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DEVELOPMENT OF FRAGILITY CURVES FOR SEISMIC EVALUATION OF A REINFORCED CONCRETE BRIDGE

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ABSTRACT

Fragility curves are a very useful tool for a seismic risk assessment of bridges. They describe the probability of a structure being damaged beyond a specific damage state for different levels of ground shaking. Since, more than half of all bridges in Algiers region are in service for more than thirty years and were designed before the new Algerian seismic design code (RPOA-2008), generating fragility curves for these structures is more than necessary. They can be used to estimate damage and economic loss due to an earthquake and prioritize repairs or seismic rehabilitations of bridges. In this work, the derivation of fragility curves of four bridge piers type (circular pier, hollow core pier, wall pier and hammer head pier) located in a seismic prone area in Algeria is introduced. The methodology uses a non linear time-history analyses and a detailed SDOF analytical model subjected to earthquake ground motion.

INTRODUCTION

Past earthquakes, such as the 1971 San Fernando earthquake, the 1994 Northridge earthquake and the 1995 Kobe earthquake, have demonstrated that bridges are one of the most vulnerable components of highway transportation systems. Following an earthquake, the highway transportation systems might not be fully functional for a long period of time, and the regional economy might suffer significantly (Werner et al. 1995; Basoz and Kiremidjian 1998; Shinozuka et al. 1998). Because highway systems are critical lifelines for people living in an urban area, it is important to evaluate the vulnerability of bridges and highway transportation systems in this urban area.

Fragility curves, which are conditional probability statements of a bridge's vulnerability as a function of ground motion intensity, have been a common tool with which we make these seismic assessments. Several methodologies for generating seismic fragility curves for bridges have been developed over the years (Kurian et al. 2006; Seongkwan et al. 2007; Padgett and DesRoches 2008; Moschonas et al. 2009). The Applied Technology Council (ATC) developed bridge fragility curves based on expert opinion (ATC 1985). Empirical methods have also been employed to generate fragility curves for bridges located in California (Basoz and Kiremidjian 1999) and Japan (Shinozuka et al. 2000; Yamazaki et al. 1999). Probably, the largest and most diverse fragility generation methodologies are those based on analytical methods. These methods include elastic spectral (Jernigan

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and Hwang 2002), non linear static (Mander and Basoz 1999; Monti and Nistico 2002) and non-linear dynamic (Choi et al.2004; Karim and Yamazaki 2003) approaches.

Fragility curve methodologies using analytical approaches have become widely adopted because they are more readily applied to bridge types and geographical regions where seismic bridge damage records are insufficient. Because of the lack of strong motion records, bridges located in Algiers are generally assed using analytical approaches (Kibboua 2012). Most of the analytical bridge fragility studies to date have considered only the bridge columns in vulnerability studies (Karim and Yamazaki 2001; Mackie and Stojadinovic 2004; Shinozuka et al. 2000; Kibboua 2012).

The purpose of this paper is to develop analytical fragility curves for typical Algerian reinforced concrete bridge piers based on a numerical approach taking into account, the structural parameters and the variation of the input ground motion. By using worldwide strong motion records, the damage indices as defined by (Park and Ang. 1985) are obtained through a non-linear dynamic response analysis via the educational NONLIN software program (Charney 1998). The obtained damage indices defined for five damage rank and the ground motion indices are then combined to derive the corresponding fragility curves for the reinforced concrete bridge piers.

METHODOLOGY

Fragility theory is a generalized branch of structural reliability which assesses the vulnerability of the structure conditioned upon some other input parameter. For seismic loading, the fragility simply looks at the probability that the seismic demand placed on the structure (D) is greater than the capacity of the structure (C). This probability statement is conditioned on a chosen intensity measure (IM) which represents the level of seismic loading. The generic representation of this conditional probability is given as:

$$Fragility = P\left[D \geq C \middle| IM\right] \tag{1}$$

Analytical fragility curves are employed for assessing the seismic performance of highway bridges when neither the actual bridge damage data nor an expert opinion is available. The procedure for the evaluation of seismic damage in terms of analytical fragility curves for some specific Algerian reinforced concrete bridge piers which is done in this manner. The yield stiffness of the piers was firstly obtained by performing a sectional static analysis using the XTRACT computer program (Chadwell et al. 2002). For the non- linear dynamic response analysis, the piers were modelled as a single degree of freedom (SDOF) system and subjected to acceleration time histories taken from a worldwide earthquake data base based on their peak ground acceleration values. For the non linear dynamic response analysis, the PGA of the selected records was normalized to different excitation level from 0.1g to 1.0g having 10 excitation levels with equal intervals. Using these acceleration time histories as an input motion, the damage indices of the bridge piers are obtained from the non linear analysis. Finally, the obtained damage indices and the corresponding ground motion indices are combined to develop the analytical fragility curves for the RC bridge piers.

SECTIONAL ANALYSIS

The sectional analysis is carried out for two reasons: (1) to find out the two possible structural failure modes, i.e., the shear or the flexural failure modes of the bridge piers and (2) to obtain the force-displacement relationships at the top of the bridge piers. In the case of a flexural analysis, there is no contribution of the shear component to the displacement, however, in the case of a shear analysis; there is contribution of both the shear and the flexural components to the displacement.

DYNAMIC ANALYSIS

To perform the dynamic response analysis, the piers are modeled as a single-degree-of freedom (SDOF) system using a bilinear model (Priestley et al., 1996). The damage assessment of the bridge piers is carried out using the Park-Ang damage index DI expressed as:

$$DI = \frac{\mu_d + \beta\mu_h}{\mu_u} \tag{2}$$

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:

$$\mu_h = \frac{E_h}{E_e} \tag{3}$$

with E_h and E_e denoting the cumulative hysteretic (obtained from dynamic analysis) and the elastic energy (obtained from elastic analysis) of the bridge piers respectively.

The damage indices of the bridge piers are obtained using Eq. 2. The obtained damage indices for the given input ground motion are then calibrated to get the relationship between the damage index (DI) and the damage rank (DR). This calibration is performed using the (Ghobarah et al., 1997) proposed method. Table 1 shows the relationship between the damage index and the damage rank. As it can be seen, each DR has a certain range of DI varying from no damage to complete damage. Using the relationship between DI and DR, the number of occurrence of each damage rank is obtained. These numbers are then used to obtain the damage ratio for each damage rank.

Table 1. Relationship between the damage index DI and damage rank DR

Damage Index DI	Damage rank DR	Definition
$0.00 < DI \le 0.14$	D	No Damage
$0.14 < DI \le 0.40$	C	Slight Damage
$0.40 < DI \le 0.60$	B	Medium Damage
$0.60 < DI \le 1.00$	A	Extensive Damage
$1.00 \le DI$	As	Complete damage

CASE STUDY

Some manageable number of typical structural bridge piers in Algeria has been selected for the fragility analysis, considering four typical RC bridge piers. As it deals with piers that are not designed according to the 2008 new Algerian seismic design code for bridges (RPOA 2008), it is assumed that only the size and the reinforcement of the piers can be changed with other conditions such as their height, the length and the weight of the superstructure. The four sample bridges used to perform the analysis are listed in Table 2 and shown in Figs. 1 and 2. A brief description of these bridges is given here after:

- Bridge 1 consists of a four spans with an overall length of 116.80m. The superstructure consists of a longitudinally reinforced concrete deck slab of 10m wide and it is supported by three sets of columns and by an abutment at each end. Each set has three columns with a circular cross section of 1.20m diameter.

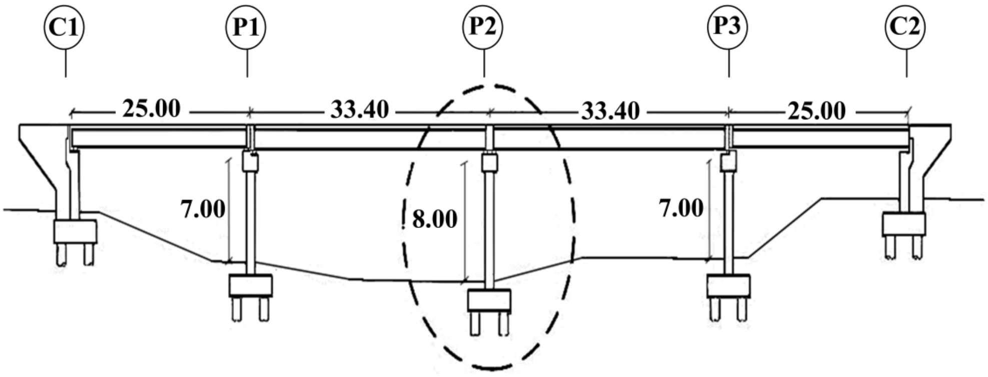
- Bridge 2 has an overall length of 116.00m with three spans. It is supported by two hollow core concrete bridge piers of rectangular cross section having external dimension of 6.0m x 3.5m with a hollow core of 4.80m x 2.30m. The deck width is 15.70m. The piers have a varying height with the taller one of 15.00m and the shorter one of 8.50m.

- Bridge 3 has an overall length of 64.20m with two spans. It is supported by a wall pier type of a rectangular cross section having 8.61m x 0.80m dimensions and 6.81 m height. The deck width is 10.05m.

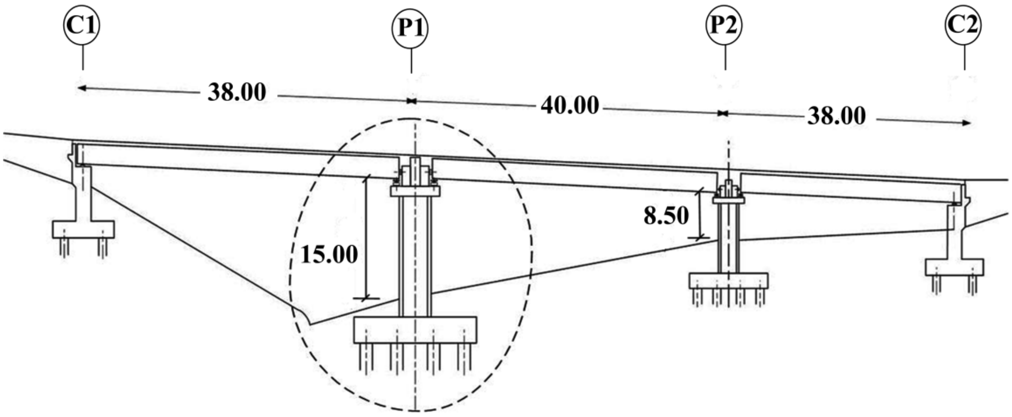
- Bridge 4 has an overall length of 151.80m with four spans. The bridge is supported by three hammerhead piers with a cross section of 5.00m x 1.80m. The deck width is 13.06m. The piers near the abutments have 14.00m in height while the central one has a height of 17.00m.

Table 2. Description of four sample bridges

Bridges	Overall length (m)	Number of spans	Deck width (m)	Column height (m)
1	116.80	4	10.00	7.00-8.00-7.00
2	116.00	3	15.70	15.00-8.50
3	64.20	2	10.50	6.81
4	151.80	4	13.06	14.00-17.00-14.00

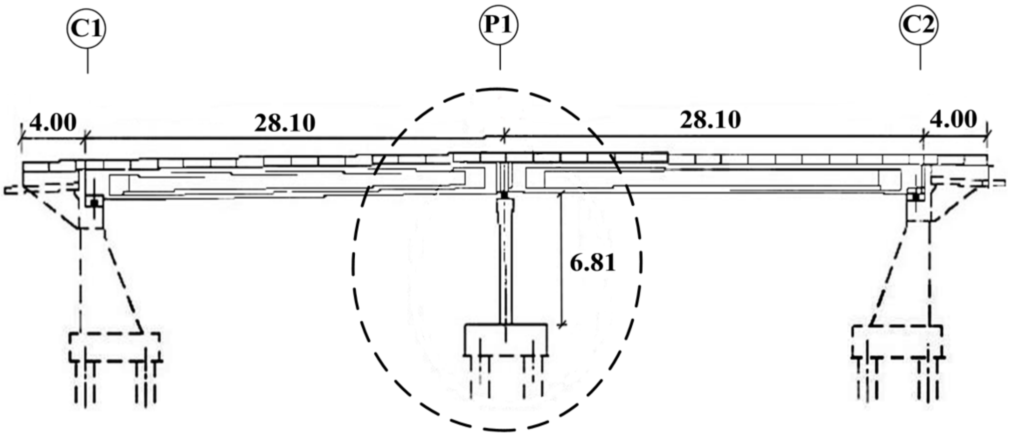


(a) Bridge 1

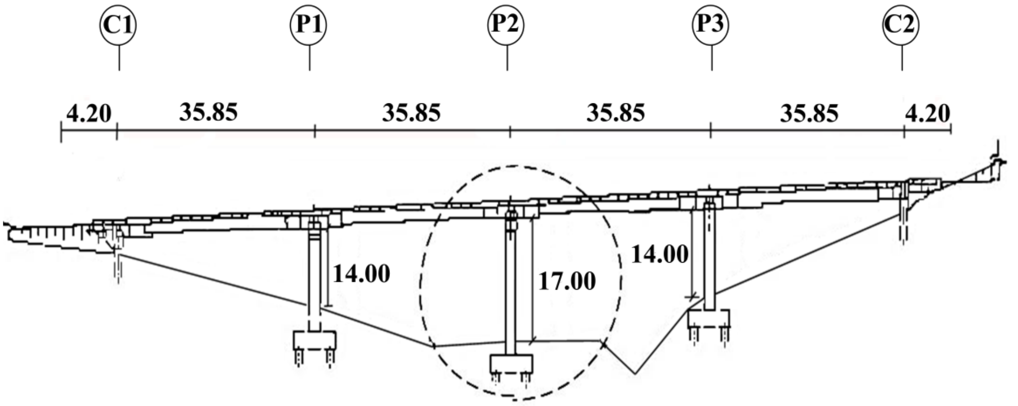


(b) Bridge 2

Figure 1. Elevation of sample bridge1 and bridge 2



(c) Bridge 3

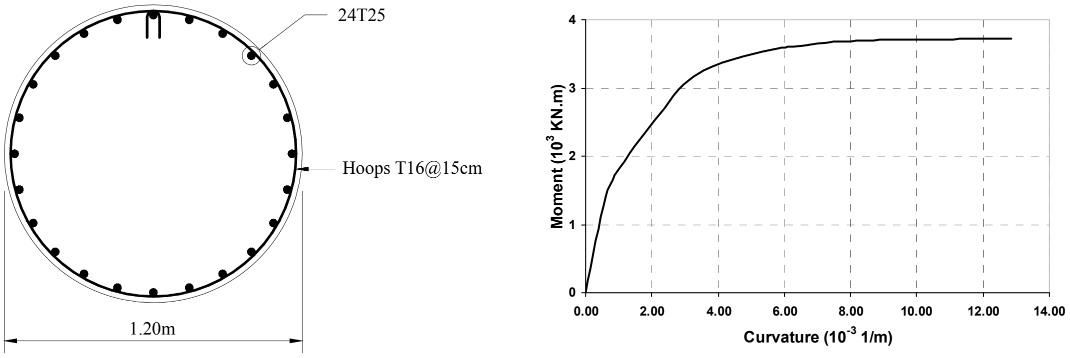


(d) Bridge 4

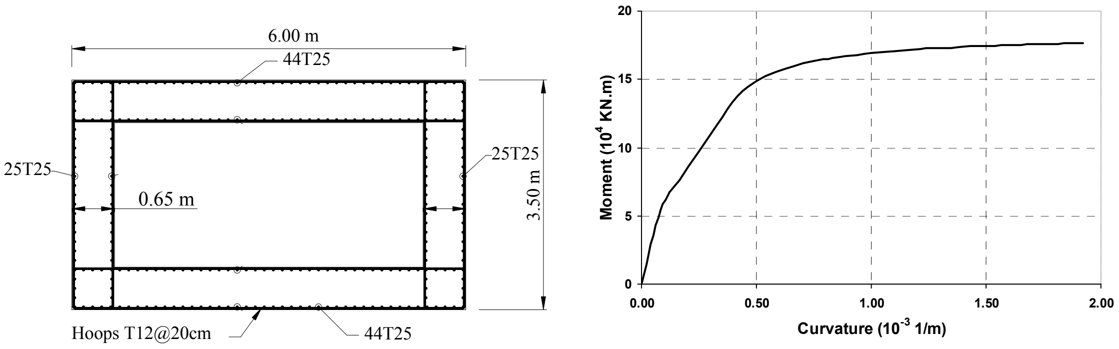
Figure 2. Elevation of sample bridge 3 and bridge 4

MOMENT CURVATURE CURVES

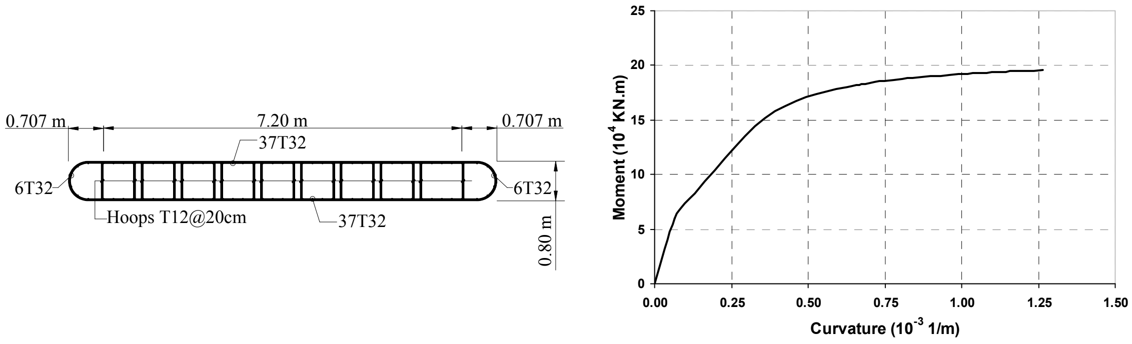
The sectional analysis of the bridge pier in the lateral direction is carried out to get the moment curvature relationship necessary for the non linear analysis. In this respect, the cross sectional dimension of the pier bridge, the yield strength of steel σ_{sy}, the compressive strength of concrete σ'_c, the diameter of the longitudinal reinforcement bars as well as the tie reinforcement bars are taken as input parameters. Figures 3a, 3b, 3c and 3d show the cross sections and the resulting moment-curvature curves of the bridge piers. For the sectional analysis, the height of the pier bridge taken into consideration is: 8m, 15m, 6.81m and 17m respectively for bridge 1, 2, 3 and 4. It is found that in most cases, the flexural failure governs the failure mode.



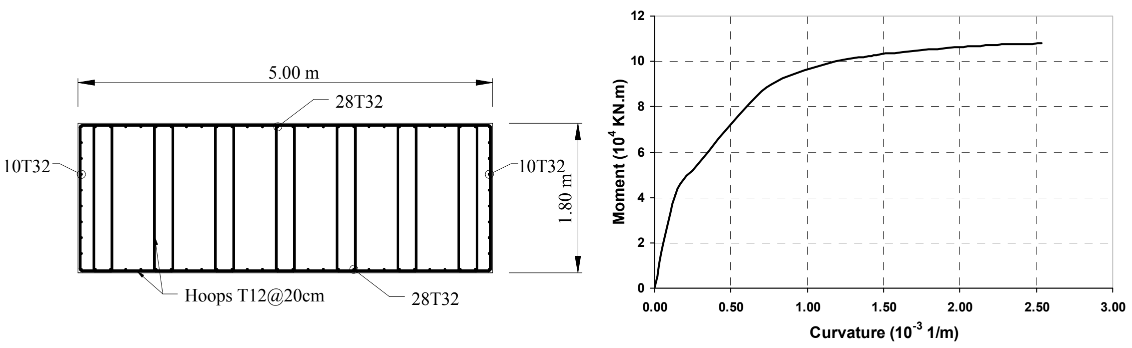
(a) Bridge 1



(b) Bridge 2



(c) Bridge 3



(d) Bridge 4

Figure 3. Cross sections and moment-curvature curves for the four bridge piers

FRAGILITY CURVES

Established fragility curves are constructed with respect to PGA. The damage ratio for each damage rank at each excitation level is obtained by calibrating the DI using Table 1. Based on this data, fragility curves for the bridge piers are derived assuming a lognormal distribution. The cumulative probability of occurrence P_R of a damage equal or higher than rank R is given as:

$$P_R = \Phi\left[\frac{\ln X - \lambda}{\zeta}\right] \tag{4}$$

Where Φ is the standard normal distribution, X is the ground motion indices in term of PGA, The two parameters of the distribution λ and ζ are the mean and the standard deviation of ln X. The log-normal distribution has a probability density function:

$$f(x,\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\left(\frac{(\ln(x)-\mu)^2}{2\sigma^2}\right)} \tag{5}$$

Where x is the value at which the function is evaluated, μ is the median value of the PGA and σ is the log-standard deviation.

The cumulative log-normal distribution is obtained by integration of the area below the density function shown in Eq. 6.

$$F(x,\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}} \int_0^x \frac{e^{-\left(\frac{(\ln(x)-\mu)^2}{2\sigma^2}\right)}}{t} dt \tag{6}$$

In order to obtain the two parameters that define the log-normal distribution (μ, σ), the Microsoft Excel Solver tool was used. Microsoft Excel applies the Generalized Reduced Gradient Nonlinear Optimization Code. The following steps outline the procedure:

1. Define a preliminary value for the median and standard deviation (μ, σ) ;
2. Plot the values obtained from the data ;
3. Calculate the cumulative log-normal distribution using the two preliminary values of μ and σ ;
4. Calculate the sum of the difference between the probability found from the lognormal probability plot constructed in step (iii) and the probability plot constructed in step (ii) ;
5. Perform the optimization code included in Microsoft Excel ;
6. Repeat this procedure for each damage state.

Figures 4 and 5 show the fragility curves, for each damage state and for the entire sample pier bridges.

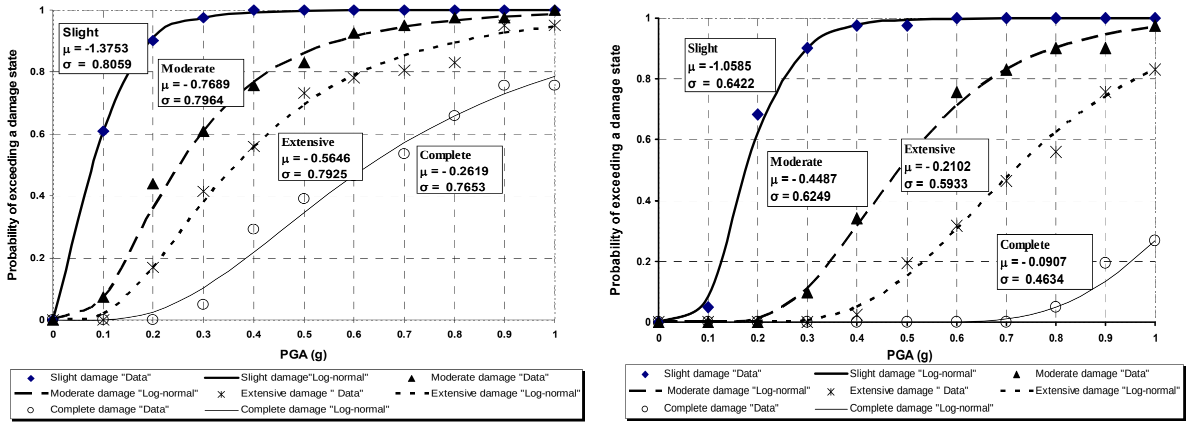


Figure 4. Fragility curves for all damage states of bridges 1 & 2

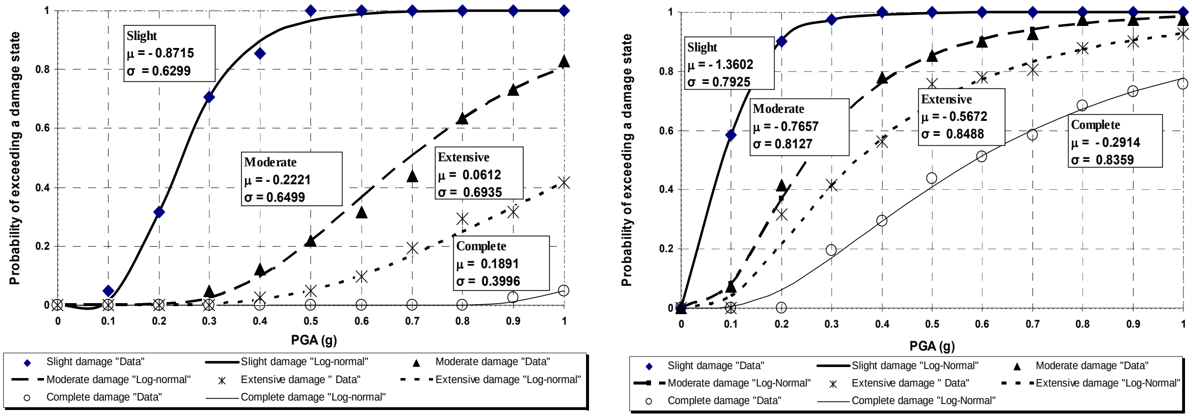


Figure 5. Fragility curves for all damage states of bridges 3 & 4

The Cumulative density functions (CDF), which should be converted to discrete damage-state probability curves are obtained by taking the difference in probability between adjacent damage state fragility curves. It means that the discrete slight probability is obtained by subtracting the slight damage state to the moderate damage state at each PGA value. The same step is done for each damage state curve. The following figures 6 and 7 show the discrete damage state probability curves for the bridges.

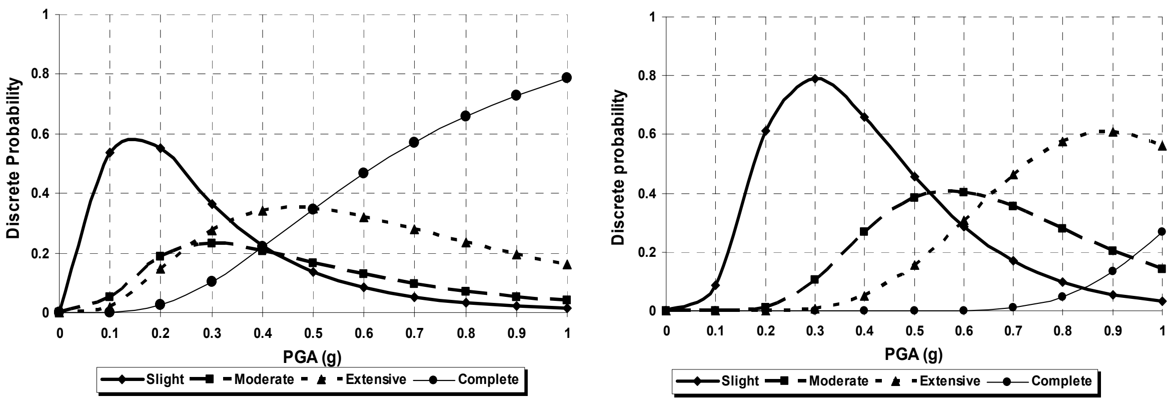


Figure 6. Discrete damage state probability curves of bridges 1 & 2

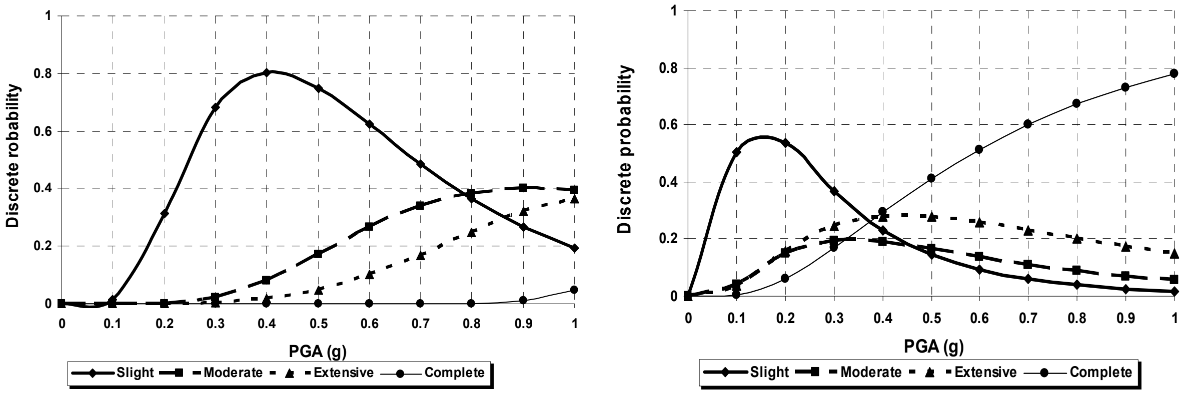


Figure 7. Discrete damage state probability curves of bridges 3 & 4

Figure 8 shows the comparison between slight, moderate, extensive and complete damages for the four typical RC bridge piers.

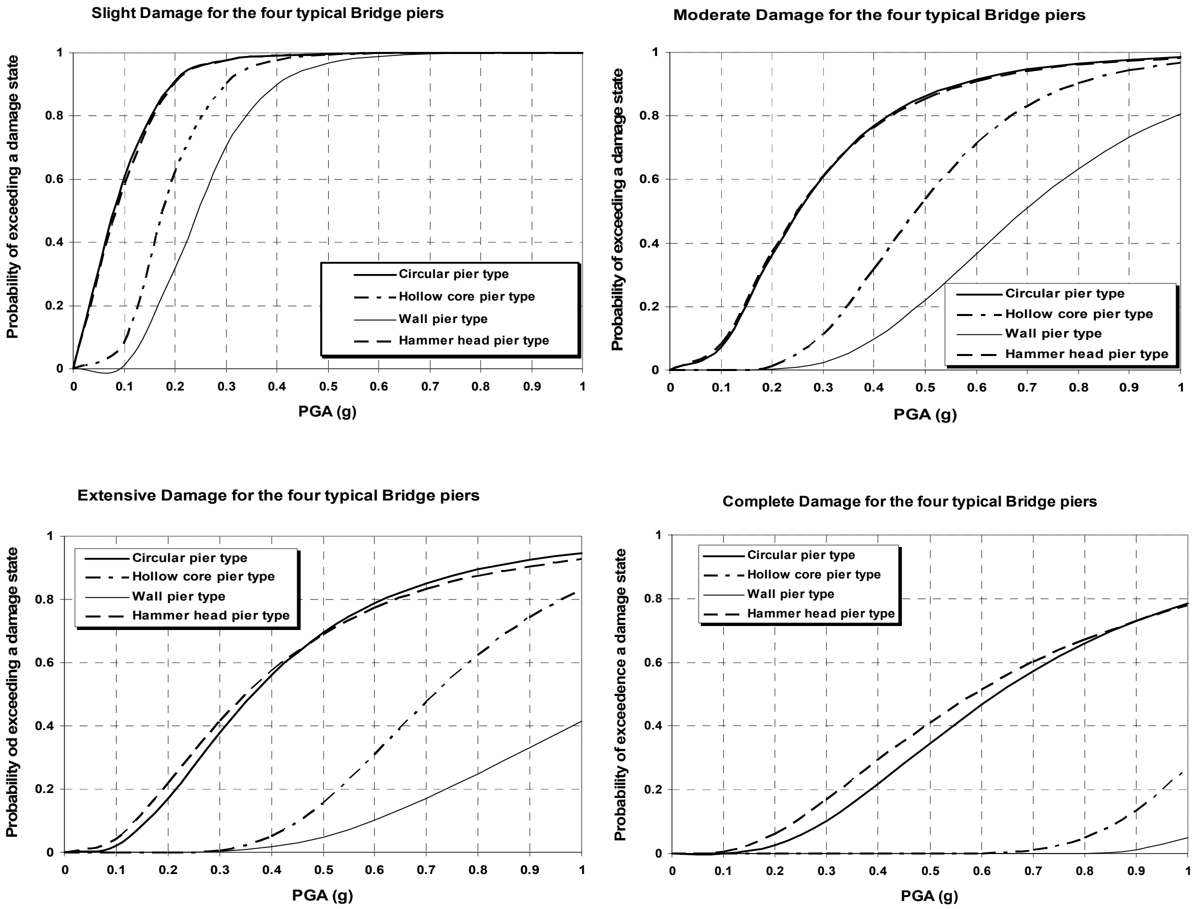


Figure 8. Fragility curves between slight, moderate, extensive and complete damages for the four typical bridge piers

RESULTS INTERPRETATION

Analytical fragility curves for four typical Algerian reinforced concrete bridge piers having different structural properties (Fig. 3a, Fig. 3b, Fig. 3c and Fig. 3d) were obtained with respect to the peak ground acceleration based on numerical simulation using worldwide accelerometer records assuming a lognormal distribution. It was found that there is a significant effect on the fragility curves due to the variation of structural parameters in terms of the cross section shapes, the longitudinal reinforcement and the tie reinforcement. The level of damage probability in the cases of slight, moderate, extensive and complete damage is the same for bridge type 1 (circular pier type) and bridge type 4 (hammerhead pier type). The bridge type 3 (wall pier type) has a lower level of damage probability than the other ones. However, the level of damage probability for the bridge type 2 (hollow core pier type) is lower than bridges type 1 (circular pier type) and 4 (hammerhead pier type) but higher than the bridge type 3 (wall pier type). It implies that the bridge type 3 which is supported by a wall pier type performs better against seismic forces than the others. The same observation can be done for the bridge type 2 that is supported by two hollow core piers type which performs better than the bridge type 1 (circular pier type) and bridge type 4 (hammerhead pier type).

CONCLUSIONS

To predict the extent of probable damages of bridge structures, fragility curves are regarded to be a useful tool. The vulnerability assessment of bridges is useful for seismic retrofitting decisions, disaster response planning, estimation of direct monetary loss, and evaluation of loss of functionality of highway transportation systems. Using the analytical approach developed by Karim and Yamazaki for typical Japanese bridge piers, this paper illustrates the results of the seismic vulnerability study aimed to develop the analytical fragility curves for typical Algerian bridge piers based on numerical simulations. Bridge piers designed with the simplified seismic design method for bridges in Algeria are analyzed, and a large number of worldwide accelerometer records from which, Algerian strong motion records and earthquake records from some major event, e.g., the 1995 Kobe, the 1994 Northridge were selected in order to get a wide range of the variation of input ground motions. The fragility curves for the bridge piers are then developed by performing both, the static and the non linear time history analyses. One pier model has been selected as a representative of all other piers for a particular bridge structure. It can be seen that the analytical fragility curves for the four bridge piers show a very different level of damage probability with respect to PGA. This difference is due to the shape of the cross section and the percentage of the longitudinal and tie reinforcements. The wall pier type shows the best seismic performance while compared to the others (circular pier, hollow core pier and hammer head pier). The effect of soil-structure interaction is not taken into account for deriving the analytical fragility curves, for which a further study is also necessary.

The results produced from the assessment of damage to bridges and highway transportation systems in the event of an earthquake can be used to prioritize bridges for retrofitting, to prepare a pre-earthquake preparedness plan, and to develop a post earthquake emergency response plan. Furthermore, the results might also be used to assess the regional economic impact from the damage to highway transportation systems.

REFERENCES

ATC (1985) “Earthquake damage evaluation data for California”, *ATC-13,* Applied Technology Council

Basoz N., and Kerimidjian A (1998) “Risk assessment for highway transportation systems”, *Proc, 6th U.S. Nat. Conf on Earthquake Engrg*, Earthquake Engineering Research Institute, Oakland, Calif (on CD-ROM)

Basoz N, and Kerimidjian A (1999) “Development of empirical fragility curves for bridges”, *5th US Conference on Lifeline Earthquake Engineering*, ASCE: Seattle, WA, USA

Chadwell CB, Imbsen and Associates (2002) XTRACT-Cross Section Analysis Software for Structural and Earthquake Engineering, *http://www.imbsen.com /xtract.htm*

Charney FA (1998) “NONLIN – Nonlinear Dynamic Time History Analysis of Single Degree of Freedom Systems”, *Federal Emergency Management Agency Training Center*, Emmitsburg, Maryland, Advanced Structural Concepts, Golden, CO and Schnabel Engineernig, Denver, Co

Choi E, DesRoches R, Nielson B (2004) “Seismic fragility of typical bridges in moderate seismic zones”, *Engineering Structures*, 26:187-199

Ghobarah A, Aly NM and El-Attar M (1997) "Performance level criteria and evaluation", *Proceedings of the International Workshop on Seismic Design Methodologies for the next Generation of Codes,* Balkema: Rotterdam, 207–215

Jernigan JB and Hwang H (2002) "Development of bridge fragility curves", *Proc, 6th US Nat Conf on Earthquake Engrg*, Earthquake Engineering Research Institute, Oakland, Calif (on CD-ROM)

Karim KR and Yamazaki F (2001) "Effect of earthquake ground motions on fragility curves of highway bridge piers based on numerical simulation", *Earthquake Engineering and Structural dynamics*, 30: 1839-1856

Karim KR and Yamazaki F (2003) "A simplified method of constructing fragility curves for highway bridges", *Earthquake Engineering and Structural dynamics*, 32:1603-1626

Kibboua A (2012) Développement d'une méthodologie d'analyse pour la vulnérabilité sismique des piles de ponts algériens, Ph.D. Thesis, Université des Sciences et de la Technologie Houari Boumediene (USTHB), Algiers, Algeria

Kurian SA, Deb SK and Dutta A (2006) "Seismic vulnerability assessment of a railway overbridge using fragility curves", *Proceedings of 4th International Conference on Earthquake Engineering*, paper Number 317, Taipei, Taiwan

Mackie KR and Stojadinovic B (2004) "fragility curves for reinforced concrete highway overpass bridges", *13th World Conference on Earthquake Engineering*, Vancouver, BC, Canada, 2004

Mander JB and Basoz N (1999) "Seismic fragility curves theory for highway bridges", *Proceedings of 5th U.S. Conference of Lifeline Earthquake Engineering*, ASCE, 31-40

Monti G, Nistico N (2002) "Simple probability-based assessment of bridges under scenario earthquakes", *Journal of Bridge Engineering,* 7:104-114

Moschonas IF, Kappos AJ, Panetsos P, Papadopoulos V, Makarios T, Thanopoulos P (2009) "Seismic fragility curves for greek bridges: methodology and case studies", *Bull Earthquake Eng*, (7):439-468

Padgett JE and DesRoches R (2008) "Methodology for the development of analytical curves for retrofitted bridges", *Earthquake Engng Struct Dyn,* (37):1157-1174

Park YJ and Ang AHS (1985) "Seismic damage analysis of reinforced concrete buildings", *Journal of Structural Engineering*, *ASCE*, 111(4):740-757

Priestley MJN, Seible F and Calvi GM (1996) Seismic Design and Retrofit of Bridges, John Wiley & Sons Inc, New York

RPOA (2008) Règles Parasismiques Applicables au Domaine des Ouvrages d'Art, *Document Technique Règlementaire*, Ministère des Travaux Publics, Alger, Algeria

Seongkwan ML, Tschangho JK and Seung LK (2007) "Development of Fragility Curves for Bridges in Korea", *KSCE Journal of Civil Engineering*, 3(11):8- 15

Shinozuka M, Feng MQ, Kim HK and Kim SH (2000) "Nonlinear statistic procedure for fragility curve development", *Journal of Engineering Mechanics*, 126:1287-1296

Shinozuka M, Feng MQ, Lee J and Naganuma T (2000) "Statistical analysis of fragility curves", *Journal of Engineering Mechanics*, 126:1224-1231

Shinozuka M, Moore J, Gordon P, Richardson HW, Chang S, and Cho SB (1998) "An Integrated model of highway networks and the spatial metropolitan economy: Towards a general model of how earthquake losses affect the economy", *NCEER Bul.*, 12(1):8-15

Werner SD, Jernigan J, Taylor CE, and Hwang H (1995) "Seismic vulnerability assessment of highway systems", *NCEER Bull*, 9(4):1-11

Yamazaki F, Hamada T, Motoyama H, Yamuchi H (1999) "Earthquake damage assessment of expressway bridges in Japan", *Technical Council on Lifeline Earthquake Engineering Monograph*, 361-370