16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 1475

Registration Code: S-S1463089247

SENSITIVITY ANALYSIS OF LOAD FACTOR FOR BRIDGE DESIGN BASED ON EARTHQUAKE AND TRUCK LOADS

SUN Dezhang(1), WANG Xu(2), SUN Baitao(3), LEI Huan-zhen(4) and ZHANG Ren-peng(5)

(1) *Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, China Earthquake Administration; 29Xuefu Rd, Harbin, 150080, China; Email: sundz@iem.ac.cn*

(2) *State Key Laboratory Breeding Base of Mountain Bridge and Tunnel Engineering, Chongqing Jiaotong University, Chongqing 400074, China; E-mail: wx00012224@163.com*

(3) *Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, China Earthquake Administration; 29Xuefu Rd, Harbin, 150080, China; Email: sunbt@iem.ac.cn*

(4) *Changchun Earthquake Reporting Center, Changchun 130012, China; E-mail: 778552467@ qq.com*

(5) *Jilin province earthquake engineering research center, Jilin 130022 China; E-mail: 768354524@ qq.com*

Abstract

Bridge design specifications in the United States calibrate common loads and single extreme loads, but do not consider multiple hazards. They also do not provide a probabilistic basis for single extreme loads, particularly seismic loads. Previous research has provided a framework for analyzing multiple hazards, load combinations, and determination of load factors. This paper presents sensitivity analysis for seismic and truck load factors, based on partial failure probabilities and a limit state framework. A typical bridge case study was employed to analyze the influence of different factors when subjected to earthquake and truck loads. Different load factors were obtained through varying the load parameters.

Keywords: Earthquake load; Bridge design；Truck load；Load factor; Sensitivity analysis

1. Introduction

The tsunami following the 11 March, 2011 earthquake in Japan was a devastating blow to buildings, bridges, and other infrastructure systems, along with the subsequent nuclear radiation hazard. The damage caused by multiple hazards was more serious where consideration of hazard combinations had not been incorporated in the structural designs. This has raised concerns regarding the issue of multiple hazard resilience for structure designs, particularly seismic resilience.

Current bridge specifications usually consider extreme loads individually. Specification for bridge design in the United States [1,2] include several extreme and common load combinations. Common combination load factors are obtained by the reliability method. Extreme load factors are not probability based, but are usually given a coefficient of 1.0 to completely consider the influence of extreme load effects, e.g. the earthquake load factor is 1.0 when combined with other loads.

Nowak et al. [3–6] suggested a combination of gravity and truck load factors from analyzing statistical regularities of truck loads and considering material uncertainties. Barker et al. [7] used a mixed optimization design method to calculate resistance factors. Jordan et al. [8] obtained load factors using updated weigh in motion data of vehicle loads and equations to provide guide specifications, which had good reliability and effectiveness. Kitjapat [9] developed a simplified equation based on the AASHTO LRFD equation that did not require an iterative procedure. Forty-three representative bridges were selected and analyzed to calculate load factors for the steel girders. Many other load factors have been developed using reliability theory [10–13]. The various load factors usually refer to previous specifications, e.g. load factors in guide specification for bridge design of ASD, LFD to LRFD in the United States, which can be easily understood by engineers and enable the specifications to evolve.

Based on multiple hazard load combinations [14], Sun et al. proposed a method to calculate multiple hazard load factors [15] using partial failure probabilities and a limit state framework. This paper uses earthquake and truck loads for a typical bridge to analyze the load factor sensitivity. Earthquake load parameters were simulated, and the sensitivity of combined load factors illustrated.

2. Load factors for earthquake load and truck load

According to reliability theory, reliability index can be obtained using Eq. (1), which is,

$$\beta = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}} = \frac{1 - \frac{\mu_S}{\mu_R}}{\sqrt{COV_R^2 + COV_S^2 (\frac{\mu_S}{\mu_R})^2}} \quad (1)$$

where, μ_R and μ_S are the mean, σ_R and σ_S are the root mean squared error, and COV_R and COV_S are the coefficients of variation (COV) of resistance and load, respectively.

Let r = μ_R/μ_S, then Eq. (1) can be expressed as

$$r = \frac{1 - \sqrt{1 - (1 - \beta^2 COV_S^2)(1 - \beta^2 COV_R^2)}}{1 - \beta^2 COV_S^2} \quad (2)$$

The probability of failure of the structure is closely related to individual part failure probabilities caused by each load [16]. Considering earthquake and truck loads, the total bridge failure probability consists of three failure probabilities from the individual earthquake and truck loads and the two combined. The commonly used relationship, $P_f = \Phi(-\beta)$, only applies for small P_f [17]. More correctly, the combination of failure probabilities in Eq. (2) should be divided into three conditions,

$$r_i = \frac{1-\sqrt{1-(1-\beta_i^2 COV_i^2)(1-\beta_1^2 COV_R^2)}}{1-\beta_i^2 COV_i^2}; i=1,2,3 \tag{3}$$

where, COV_is (i=1,2,3) are the coefficients of variation of dead load and truck load, dead load and earthquake load, dead load and combined load of truck load and earthquake load, respectively. The partial reliability index for each case can be obtained following [15].

We can express r in terms of the mean and nominal values

$$r_i = \frac{\mu_D + \mu_i}{\mu_R} = \frac{b_D N_D + b_i N_i}{b_R N_R}; i=1,2,3 \tag{4}$$

where, μ_D and μ_R are the mean of dead load and resistance, respectively. μ_is (i=1,2,3) are the mean of truck load, earthquake load, combined load of truck load and earthquake load, respectively. b_is (i=1,2,3) are the biases of truck load, earthquake load, combined load of truck load and earthquake load, respectively. b_R is bias resistance.

In order to meet the design requirements, we need to make the model of LRFD workable.

$$\phi R_n \geq \sum \eta_i \gamma_i Q_i \tag{5}$$

Where, ϕ and γ_i are the resistance factor and load factor, respectively. R_n and Q_i are the nominal values of resistance and load, respectively. η_i is the correction factor of loads. Let $\eta_i = 1.0$, and based on Eq. (4), we have,

$$\phi R_n \geq \frac{\phi}{b_R r_i}(b_D N_D + b_i N_i); i=1,2,3 \tag{6}$$

Note that when i is 3, the Eq. (6) should be revised as,

$$\phi R_n \geq \frac{\phi}{b_R r_3}(b_D N_D + b_3^1 N_3^1 + b_3^2 N_3^2) \tag{7}$$

where, b_3^1 is the bias of truck load distribution that combined with earthquake load and b_3^2 is the bias of earthquake load distribution that combined with truck load, which are very different. N_3^1 is the nominal value of truck load distribution that combined with earthquake load and N_3^2 is the nominal value of earthquake load distribution that combined with truck load.

Based on the LRFD model and Eq. (6) to Eq. (7), the load factors can be obtained using the following equation.

$$\gamma_i = \frac{\phi}{3b_R}\left(\frac{b_i}{r_i} + \frac{b_3^i}{r_3}\right); i=1,2 \tag{8}$$

where, γ_i s (i=1,2) are load factors of truck load and earthquake load, respectively.

Because the bias has changed in the process of calculating, let μ_o is the mean value and b_o is the bias of a distribution. μ_n is the mean value of the distribution after a series of conversions, such as convolution, time t interval to design period T (see [14]), then the bias b_n after conversions can be obtained using Eq. (9).

$$b_n = \frac{\mu_n}{\mu_o} b_o \tag{9}$$

The load factors can be calculated as follows

1. Determine the load information and design a typical bridge;
2. Calculate the reliability index and determine the resistance information;
3. Calculate the partial reliability indexes following [15];
4. Calculate r_i using Eq. (3);
5. Calculate the biases using Eq. (9);
6. Calculate the load factors using Eq. (8).

3. Sensibility analysis of load factors

Earthquake load characteristics differ for different regions, and the load factor may also vary correspondingly. For example, earthquake load in California is larger than in St. Paul, Seattle of the United States. A typical bridge model from the Washington State Department of Transportation was employed to analyze load factor sensitivity, as shown in Figs. 1 and 2.

The bridge parameters were: three 44.2 m spans with two piers, 20.3 cm thick deck slab, 14.3 m pier width, 1.52 m diameter pier columns. The total weight of superstructure was 538 ton, each bent cap was 830 kN, and the live load of the bridge deck was 43 kN/m.

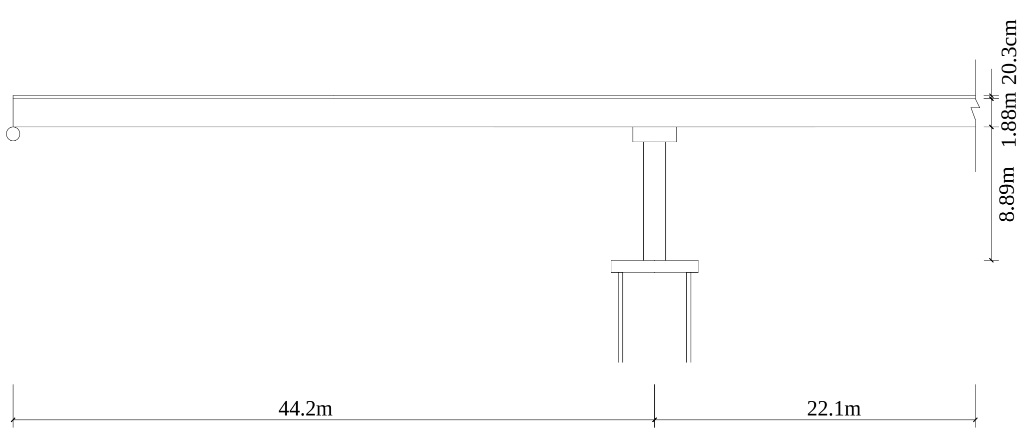

Fig.1 Longitudinal profile of the typical bridge

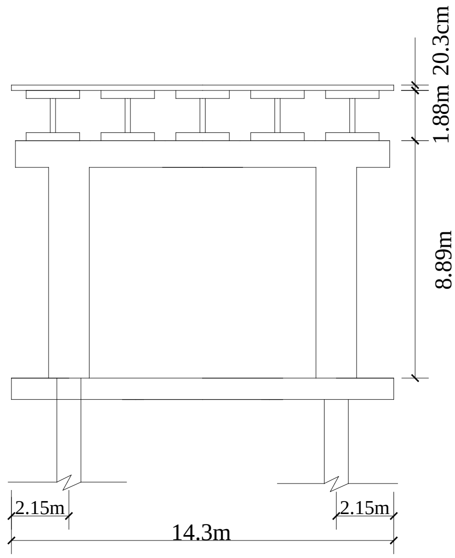

Fig.2 Transverse profile of the typical bridge

To illustrate the method, let the truck load be $M_1 = W_1 \cdot \varepsilon$, where W_1 is the truck weight, and ε =3.0 m is the eccentricity between the vertical center axis of the truck and the vertical axis of the column. The earthquake load is $M_2 = W_2 \cdot A \cdot H$, where M_2 is the column bent moment, W_2 is the superstructure weight, A is the peak ground acceleration and H is the column height. The maximum number of trucks in one lane was assumed to be two, in a special site truck may have an average number of 1000. Moses [10] suggested truck load approach a normal distribution with mean 300 kN and standard deviation 80 kN (COV_1=26.5%). Heavier truck situations can be obtained by modifying the basic assumptions. The bridge was considered to be located in San Francisco, USA, with earthquake and truck loads as shown in Figs. 3 and 4.

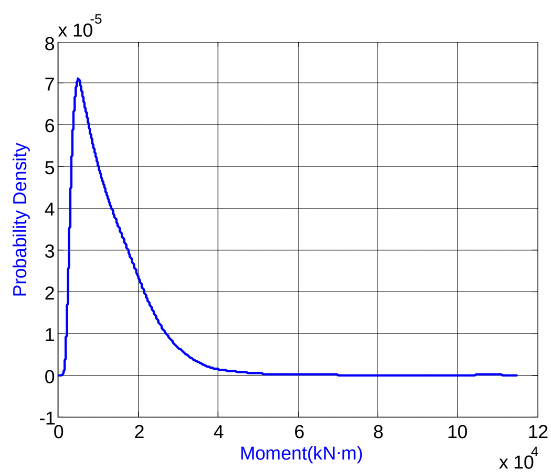

Fig.3 Probability distribution of earthquake load effects in 75 years in San Francisco

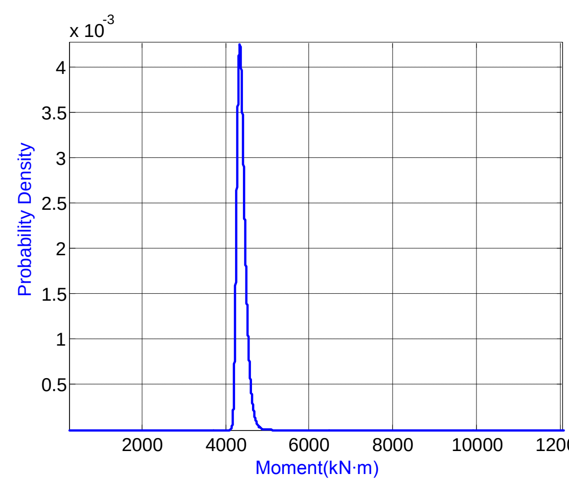

Fig.4 Probability distribution of heavy truck load effects in 75 years

Nowak [5] showed resistance was lognormal distributed. The COV of resistance for different materials differ, but for concrete, as in the typical bridge chosen, COV = 0.11–0.13 [18,19]. The resistance parameter can be determined through optimization based on the resistance distribution, COV, load distributions, and the reliability index. We set the target reliability index as 3.5, the COV of resistance as 0.11 and then other paramentes of the resistance can be obtained.

Finally, the load factors can be obtained using Eq. (8) for the typical bridge example parameters.

However, site to site variations, e.g. bridge length, mean the load factors will also vary. The impact factors include load intensity, combined load intensity, combined load variance, load distribution variance, mean resistance, COVs of loads, etc. The most significant [18] impact factor is COV, so the load factor sensitivity analysis focused on COV variance.

A set of load factors can be obtained using Eq. (8) with varied COVs in Eq. (3). Figure 5 shows the load factors for varying earthquake load parameter and Figure 6 for varying combined earthquake and truck load parameter.

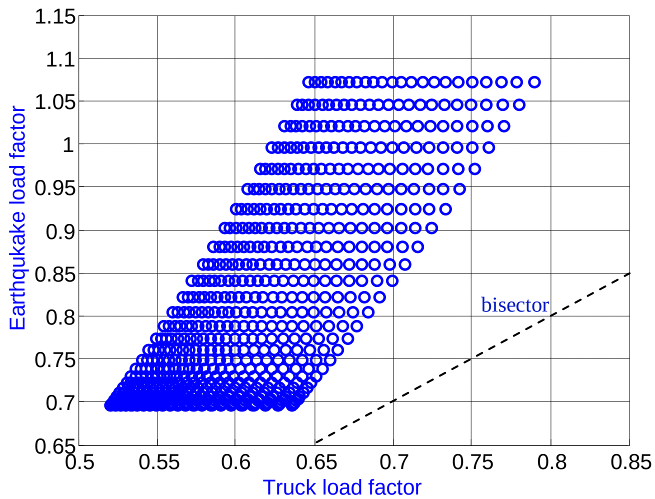

Fig5. Load factors for varying the parameter of earthquake load in San Francisco

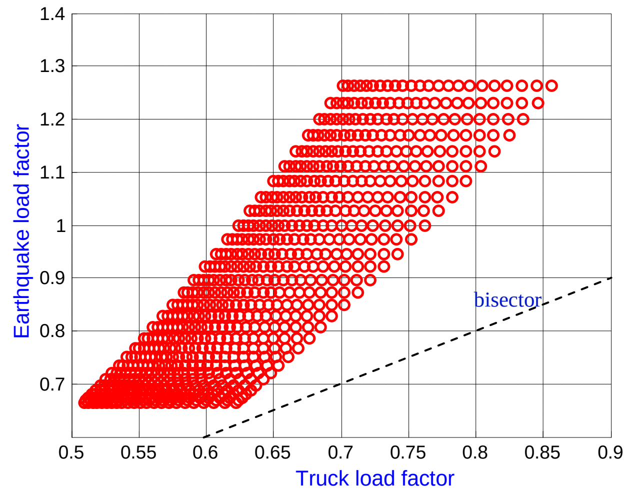

Fig.6 Load factors for varying the parameter of combined earthquake and truck load in San Francisco

The general trends are similar in Figs. 5 and 6, with more concentrated points toward the lower bound and the truck load factor ranges are almost the same when earthquake load factor is 1.0. Load factor points all locate above the bisector and the average slope in Fig. 5 is larger than that in Fig.6, which mean that they are more infulenced by earthquake load parameters. The effect area is smaller in Fig. 5, which means earthquake load factor sensitivity is relatively stable.

We used Seattle, which has only moderate earthquake intensity, as shown in Fig. 7, as an alternate site to contrast the San Francisco loadings, with the same bridge configuration. Figures 8 and 9 show the load factors for varying earthquake and combined earthquake and truck loads, respectively.

The general trends are significantly different between Figs. 8 and 9, the former gathering to the lower bound and the later concentrating to the left tangent region. The differences between the San Francisco and Seattle examples arise because the earthquake intensity is moderate in Seattle, whereas it tends to dominate in San Francisco. Thus, the truck load contribution is particularly significant in Seattle and the combined load dominates.

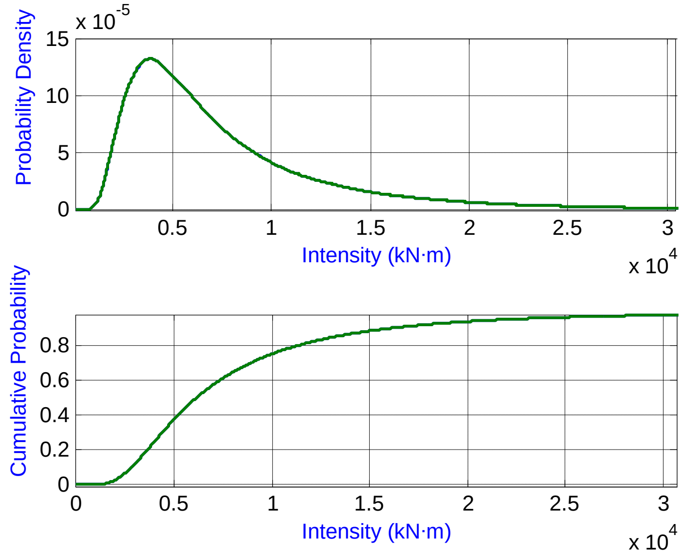

Fig.7 Probability distribution of earthquake load effects in 75 years in Seattle

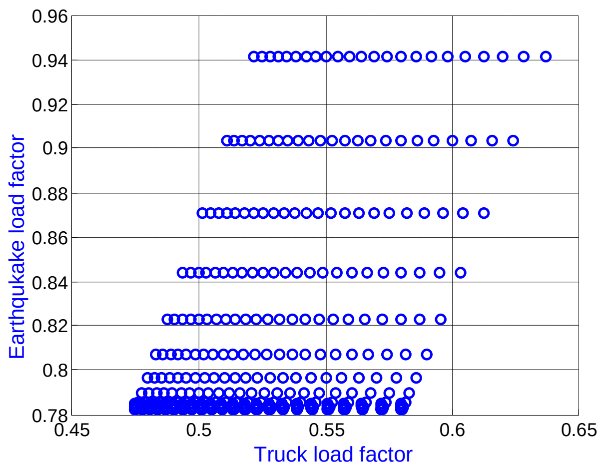

Fig.8 Load factors for varying the parameter of earthquake load in Seattle

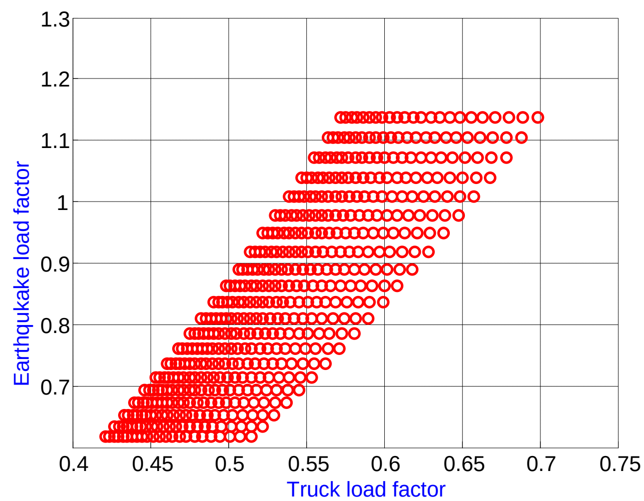

Fig.9 Load factors for varying the parameter of combined earthquake and truck loads in Seattle

4. Conclusions

This paper analyzed the sensitivity of earthquake and truck load factors based on load probabilities. A typical bridge case study was employed to analyze the influence of different parameters to load factors when subjected to earthquake and truck loads. COV is the most significant impact, and the sensitivity analysis focused on this variation. The trends of earthquake and combined earthquake and truck loads were similar but showed different slope and impact area. Earthquake load sensitivity was smaller than the combined earthquake and truck load sensitivity for San Francisco.

We also considered the more moderate earthquake intensity for Seattle. Load factor trends were significantly different than the San Francisco case, since the earthquake load does not dominate the truck load in Seattle. And the final load factors can be determined by considering the inheritance of dead load factor, load characteristics in different regions.

4. Acknowledgements

This study is jointly funded by Scientific Research Fund of Institute of Engineering Mechanics, China Earthquake Administration (Grant No. 2016B06), Special Research Fund for Seismology of China Earthquake Administration (Grant No. 201508023), the National Natural Science Fund of China (NSFC) (Grant No. 51308510, 51678544). The results and conclusions presented in the paper are related to the authors and do not necessarily reflect the view of the sponsors.

5. References

[1] AASHTO (2009): *AASHTO Guide Specification for LRFD Seismic Bridge Design*, 1st Ed., Washington, DC.

[2] AASHTO (2007): *AASHTO LRFD Bridge Design Specifications*, 4th Ed., Washington, D.C.

[3] Andrzej S. Nowak, Chan-Hee Park, Peter Ojala (2001): Calibration of Design Code for Buried Structures [J]. Can. *J. Civ. Engineering*. 28: 574-582.

[4] Artur A. Czarnecki, Andrzej S. Nowak (2008): Time-variant Reliability Profiles for Steel Girder Bridges [J]. *Structural Safety*. 30: 49-64.

[5] Nowak A. S., Chan-Hee Park, J.R. Casas (2000): Reliability Analysis of Prestressed Concrete Bridge Girders: Comparison of Eurocode, Spanish NORMA IAP and AASHTO LRFD[C]. *8th ASCE Specialty Conference on Probabilistic Mechanics and Structural Reliability*.

[6] Nowak A.S., Hong Y. K. (1991): Bridge Live Load Models. *ASCE Journal of Structural Engineering*. 117(9).

[7] R. M. Barker, J. M. Duncan, K.B. Pojiani et al. (1991): Manuals for the Design of Bridge Foundations [R]. *NCHRP Rep. 343*, Transportation Research Board, National Research Council, Washington, D.C..

[8] Jordan Pelphrey, et al. (2008): State-Specific LRFR Live Load Factors Using Weigh-in-Motion Data. *Journal of Bridge Engineering*, **13**(4), 339-350.

[9] Kitjapat PHUVORAVAN (2006): Load distribution factor equation for steel firder bridges in LRFD design. *Symposium on Infrastructure Development and the Environment*, SEAMEO-INNOTECH.

[10] Fred Moses (2001): Calibration of Load Factors for LRFR Bridge Evaluation.*NCHRP 454*. Transportation Research Board, National Research Council, Washington, D.C..

[11] Ellingwood, B., et al. (1982): Probability-based load criteria: load factors and load combinations. *J. Struct. Div. ASCE* **108**(5):978-997.

[12] Laramie WY, Newark DE (2007): Simplified Live Load Distribution Factor Equations. *NCHRP 592*. Transportation Research Board, National Research Council, Washington, D.C..

[13] Sivakumar, B., Moses, F., Fu, G., & Ghosn, M. (2007). Legal truck loads and aashto legal loads for posting. *Nchrp Report*.

[14] SUN Dezhang, SUN Baitao, George C. Lee (2011): Study on combination of internal forces on bridges subjected to earthquake and heavy trucks based on Ferry Borges theory. *Journal of Earthquake Engineering and Engineering Vibration*. **31**(6): 8-13. (In Chinese)

[15] SUN Dezhang, SUN Baitao, George C. Lee (2012): Method of load factor determination for multi-hazards bridge design [J]. China Civil Engineering Journal. **45**(2), 76-79. (In Chinese)

[16] Wen Y. K. (1994): Development of Reliability-Based Design Criteria for Buildings Under Seismic Load. *Technical Report 1994/08*. Buffalo.

[17] ZHANG Ming (2009): *Reliability analysis of structure- method and program*. Science press, Beijing. (In Chinese)

[18] Macgregor, J. G. (1980): Development of a Probability Based Load Criterion for American National Standard A58-Building Code Requirements for Minimum Design Loads in Buildings and Other Structures. U.S. Department of Commerce/National Bureau of Standards.

[19] Michel Ghosn, Fred Moses, Jian Wang (2003): Design of Highway Bridges for Extreme Events. *NCHRP 489*. Transportation Research Board, National Research Council, Washington, D.C..