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A Multi-Hazard Safety Evaluation Framework for a Submerged Bridge using Machine Learning Model

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ABSTRACT: This study proposes a submerged bridge safety evaluation process against seismic and flood hazards. Due to the uncertainties in the scours, seismic hazard, and structural performance for a given seismic excitation are inevitable, reliability analysis is adopted. A machine-learning based scour risk curve, which is established by the multivariate adaptive regression splines (MARS) incorporated with firefly algorithm (FA), is built to reflect the flood hazard. The seismic hazard is measured using a code-based probabilistic seismic hazard curve. A series of nonlinear time-history analyses are performed to determine the structural performance under different peak-ground-acceleration values. Displacement ductility is used to measure the bridge performance under attacks of both hazards. The influence of the immersed water depth on a bridge's performance is investigated. A case study, in which the nonlinear behaviors in concrete (including core and cover areas), steel bar and soil are included in a bridge model, is conducted to illustrate the proposed methodology and the structural performances with added mass are investigated to show the submerged water effect. According to the results obtained, highly variability of seismic performances is observed and it is important to include the immersed water depth to capture the seismic capacity of a bridge if the submerged bridge depth is great.

1. INTRODUCTION

River bridges is an essential construction in Taiwan's transportation network. Due to the geographic characteristics in Taiwan, in which the elongation in the northern and southern directions with mountains rising in the central regions cause the rivers in the east and west to flow at high speeds such that riverbeds are eroded and the foundations of bridges are likely to be scoured. In the past, several bridge disasters have occurred. A similar observation was reported in USA, Wardhana and Hadipriono (2003) have investigated 500 bridge structure failures in the United States between 1989 and 2000, founding that the most frequent causes of bridge failures could be attributed to hydraulic causes. For example, flooding and scouring were the leading causes of bridge failures (48.31% of the total). Despite the lack of official statistical data concerning the causes of bridge failures in Taiwan, it is commonly recognized that the situation in Taiwan is likely to have the same trends as that in the United States. It is known that uncertainties are often inevitable in a bridge's analysis/design. Using a deterministic analysis with a safety factor to take these uncertainties into consideration is a common approach. The safety factor approach, however, cannot identify which design parameters are more critical since all the uncertainties are represented by a single factor. Many scholars have proposed prediction equations for local scour depth. Most of them has focused on the scour with uniform piers, which had not considered the impacts of the pile-caps and pile groups on the scour depth. A non-uniform pier referring to a bridge when its cross-sectional dimension over the length of the pier is identical. In the early days, the scour formula with a uniform foundation was often used. However, most piers of the bridges are not uniform. Thus, the applicability of the uniform pier formulae is questionable. For scours of non-uniform piers, many important impact factors should be considered, such as the soil covering depth, pier width, pile-cap width, flow velocity, riverbed materials, scouring period and so on. On the other hand, HEC-18 and Meliville & Coleman (2000) proposed equations to consider the scours for the non-uniform pier, in which HEC-18 uses the concept of the superposition method to calculate the maximum scour depth at a non-uniform pier.

Friedman (1991) proposed the multivariate adaptive regression splines (MARS) with incorporation of the firefly algorithm (FA). This study extends the idea to predict the local scour depth. The first step is to collect 174 experimental data. These data consist of different pier sizes, flow depths and soil covering depths. In construction the MARS prediction model, the high-dimensional space is converted into several sub-ranges for input factors and a relationship between the input factors and the desired outcomes is built using multiple linear equations (Friedman 1991, Parsaie et al. 2016).

This study uses a probabilistic seismic hazard curve that is built from National Center for Research on Earthquake Engineering (NCREE). A bridge safety analysis is performed by considering two major hazards including earthquakes and flood. Several uncertainties, like scour depth, are considered into the proposed evaluation process. To illustrate, a numerical example is provided, in which the commercial software, SAP2000, is used for the simulation. Nonlinear behavior of the substructure such as plastic hinge formulated in the pier is modeled by a nonlinear link element. In addition, Xtract is adopted to consider the constitutive laws of core concrete, cover concrete and steel bar. The soil behavior is simulated by a series of depth-dependent soil springs around the caisson. The stiffness/coefficient of soil spring varies significantly for different empirical equations. A code-based formula based on the standard penetration test is used to calculate the soil property. Details of the proposed methodology is provided below.

2. THE PROPOSED METHOD

As mentioned earlier, this study uses a machine-learning based scour risk curve, established by the multivariate adaptive regression splines (MARS) incorporated with firefly algorithm (FA), to reflect the flood hazard. The seismic hazard is measured using a code-based probabilistic seismic hazard curve. A series of nonlinear time-history analyses are performed to determine the structural performance under different peak-ground-acceleration values. Displacement ductility is used to measure the bridge performance under attacks of both hazards. The influence of the immersed water depth on a bridge's performance is investigated. The above evaluation process reveals that two ideas, machine-learning based scour depth prediction and a submerged pier, are relative new concepts of the proposed approach compared to other existing bridge safety evaluations. Thus, they are explained as follows.

2.1. Description of MARS

The purpose of using machining learning in this study is to predict the scour depth. Earlier approaches are summarized as follows. In the HEC-18 approach, a foundation is separated as three parts. The three parts are the pier stem, pile cap and pile group. The scour depth of each part is first determined, then combination of each of them is computed to obtain the scour depth. Melville and Raudkivi (1996), on the other hand, used an equivalent uniform pier width to calculate the scour depth. Such method is often considered as an effective approach since it simplifies the non-uniform pier into a uniform pier. Melville and Coleman (2000) proposed to calculate the uniform pier local scour depth by multiplying several empiric correction parameters including the categories of the pier foundation shape and dimension, water flow velocity, sediment dimension, angle of attack of water flow, river channel shape, time factor, etc.

MARS (Friedman 1991) is a novel method for constructing modeling equations from the collecting data. This method divides the high-dimensional learning space into several sub-ranges of the prediction variables to establish a mapping relationship between the prediction variables and the targeted output variable (Parsaie et al. 2016). MARS uses a piecewise linear function for fitting each local model and employs an adaptive approach to finalize model. Evidences of MARS as a powerful machine learning tool are observed in plentiful previous studies (Cheng and Cao 2016). MARS-based model is expressed through a series of simple basis functions (BFs) which characterize the relationship between input and output variables. A BF is shown as follows:

$$b_m(x) = \max(0, C - x) \tag{3}$$

$$b_m(x) = \max(0, x - C) \tag{4}$$

where bm denotes a BF; x is an input variable; C represents a threshold parameter used to divide the original range of x into sub-ranges. The general form of the MARS model is expressed as follows:

$$f(x) = \alpha_0 + \sum_{m=1}^{k} \alpha_m b_m(x) \tag{5}$$

where $\alpha_0, \alpha_1, ..., \alpha_M$ are weighting coefficients; *f*(*x*) represents the model output. *k* denotes the number of weighting coefficients. The model establishment of MARS is broken down into two steps: forward and backward steps. In the first step, *BF*s are added into the model so that they can help to reduce the training error; this process is terminated when the maximum number of *BF* is reached. The second step is to alleviate overfitting phenomenon by pruning redundant *BF*s.

2.2. FIREFLY ALGORITHM (FA)

The tuning parameters, the maximum number of BFs (kmax) and the penalty coefficient (c), are tuned and determined. FA proposed by (Yang) 2008 and Yang (2010) is utilized here for this purpose. Details of the FA is described as follows. Often, the pattern of firefly flashes is unique for a particular species. In essence, each firefly is attracted to brighter ones as it randomly explores while searching for prey. Based on the FA' nature phenomenon, which means FA is formulated as a global optimization method to locate the optimum. Three regulations of FA are summarized: (1) all fireflies are unisex and is attracted to other fireflies, (2) the attractiveness of a firefly is proportional to its brightness and decreases as the distance increases. A firefly moves randomly if no other firefly is brighter, and (3) the brightness of a firefly is influenced by the objective function.

To predict the local scour depth, the first step is to collect 174 experimental data. These data consist of different pier sizes, flow depths and soil covering depths. In construction the MARS prediction model, the high-dimensional space is converted into several sub-ranges for input factors and a relationship between the input factors and the desired outcomes is built using multiple linear equations

2.3. Consideration of the submerged effect

As the natural vibration frequency of the river-crossing bridge will vary according to the water level, the influence when soaking the structure in the water should be discussed. The immersing effect is considered in the Morison Equation proposed by Morison, et al. (1950) The Added Mass Ratio Method (AMRM) proposed by Wanli Yang, et al. (2013) is developed according to the Morison equation by which, rational method is inducted for calculating the added mass and Finite Element Software (ANSYS) is used for verification. In this article, the AMRM Method is used and the Added Mass calculation equation is as below:

$$\Delta m_{cir} = \rho_{con} \cdot \frac{\pi D^2}{4} \cdot p_{cir}(H, D) \tag{6}$$

where, the Added Mass ratio of each cylinder section is calculated as below:

$$p_{cir}(H, D) = [0.0133\, ln(H) - 0.112]\, ln(D) + 0.0002H + 0.4 \tag{7}$$

ρ_{con} represents the density of concrete, H means the pier height and D means the diameter of pier section. The Added Mass of the considered bridge is calculated from the pier bottom for every 1m interval and then the calculated Added Mass will be applied to each point, as shown in Figure 1.

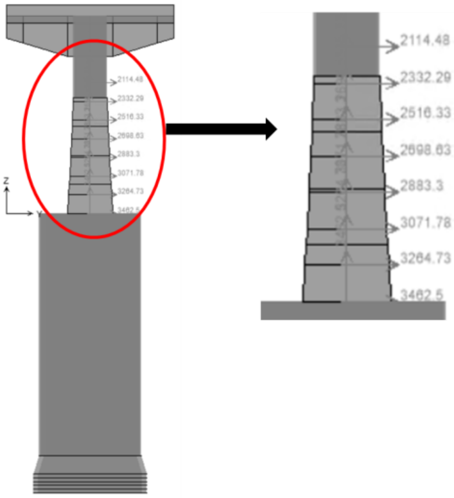

Figure 1. Illustration of the Added Mass used in the demonstrated pier

2.4. *Utilization of Fragility Curve*

Fragility analysis is utilized in this study to illustrate the issue for a given bridge. To construct the fragility curve under multiple hazards, the analysis procedure is displayed in Figure 2. First, information such as the situated location, soil characteristics and hydraulic condition, etc. of the bridge site are collected. The structural configuration information is collected as well, including the design drawings, material characteristics and cross sectional dimensions. To obtain the structural nonlinear property, the sectional property of the substructures is included. According to the flexural, shear or combined failure modes, the plastic hinge property is determined. The soil nonlinear elastic model is established according to the soil information. Earthquake records are collected and their response spectrums are scaled to fit the design response spectrum. For example, the response spectrum of the selected earthquakes falling in between 0.2 T and 1.5 T (T is the fundamental period) may not be lower than 90% of the corresponding design spectral acceleration for a damping ratio of 5%. In addition, the mean value of the response spectrum within the designated period range may not be lower than the average value of the corresponding design spectral accelerations. Nonlinear time history analysis is performed with the scaled ground motions. Based on the analysis results, a fragility curve is established by using the displacement ductility as an index. Together with the occurrence probabilities of the seismic hazard level and scouring hazard, the joint probability distribution function is calculated.

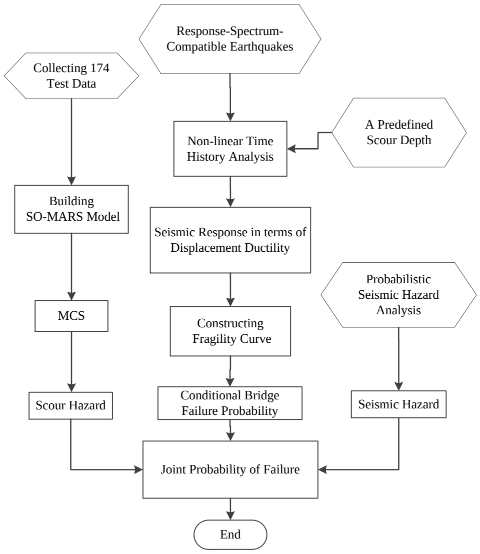

Figure 2. The flowchart of this research

3. SIMULATION OF NONLINEAR BEHAVIORS OF PIER AND CAISSON

Both cover and core concretes are considered here. The model of cover concrete proposed by Coronelli and Gambarova (2004) is adopted. The parameter represents the softening effect resulting from the corrosion.

$$\sigma_a = \zeta\, f_c \left[2\left(\frac{\varepsilon}{\zeta\varepsilon_0}\right) - \left(\frac{\varepsilon}{\zeta\varepsilon_0}\right)^2 \right] \tag{8}$$

$$\sigma_d = \zeta\, f_c \left[1 - \left(\frac{\dfrac{\varepsilon}{\zeta\varepsilon_0} - 1}{\dfrac{2}{\zeta} - 1} \right)^2 \right] \tag{9}$$

The presence of transverse rebar results in a greater strength of the core concrete. Methods proposed by Mander et al. (1988) is adopted in this study to evaluate the confinement effect. Due to a solid circular section with a hollow section, two types of core concretes are considered. The circular section is evaluated using the model proposed by Mander et al. (1988). The hollow section is simulated using a modified model to consider the different force distributions.

4. SIMULATION OF NONLINEAR BEHAVIORS OF SOIL

The regulations of modeling the soil behavior suggested by the Taiwan code are adopted in this study (Chang et al. 2009). The bilinear link element of SAP2000 is used to simulate the soil. Three types of soil spring are considered, in which the horizontal resistance of the caisson, and the vertical and the friction resistances on the caisson bottom are considered. In addition, the passive-earth force is used as the upper limit in the bilinear model. This study ignores the friction effect between the caisson and the soil along the peripheral side. Similarly, a bilinear link is used for the vertical direction of the bottom surface, in which the bearing force is considered as the upper bounds.

5. RESULTS

Indicated in Figure 3 is the Fragility Curve under different scouring depths but with same limit states, and that in Figure 4 means the Fragility Curve under the same scouring depth but with different limit sates. The Fragility Curve indicates that the deeper the scouring depth, the higher the damage probability and that the lower the damage level, the higher the structure damage probability. Such conclusion is consistent with the concept held by general public reasoning that the strength of bridge foundation will be degraded after being scoured and eroded. However, varied water depth tends to affect the damage probability of the bridge. Indicated in Figure 5 is the Fragility Curve of each water depth under the same scouring depth (0m) and the same limit state. In spite the impact is minor according to the result, as the influence of water depth is estimated by aggressive method, the influence of water depth should be considered when using longer piers.

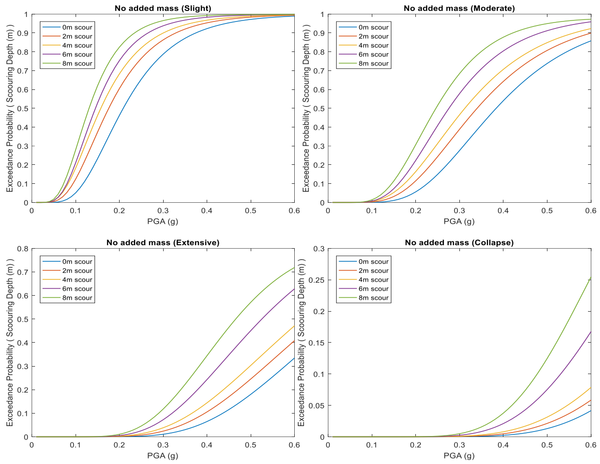

Figure 3. Fragility Curves of each Scouring Depth under 0m Bridge Water Depth and same Limit State

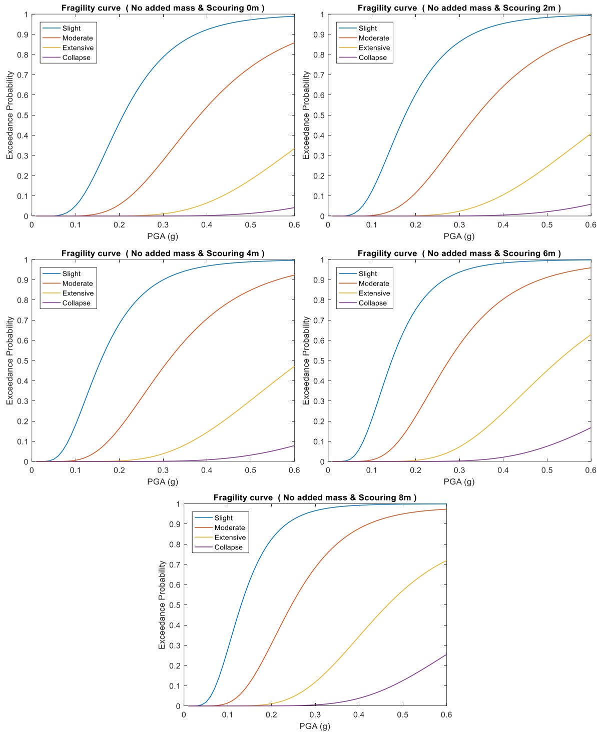

Figure 4. Fragility Curves of each Damage Level under 0m Bridge Water Depth and same Limit State

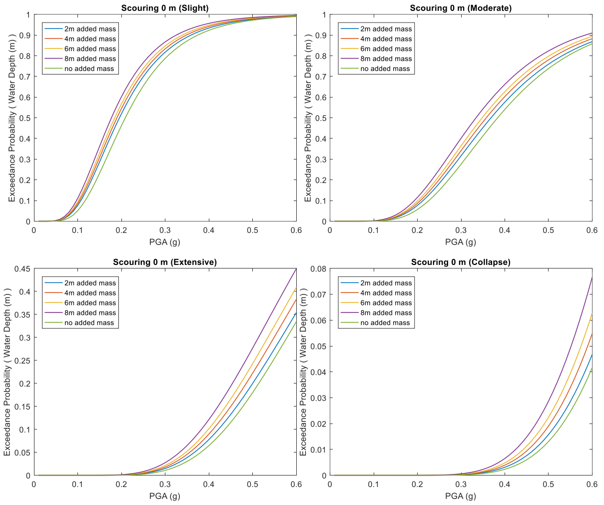

Figure 5. Fragility Curves of each Water Depth under 0m Bridge Scouring Depth and same Limit State

6. CONCLUSIONS

The study builds an analytical method for evaluating the bridge performance under multi-hazard, e.g., earthquakes and floods. Because bridges need to sustain safely for a long period, to maintain the earthquake-/flood-resistant performance during their lifetime is important. There are numerous bridges in Taiwan, thus, to simply and efficiently evaluate these bridges' performance has drawn many attentions among researchers. This study investigates the mechanical behaviors of a water-immersed bridge with different water depths, scour depths and earthquake intensity. First, pushover analysis is performed to relate the base shear force and the displacement, and further, with the supplementary non-linear dynamic analysis, the demands of displacement ductility is derived. Then, the capacity of displacement ductility is adopted from FEMA to build the fragility curves. The variability of the scouring depth varies among different return periods. The effect of water immersion on the safety assessment of bridges across rivers is not as significant as expected. It is speculated that the possible reason is that the column length is insufficient, resulting in little immersion effect; therefore, if the column length is shorter, the immersion effect can be ignored.

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