Analytical Fragility Curves for RC Bridge Piers for Different Earthquake Events

The University of Tokyo, Institute of Industrial Science, Student Member Kazi Rezaul Karim
The University of Tokyo, Institute of Industrial Science, Member Fumio Yamazaki

Introduction: Fragility curves correlate the probability of structural damage due to earthquakes as a function of ground motion indices (e.g., PGA, PGV). Yamazaki *et al.*[1)] developed a set of empirical fragility curves based on the actual damage data of highway bridges from the 1995 Hyogoken-Nanbu earthquake. It is assumed that there will be an effect on the fragility curves due to the variation of structural parameters and variation of input ground motion. However, in the empirical approach these parameters were not considered to construct the fragility curves. In this study, an analytical approach is employed to construct the fragility curves for bridge piers.

Development of fragility curves: Yamazaki *et al.*[1)] developed a set of empirical fragility curves based on the actual damage data of highway bridges from the 1995 Hyogoken-Nanbu earthquake. In the present paper, we consider an analytical approach to construct the fragility curves for bridge piers of specific bridges. A nonlinear dynamic response analysis of the piers is performed and the piers are modeled as a single-degree-of-freedom (SDOF) system. For a nonlinear dynamic response analysis, strong motion records were selected from the 1995 Hyogoken-Nanbu, the 1994 Northridge, the 1993 Kushiro-Oki and the 1987 Chibaken Toho-Oki earthquakes. A total of fifty (50) acceleration time histories were taken from each earthquake event. The records were selected on the basis of Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV). Using these acceleration time histories as input ground motion, the damage indices[2)] of the bridge piers are obtained from nonlinear analysis. Finally, using the obtained damage indices and the ground motion indices, the analytical fragility curves for RC bridge piers are constructed. The fragility curves obtained by following this approach considers both structural parameters and variation of input ground motion.

Static Analysis: To obtain the analytical fragility curves for RC bridge piers, a typical bridge structure is considered. The bridge model taken in this study is rather simple. The length of each span of the bridge is 40m and the width is 10m. The height of each pier is 8.5m. The cross-section of each pier is 4m by 1.5m. The piers are designed by using the 1964 seismic design code in Japan and are named as 1964 piers. The ductility capacity is obtained as 4.94.

Dynamic Analysis: A bilinear hysteretic model was considered and the post yield stiffness was taken as 10% of the yield stiffness of the pier with 5% damping ratio. The yield stiffness of the piers is obtained using the yield force and yield displacement. The ductility demand at the top of the bridge pier is obtained. The ductility is defined as the ratio of the maximum displacement (obtained from the nonlinear dynamic response analysis) to the yield displacement (obtained from the static analysis). The ductility factors thus obtained are used to evaluate the damage of the bridge piers. For the damage assessment of the bridge piers, Park-Ang[2)] damage index was used in this study. The damage index *DI* is expressed as

$$DI = (\mu_d + \beta \cdot \mu_h) / \mu_u \qquad (1)$$

where μ_d is the displacement ductility, μ_u is the ultimate ductility of the bridge piers, β is the cyclic loading factor taken as 0.15 and μ_h is the cumulative energy ductility defined as $\mu_h = E_h / E_e$ with E_h and E_e being the cumulative hysteretic and elastic energy of the bridge piers. The obtained damage indices for the given input ground motion are calibrated to get the relationship between the damage index (DI) and damage rank (DR). This calibration is conducted using the method that was proposed by Ghobarah *et al.*[3)] **Table 1** shows the relationship between the damage index and damage rank. Using the relationship between DI and DR, the number of occurrence of each damage rank is obtained. The number of occurrence of each damage rank is counted normalizing PGA to different excitation levels. Using the numbers, the damage ratio is obtained for each damage rank. **Figure 1** shows the number of occurrence of each damage rank in each excitation level with respect to both PGA and PGV due to the Kobe earthquake. It can be seen that as the excitation level increases the number of occurrence of slight

Table 1 Relationship between the damage index and damage rank[3)]

Damage Index (DI)	Damage Rank (DR)	Definition
0.00<DI≤0.14	D	No Damage
0.14<DI≤0.40	C	Slight Damage
0.40<DI≤0.60	B	Moderate Damage
0.60<DI<1.00	A	Extensive Damage
1.00≤DI	As	Complete Damage

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Contact Address: 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan. Tel: 03-5452-6390, Fax: 03-5452-6389

damage decreases, whereas the number of occurrence of complete damage increases.

Fragility Curves: For each damage rank we have one data set, i.e., PGA and damage ratio and similarly PGV and damage ratio. Based on these data, fragility curves for the bridge piers are constructed assuming a lognormal distribution. For the cumulative probability P_R of occurrence of the damage equal or higher than rank R is given as

$$P_R = \Phi[(\ln X - \lambda)/\zeta] \qquad (2)$$

where Φ is the standard normal distribution, X is the ground motion indices (PGA and PGV), λ and ζ are the mean and standard deviation of $\ln X$. Two parameters of the distribution (i.e., λ and ζ) are obtained by the least square method on a lognormal probability paper. The parameters λ and ζ for the empirical fragility curves[1)] were also taken for a comparison. **Figure 2** shows the plots of the empirical and analytical fragility curves for the 1964 Japanese bridge pier due to different earthquake events. Note that there is five damage ranks that are shown in **Table 1**. For simplicity, the fragility curves only for extensive damage cases are shown in the plots. One can see that the empirical and analytical fragility curves show a very similar level of damage probability with respect to PGA. However, with respect to PGV some difference is observed between the two. One can also see that the fragility curves obtained by using the records from the Chibaken earthquake show a very lower level of damage probability with respect to PGV.

Conclusions: An analytical method to develop the fragility curves for the RC bridge piers was presented. The analytical fragility curves for a pier designed by the 1964 seismic design code were constructed with respect to both PGA and PGV using the records from different earthquake events. The obtained analytical fragility curves were compared with the empirical ones. Good agreement was observed with respect to PGA but not with PGV. Although only one pier model and different sets of earthquake records are used in this study, the method presented herein is useful to demonstrate the effects of structural parameters and input motion characteristics on fragility curves.

References

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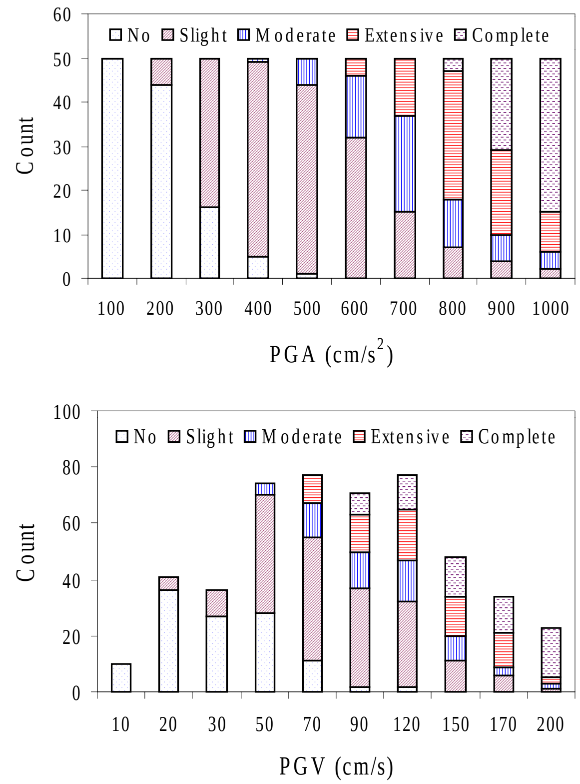

Fig. 1 Number of occurrence of each damage rank in different excitation levels

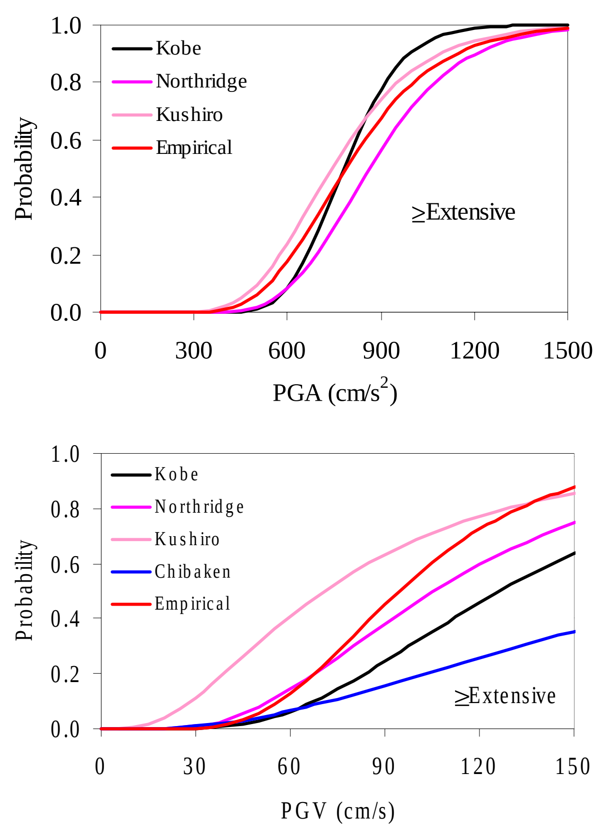

Fig. 2 Fragility curves for bridge piers with respect to both PGA and PGV