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Flood fragility analysis for multiple failure modes of bridges by finite element reliability analysis

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ABSTRACT

Flood fragility analysis has received less attention compared to seismic fragility analysis, even though flood is one of the major causes of bridge damage. Many aged bridges have collapsed with various failure modes due to flood-related causes, and this has prompted the requirement for performing reliability analysis in conjunction with sophisticated finite element analysis to obtain the accurate fragility curve of a bridge for various limit state functions. In the present study, finite element reliability analysis is applied to the flood fragility analysis of an old bridge in Korea. Different flood-related factors such as increased water velocity, scouring, and debris accumulation are used to take into consideration a variety of bridge failure modes such as excessive displacement, lack of ductility, and excessive stress.

1. INTRODUCTION

Bridges are some of the essential infrastructure that are known to be vulnerable to flood-induced failure. A study on the causes of bridge failure in the US between 1987 and 2011 revealed that flood-related hydraulic factors such as increased water velocity, scouring, and debris accumulation account for more than 50% of bridge failures (Cook 2014). In particular, many aged bridges are liable to unexpected damage by external loads such as rapid increase in water pressure. It was also found that the average age of bridges in New York that collapsed due to hydraulic factors such as scouring or debris accumulation was about 40–50 years (Cook 2014), which is shorter than the expected ages.

Accurate flood risk assessment is a crucial key to the effective structural maintenance. A new methodology of performing reliability analysis in conjunction with finite element (FE) analysis (i.e. finite element reliability analysis) was recently introduced to derive flood fragility curve of bridges in consideration of structural deterioration (Lee 2016). However, fragility analysis was conducted only with one

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failure mode in the paper, even though FE analysis can simulate various failure modes of bridges such as excessive displacement, lack of ductility demand, and excessive stress. This paper proposes to perform finite element reliability analysis for flood risk assessment for multiple probable failure modes.

2. PROPOSED METHODOLOGY FOR FLOOD FRAGILITY ANALYSIS

For the accurate fragility analysis of a structure, the maximum load resistance ability and the potential input forces need to be considered as random variables accounting for their uncertainty. Various failure modes need to be also defined to calculate the failure probabilities based on the random variables. In the present study, the resistance, load, and multiple failure modes are taken into consideration in the proposed methodology of flood fragility analysis as follows.

2.1 Resistance: structural nonlinear behavior and bridge scouring

For a more realistic FE model, the structural nonlinear behavior is examined in this study by considering the material nonlinear properties. In materials, the stress does not significantly increase after yielding, but the strain rapidly increases until failure. Consideration of the material nonlinearity is critical to reliable failure probability calculation because the characteristic significantly affects the structural response. Several experiments have been performed towards explaining the nonlinear behavior of materials, the stress-strain curve of steel shown in Fig. 1 is employed for the present numerical example.

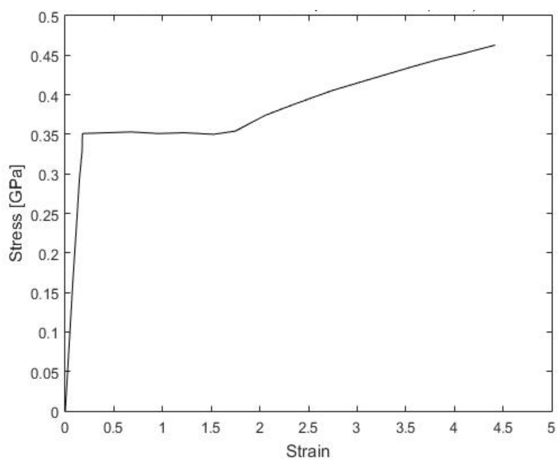

Fig. 1 Strain-stress curve of steel

Scouring is another major cause of flood-related bridge failure. According to the abovementioned study of Cook (2014), more than 20% of bridge failures in the US were due to scouring. In this study, scouring is taken into consideration to provide more realistic condition of bridge foundation for the FE model. In the model, piles and bridge foundations are fixed by several springs placed at regular intervals, with the springs having the same stiffness. In other words, the spring forces used to fix the piles act as ground fixing forces. In the event of scouring, however, the stiffness values of springs down to at the scouring depth are reduced to zero, implying soil elimination. The nonlinear lateral resistance of the soil with respect to the structural deflection is calculated as follows (API 2000):

$$p = A \times p_u \times \tanh\left[\frac{k \times H}{A \times p_u} \times y\right] \tag{1}$$

where p is the lateral soil resistance, A is the factor used to account for cyclic or static loading, p_u is the ultimate bearing capacity at the scouring depth H, k is the initial modulus of the subgrade reaction, and y is the lateral deflection. The scouring depth H can be calculated by

$$p_u = (C_1 \times H + C_2 \times D) \times \gamma \times H \tag{2}$$

where C_1 and C_2 are the coefficients determined by the angle of the internal friction, D is the average pile diameter between the surface and the scouring depth, and γ is the effective soil weight.

Considering the difficulty of measuring the scouring depth H, various studies have been conducted on its estimation. The Colorado State University equation, which is recommended by the Federal Highway Administration (FHWA), was used for the estimation in the present study based on the water velocity. The equation is as follows (Yanmaz 2000):

$$H = 1.564 \times \chi^{0.405} \times \left(\frac{\upsilon}{\sqrt{g \times d}}\right)^{0.413} \tag{3}$$

where χ is the relative approach flow depth, v is the water velocity, g is the gravitational acceleration, and d is the depth of the approach flow.

2.2 Load: flood loads

Floating objects, which are referred to as debris, have also been investigated as one of the major causes of flood-related bridge failure. There are two processes through which debris impact bridges, namely, debris accumulation and debris collision. In some standards such as the AASHTO (American Association of State Highway and Transportation Officials) standard, debris collision is considered to negligibly affect bridge failure. Conversely, debris accumulation is thought to significantly increase the water pressure acting on bridge piers.

Consequently, in the present study, only the water pressure on the piers in the presence of accumulated debris is considered in the flood load. AASHTO (2012) and KHBDS (Korean Highway Bridge Design Specification, 2010) introduced the following relationship between the water velocity and the water pressure:

$$p_w = 5.14 \times 10^{-4} \times C_D \times \upsilon^2 \tag{4}$$

where p_w is the water pressure, C_D is the drag coefficient, and v is the water velocity. In the case of "debris lodged against the pier" which is assumed in this study, the recommended value of the drag coefficient is 1.4.

In addition, the water level is assumed to be above the piers in the present FE model. Hence, the water pressure calculated by the above equation is applicable to the force exerted on the entire piers.

2.3 Failure modes

When a bridge is subjected to a heavy flood, it may fail in several different modes such as deck dropping, pier rebar rupture, and lack of ductility of pile. In this study, these failure modes are taken into consideration, and the corresponding fragility curves are derived.

As mentioned in Sec. 2.1, structural materials behave nonlinearly after yielding. That is, only the strain increases significantly beyond the yield point. For structural risk assessment considering such material nonlinearity, Caltrans (2006) suggested using the displacement ductility demand (M_d) parameter, which is the ratio between the maximum displacement and the displacement at yielding of the reinforcement bars. The concept can be used to easily determine the structural damage state for a failure mode of lack-of-ductility. Based on the concept, in this study, three damage states shown in Table 1 are defined for bridge piles.

Damage state	Displacement ductility demand
Minor damage	$1.0 \le M_d < 3.3$
Major damage	$3.3 \le M_d < 7.0$
Collapse	$M_d \ge 7.0$

Table 1. Damage states and corresponding ductility demands for pile

Furthermore, in many cases, slabs are not directly connected to piers and may fall off if piers excessively move. This failure mode constitutes a brittle failure rather than a ductile one, which leads to define only one damage state, collapse, unlike in the case of lack-of-ductility. Another brittle failure mode that needs to be recognized involves rebar rupture, which means the stress of reinforcement bars of pier exceeds their ultimate strength.

3. NUMERICAM EXAMPLE

3.1 Bridge description and statistical parameters

As a numerical example, the proposed flood fragility analysis is applied to Wolam Bridge in South Korea, which was introduced as a numerical example in Lee (2016). The reinforced concrete bridge is 30m broad and 63m long and consists of piles, abutments, piers, mass concrete, and slabs. It has three rows of eight piers aligned symmetrically on the front and rear sides, forming six groups of four piers each. The six pier groups are not directly connected to the deck, and can thus be considered to behave independently under flood loads. Consequently, only the central group of piers is assessed to simplify the FE model, as shown in Fig. 3. The steel reinforcement bars of the bridge are SD30 bars, and the piles are of the ϕ508*12t type. The design strengths of the pier concrete, steel reinforcement bars, and piles are 23.5, 294.2, and 307 in MPa, respectively. The more details of this bridge can be found in Lee (2016).

In this example, three types of uncertainties are considered as the random variables: mass density, water pressure intensity, and scouring depth. Those are assumed to be statistically independent each other, and the statistical information is determined based on a comprehensive literature review (Lehký 2012, Ju 2014, Kolisko 2012, Yanmaz 2000), as shown in Table 3.

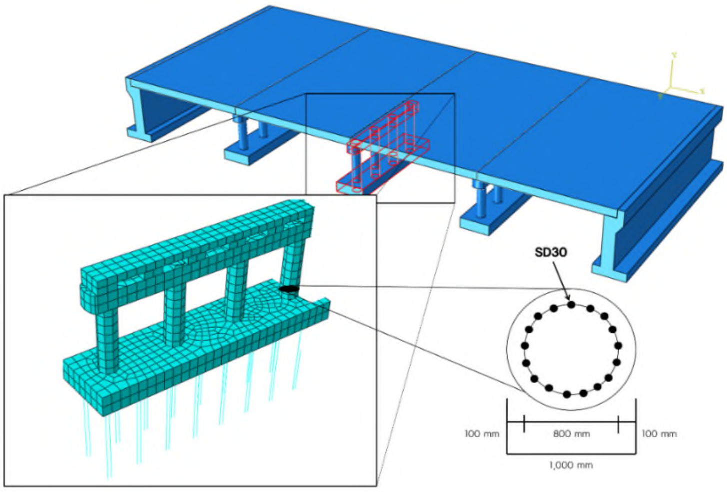

Fig. 3 FE model of Wolam Bridge

	Mean	Coefficient of variation	Distribution type
Concrete mass density	2,300 [kg/m^3]	0.05	Normal
Concrete Young's modulus	17 [GPa]	0.0917	Normal
Steel mass density	7862.3 [kg/m^3]	0.04	Normal
Water pressure intensity	1	0.10	Normal

Table 3 Statistical parameters of random variables

3.2 Fragility curves

Using the proposed methodology, the flood fragility analysis is performed for Wolam Bridge for the three failure modes described in Sec. 2.3, and Fig. 4 shows the corresponding fragility curves. Upper-left figure is about dropping out of deck due to excessive displacement and upper-right one is about rebar rupture due to excessive stress at piers. In addition, the fragility curve at the bottom is about lack-of-ductility of piles.

As abovementioned, the first two failure modes are brittle modes, so there is only one curve in thetwo upper figures in Fig. 4, whereas the fragility curve at the bottom which is about lack-of-ductility shows exceedance probabilities of various damage states. In all figures, exceedance probabilities increase with the increasing water velocity, because it affects to water pressure and scouring depth.

The flood risk of this numerical example (i.e. Wolam Bridge) was investigated in Lee (2016) where scouring was not considered. When the fragility curves in Fig. 4 are compared with the one in Lee (2016), it is noticeable that the level of failure probability becomes higher in Fig. 4, which means the flood risk is evaluated to be larger at the same water velocity when bridge scouring is considered.

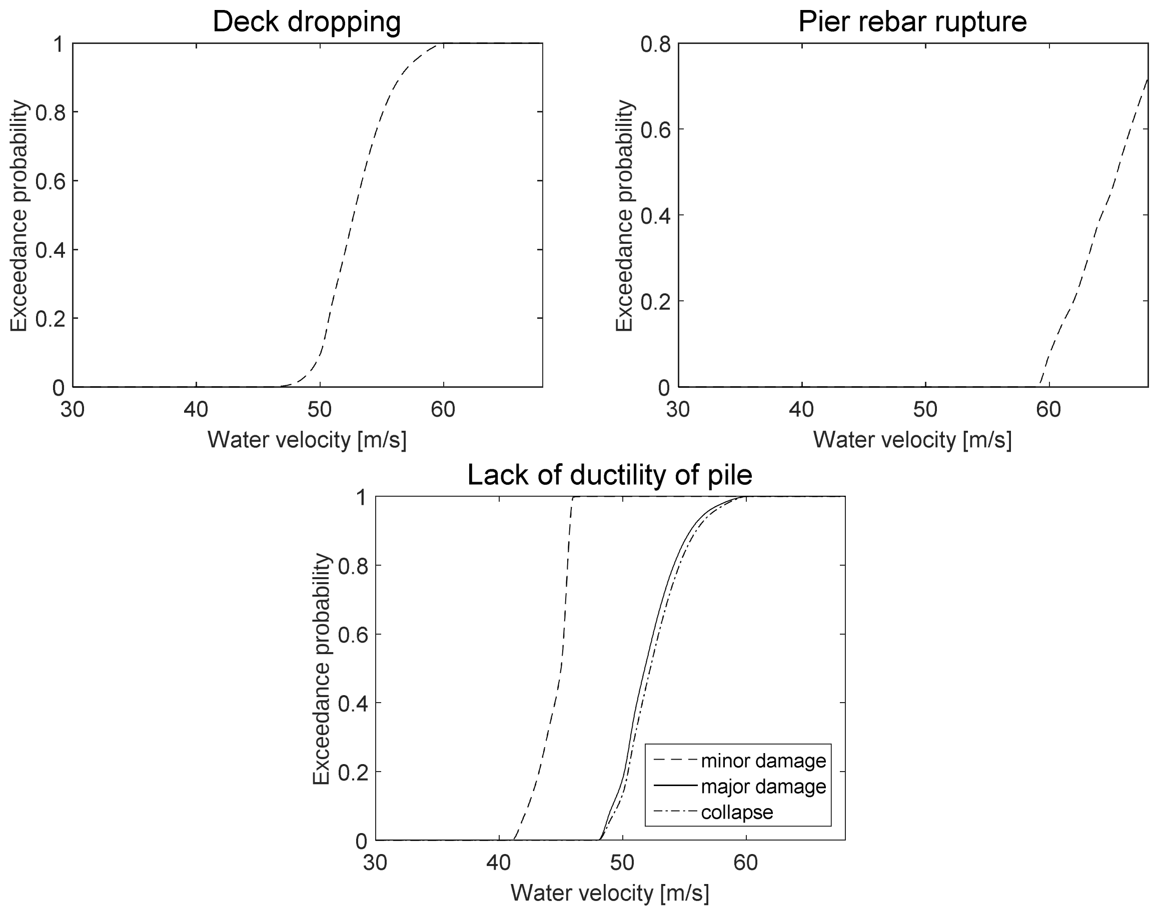

Fig. 4 Flood fragility curves of Wolam Bridge

4. CONCLUSION

This study proposes a novel methodology for flood fragility analysis of bridges for multiple failure modes. This requires performing reliability analysis in conjunction with sophisticated finite element analysis that can represent several failure modes of bridges due to floods. The proposed method was applied to a numerical example of Wolam Bridge in Korea, and flood fragility curves were successfully derived for multiple failure modes such as deck dropping, pier rebar rupture, and lack of ductility of pile. In all figures, exceedance probabilities increase with the increasing water velocity, because it affects to water pressure and scouring depth. It is also noticed that flood risk is evaluated to be larger considering scouring.

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