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Reliability-based Design of a Water-Immersed Bridge Considering Uncertainties in Scours, Earthquakes and Climate Change Effects

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Abstract: This research establishes a framework to evaluate the performance of a bridge against multiple hazards such as earthquakes and floods including the threat of climate change. Based on reliability evaluation, a design guideline is then proposed. The proposed analysis framework consists of nonlinear static push-over and dynamic analyses to obtain the displacement ductility which is adopted as a bridge health indicator in this study. An experiment-based scour equation is proposed to consider the flood hazard, in which the water immersed effect is considered through added mass approach. Further, in calculating scour depth, the needed information such as stream velocity and level are computed based on 2D HEC-RAS, in which the river discharge rate is calculated by Generalized Watershed Loading Function (GWLF). The effect of climate change is considered in GWLF by using future meteorological data that is generated using future meteorological data under climate change scenarios with selected General Circulation Model (GCM). The seismic hazard analysis is utilized for the time history analysis to obtain the ultimate displacement. To simplify the analysis procedure and to enhance its efficiency, the Least Squares Support Vector Machine (LSSVM) is used to build a surrogate model to obtain the displacement ductility that is used for building the fragility surfaces. To demonstrate the proposed methodology, several bridges are analyzed. A practical design rule is proposed based on bridge probabilistic performance to meet a given target reliability.

Keywords: Reliability-based Design, Uncertainty, Scour, Seismic, Climate Change.

1. General

The aim of this study is to provide an analytical method for evaluating the bridge performance under multi-disasters, e.g., earthquakes, floods and climate change effect.

There are thousands of bridges in Taiwan. Many of these bridges have been built for a long time. Therefore, inspections are necessary to ensure safe operation. Taiwan often occurs in various disasters such as floods and earthquakes, which have a huge impact on people's lives. The influence of earthquakes on bridge performance has drawn many attentions. For example, it has been observed that several types of bridge damage in Chi-Chi earthquake such as substructure damage, footing settlement, unseating span failure, abutment failure and joint failure. Floods caused by typhoons often cause serious scouring problems, which in turn affect the safety of bridges. The hazards considered involve many uncertainties. Therefore, the reliability method is used to calculate the reliability of the bridge by considering the scouring under a given earthquake, as well as the uncertainty of seismic hazards and structural performance.

The on-site bridge damage report usually implies that the damage caused by the earthquake is not easy to classify. However, during the on-site investigation, it was found that excessive displacement of the bridge superstructure is an important factor that harms the bridge. Therefore, displacement-related damage is usually found on site and its related physical quantity is a suitable choice to evaluate the performance of the bridge under the earthquake excitations.

The mechanical behaviors of a water-immersed bridge with different water depths, scour depths and earthquake intensity magnitudes are investigated as follows. First, a pushover analysis is performed to obtain the relation between the base shear force and the displacement, and further, using results of non-linear dynamic analysis, the demands of displacement ductility is derived. Then, acquiring the capacity of displacement ductility from FEMA. Due to many parameters involved in the analytical proposed workflow, the least square support vector machine (LSSVM) is used to replace analytical model to provide a possible bridge performance without scarifying the accuracy.

To further consider the effect of climate change, future meteorological data under climate change scenarios via GCM (General Circulation Model) with history meteorological data (include 1986-2005 years daily rainfall and temperature) are generated, and converting the generated future meteorological data into the watershed runoff using GWLF (Generalized Watershed Loading Function). Second, acquiring stream level and flow velocity at bridge site via 2D HEC-RAS model using the outcomes of GWLF, the goal of this part is to estimate the scouring depth of each pier. Third, establishing SAP2000 bridge model to assess the structural behaviors with different scour depths and earthquake intensity. the demands of displacement ductility are derived from pushover analysis and time history analysis.

In the end, a deterministic design scour depth is provided to assist engineers in their practice. That is, once a bridge safety with the assigned scour depth is ensured, the performance of this bridge will meet the target reliability for hazards considered in this study.

2. Methodology

The proposed analysis framework consists of nonlinear static push-over and dynamic analyses to obtain the displacement ductility which is adopted as a bridge health indicator in this study. An experiment-based scour equation is proposed to consider the flood hazard, in which the water immersed effect is considered through added mass approach. Further, in calculating scour depth, the needed information such as stream velocity and level are computed based on 2D HEC-RAS, in which the river discharge rate is calculated by Generalized Watershed Loading Function (GWLF). The effect of climate change is considered in GWLF by using future meteorological data that is generated using future meteorological data under climate change scenarios with selected General Circulation Model (GCM). The seismic hazard analysis is utilized for the time history analysis to obtain the ultimate displacement. To simplify the analysis procedure and to enhance its efficiency, the Least Squares Support Vector Machine (LSSVM) is used to build a surrogate model to obtain the displacement ductility that is used for building the fragility surfaces.

2.1 Utilizing Displacement Ductility in Constructing Fragility Curve

To display a bridge performance in terms of probabilistic way, fragility curve is used. The fragility curve is mainly affected by the demand and the capacity for a given structure. In this study, the demand is represented by the displacement ductility (R_D), that is obtained from simulation considering multiple hazards. Similarly, displacement ductility is also used to indicate the capacity level (R_C) that can be obtained from FEMA (HAZUS-MH/MR3, 2003). For example, $1 < R_c < 2$ means minor damage, $2 < R_c < 4$ means medium damage, $4 < R_c < 7$ means major damage, and $R_c > 7$ represents the structure is completely collapsed. The displacement ductility demand (R_D) of a bridge is defined as the ratio between the ultimate displacement (Δ_u) and yielding displacement (Δ_y). Displacement refers to the relative displacement between pier top and pier bottom. The ultimate displacement is the maximum value of the bridge displacements in a nonlinear time history analysis.

2.2 Building Experiment-based Scour Equation

Many scour depth formulae have been proposed. For example, HEC-18 divides the substructure into three parts and calculates separately. On the other hand, Melville and Coleman (2000) converted the non-uniform pier width to an equivalent uniform pier width for calculating the scour depth. To improve the accuracy, formulation proposed by Melville and Coleman is employed with collected scour data to develop a scour-prediction formula using an optimization algorithm. The calculation method is described in Eq. (1).

$$d_s = K_{yb} K_s K_\theta K_I K_t K_d \tag{1}$$

where K_{yb} is the water depth as expressed in Eq. (2). Ks is the pier-shape correction factor, K_θ is the correction coefficient of the angle of attack of flow, K_I is the flow intensity correction coefficient, K_t is the time-factor correction coefficient, and K_d is the river-bed-material characteristic correction coefficient.

$$\begin{cases} K_{yb} = 2.4 b_e & \dfrac{b_e}{y} < 0.7 \\ K_{yb} = 2\sqrt{y b_e} & 0.7 < \dfrac{b_e}{y} < 5 \\ K_{yb} = 4.5 y & \dfrac{b_e}{y} > 5 \end{cases} \tag{2}$$

where b_e represents the equivalent pier width perpendicular to the flow, y is the flow depth. It is seen that b_e is a very important factor in predicting the scour depth. b_e can be interpolated by b_c and b_{pc}, as displayed in Eq. (3).

$$b_e = \begin{cases} A b_c + B b_{pc}, \text{ where} \\ A = \dfrac{x_1 y + x_2 Y}{x_3 y + x_4 b_{pc}} \\ B = \dfrac{x_5 b_{pc} - x_6 Y}{x_7 y + x_8 b_{pc}} \\ A + B = 1 \end{cases} \tag{3}$$

where A and B are the weights for b_c and b_{pc}, respectively, as shown, the sum of A and B should be equal to one and they are functions of the flow depth (y), level of the top surface of the pile cap below the surrounding bed level (Y), and pile-cap width perpendicular to the flow (b_{pc}). To find their values, this study utilizes an optimization method to search A and B. The optimization results are described in Eqs. (4).

$$b_e = g(y, Y, b_c, b_{pc}) = \left(\frac{0.80y + 0.31Y}{0.83y + 1.00b_{pc}}\right) b_c + \left(\frac{0.02b_{pc} - 0.07Y}{0.75y + 0.56b_{pc}}\right) b_{pc} \tag{4}$$

2.3 Obtaining Stream Velocity and Level from 2D HEC-RAS

The HEC-RAS software is a computer program developed by the US Army Corps of Engineers Hydrologic Engineering Center (HEC) for river simulation analysis. It is an integrated software system that allows users to perform hydraulic calculations and simulate the entire open channel system. A two-dimensional hydrodynamic calculation model was added after version 5.0. The calculation grid of the two-dimensional model is easy to build and easy to operate, so this study uses version 5.0.1 for analysis.

The one-dimensional simulation of HEC-RAS has been widely used in river channel calculation and hydraulic simulation of hydraulic structures. The two-dimensional model is often used to consider sand transportation and flooding. FLO-2D and HEC-RAS are the most common software. However, this study hopes to consider that the downstream bridge of the catchment area is more in line with the real situation, that is, the water level and flow velocity of each bridge pier are different, so the two-dimensional model of HEC-RAS is used. The HEC-RAS built-in model is not used to calculate the scouring depth, and the empirical formula previously described in the section of 2.2 is used.

2.4 Obtaining Stream Discharging Rate from GWLF

Common surface runoff models can be divided into Lumped Parameter Model and Distributed Parameter Model. The lumped model assumes that the input geology and hydrology factors are the same in the entire the catchment area, ignoring the variability of related environmental parameters (such as terrain, land use, soil characteristics, etc.) and estimating the runoff using the water balance equation. The lumped model is suitable for simulating rainfall and runoff processes. Its setting parameters are simple and the amount of data required is small, which can be used as a basis for evaluating the amount of flooding under climate change. Distributed parameter model is to consider the grid of the catchment area. The physical properties of each grid in the bl catchment are different (soil parameters, terrain parameters, etc.). A large amount of background data needs to be collected. The situation closer to the reality can be obtained, which is more suitable for research that requires detailed analysis such as the change of land use situation simulated by climate change or the movement method of pollutants. Therefore, considering the computational cost, this study selects the GWLF hydrological model to estimate the discharging rate of the catchment area under various climate change scenarios. In GWLF, the flow simulation of the catchment area takes into account the physical impact and water balance relationship during the formation of the river flow, which is obtained by adding the direct surface runoff Q_t and groundwater discharge recharge to the river base flow G_t.

2.5 Constructing Surrogate Model using LSSVM

To simplify the analysis procedure and to enhance its efficiency, the Least Squares Support Vector Machine (LSSVM) is used to build a surrogate model to obtain the displacement ductility that is used for building the fragility surfaces.

A standard SVM, as described in Eq. (5), solves a nonlinear classification problem by means of convex quadratic programs (QP).

$$\underset{w,b,\xi}{\text{minimize}} \ \frac{1}{2}w^T w + c\sum_{k=1}^{N}\xi_k \qquad (5)$$

$$\text{Subject to} \begin{cases} y_k(w^T K(x_i)+b) \ge 1-\xi_k \\ \xi_k \ge 0, \ i=1,2,...,N \end{cases}$$

where w is a normal vector to the hyper-plane; c is a real positive constant; and ξ_k is the slack variable. If Gaussian radial basis function (RBF) kernel is adoptedas indicated in Eq. (6).

$$K(X, X_i) = e^{-\sigma(\|X-X_i\|)^2} \qquad (6)$$

where X is the input vector, σ is the kernel function parameter; and X_i are the support vectors. LS-SVM (Suykens et al. 2002) intend to solve a set of linear equations by modifying the standard SVM in Eq. (7).

$$\min \ \frac{1}{2}w^T w + \frac{\gamma}{2}\sum_{k=1}^{N}e_k^2 \qquad (7)$$

$$\text{s.t. } y_k(w \cdot K(x_k)+b) = 1-e_k, \ k=1,...,\text{n}$$

where γ is a constant number and ε is the error variable.

2.6 Considering the Effect of Immersing in Water

It is known that immersing water level will affect the frequency of a structure. I this study, Morison equation (Morison et al. 1950) is used to consider such effect. A semi-empirical equation is built in Morison approach to compute the additional force under water. Two major parts are included: an inertia force that depends on the value of the surrounding flow's acceleration and a drag force determined by the surrounding flow's velocity. Two empirical hydrodynamic coefficients are needed in Morison equation: an inertia coefficient (C_m) and a drag coefficient (C_d). A rational method for calculating the Added Mass and verified by finite element method, named as Added Mass Ratio Method (AMRM), is proposed by Yang and Li (2013). AMRM Method is adopted and the Added Mass (Δm_{cir}) is computed as below:

$$\Delta m_{cir} = \rho_{con} \cdot \frac{\pi D^2}{4} \cdot p_{cir}(H, D) \qquad (8)$$

where, ρ_{con} represents the density of concree, the Added Mass ratio $p_{cir}(H, D)$ of each cylinder section is calculated as below:

$$p_{cir}(H, D) = [0.0133\ln(H) - 0.112] \times \ln(D) + 0.0002H + 0.4 \qquad (9)$$

in which, H means the cylinder height and D means the diameter of cylinder section.

3. Analysis Results

The GWLF is verified with the recorded data as shown in Figure 1. It is seen that the process proposed to build the GWLF model can deliver a similar outcome as the actual data. In this study, the HECRAS model was stabilized by trial and error, and the relevant parameters were set as shown in Table 1. The magnitude of Manning's roughness coefficient is mainly referred to the study of Ke and Xu (2005). After completing the model construction according to the above process, the water level and flow rate of the considered river can then be simulated, as shown in Figure 2. After determining the position of the river cross section of the bridge, the scouring depth of a bridge pier can be calculated.

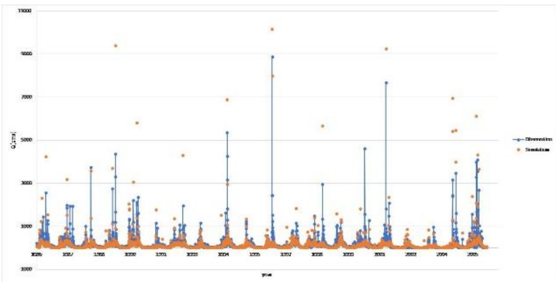

Figure 1. Verification of GWLF model.

Table 1. Parameters used in HECRAS-2D

Parameters	Value
Mesh size	50m×50m
Time Interval	5sec
Simulation Duration	2days
Manning coeff. (n)	0.035
θ	0.7

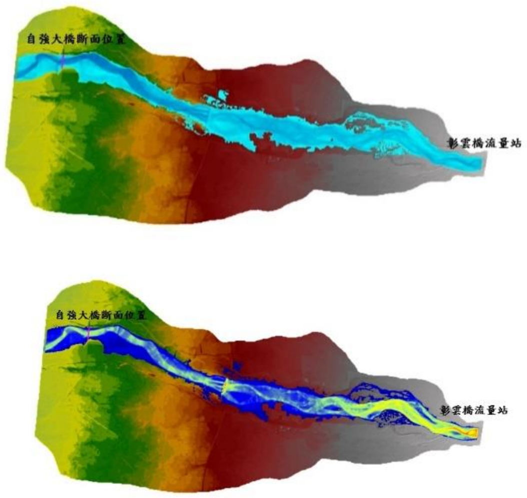

Figure 2. Simulation of stream level (top) and velocity (bottom) using HECRAS-2D.

In considering the immersing effect of the bridge, due to the appreance of a tapered bridge pier, the added mass is computed at each interval. For example, the added mass calculated from the pier bottom for every 1m interval and applied to each point are sidplayed in Figure 3.

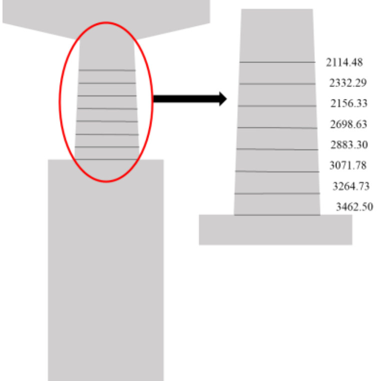

Figure 3. Illustration of the calculated Added Mass.

Figure 4 displays the fragility curve of the corresponding scouring depth under the same performance level. As seen, the scour depth is not proportional to the failure probability. In addition, the slightly damage state, as expected, has the least failure probability.

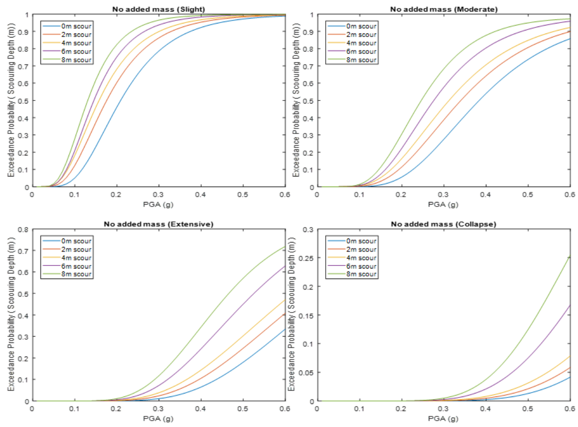

Figure 4. Fragility curves of each scouring depth under 0m bridge water level and same performance level.

In this study, LSSVM is used as a surrogate model to construct the fragility curve. Figure 5 is a direct comparison between two methods (authentic and LSSVM). As shown, the trends of two approaches are similar. The greater the scour depth, the bigger the difference. Please note that the interpolated data between authentic ones may have a higher/lower exceedance probability than that of the authentic one, as shown in Figure 5. It is suggested that the proposed surrogate model is applied only when the authentic model is not available.

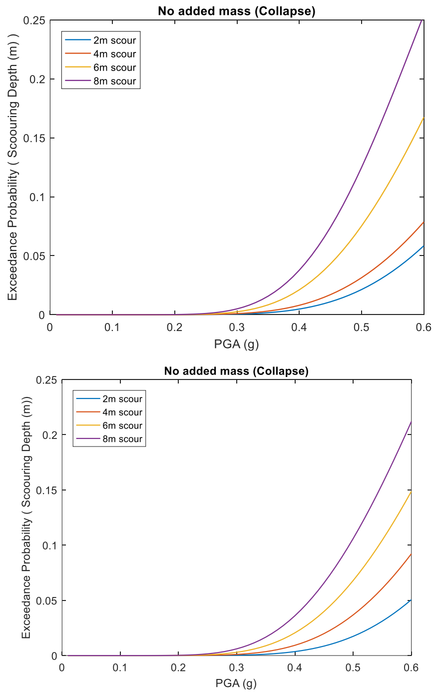

Figure 5. Fragility curves using authentic (top) and LSSVM models (bottom).

Table 2 shows the prediction result of the proposed formula-based approach. In general, the result greatly improves the accuracy of the Melville & Coleman (2000) formula. The proposed method is able to simultaneously satisfy the requirements of accuracy and simplicity. The proposed formula has the advantages of being conceptually consistent with the observed scour behaviors and provides a solid scour depth prediction, which is an important and critical step in the bridge safety evaluation if floods are considered. Figure 6 displays the fragility curves with consideration of climate change effect or not. It is seen that the effect of climate is not significant. Further study is needed.

Table 2. Accuracies of the proposed formula-based approach

Soil covering depth	MAPE
(1) $Y > 2.4b_c$	5.1
(2) $2.4b_c > Y \geq 0$	30.4
(3) $0 > Y > -y$	34.2
(4) $Y \leq -y$	24.8
Average	28.9

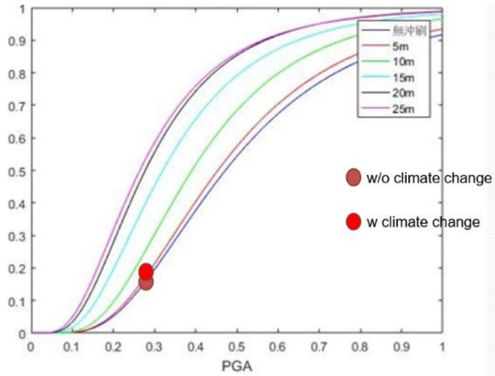

Figure 6. Fragility curves using authentic (top) and LSSVM models (bottom).

4. Conclusions

This research establishes a framework to evaluate the performance of a bridge against multiple hazards. The proposed analysis framework consists of nonlinear static push-over and dynamic analyses to obtain the displacement ductility. An experiment-based scour equation is proposed to consider the flood hazard, in which the water immersed effect is considered through added mass approach. GWLF and 2D HEC-RAS is used to calculate the river discharge rate. The effect of climate change is considered To simplify the analysis procedure, the LSSVM is used to build a surrogate model for building the fragility surfaces. Some important notes are described below.

1. Only scour effect is considered in flood hazard.
2. The sequence of multi-hazards is predetermined.
3. Because the stream velocity employed in this research is not so fast and the pier is not long enough, the immersing effect is not significant.
4. The trend of fragility curve derived from LSSVM is very close to that established with the original model. Therefore, it can significantly shorten the time required for the fragility analysis.
5. A deterministic design value, considering both scour and seismic hazards can be delivered based on the proposed analysis results.
6. The effect of climate is not significant. Further study is needed.

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