_0, the secant lateral stiffness k_h of the soil starts to decrease. k_h can be calculated according to Eq. (2) [23].

$$k_h\ (\mathrm{kg/cm^3}) = k_{h0}\left(\frac{s}{s_0}\right)^{-0.5} \tag{2}$$

The flow-induced load imposing on the prototype bridge is estimated in compliance with [24]. The flow pressure acting on the pier is assumed to be linearly distributed, with magnitudes of $2p_{avg}$ and 0 at the water level and the riverbed, respectively; p_{avg} denotes the average flow pressure and can be approximated using the average stream velocity, V_{avg} (m/s), as [24]:

$$p_{avg}\ (\mathrm{kPa}) = 0.52K(V_{avg})^2 \tag{3}$$

where K is a constant accounting for the influence of the pier shape; $K = 1.4$ for square ended piers, $K = 0.7$ for circular piers, and $K = 0.5$ for pier ends angled less than 30°. The flow-induced load acting on the ith pier can then be calculated by multiplication of the stream pressure and the projected area of the piles.

4. Failure behavior of bridge unit P10–P13 during the flood event in 2009

The failure behavior of bridge unit P10–P13 is investigated in the study using nonlinear pushover analysis. Based on the