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SEISMIC VULNERABILITY EVALUATION OF EXISTING REINFORCED CONCRETE BRIDGE STRUCTURE

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Abstract

The present paper describes a methodology with its different steps used for assessing the vulnerability of existing reinforced concrete bridges at the capital city of Algeria, Algiers. The methodology was applied to 148 reinforced concrete bridges localized at Algiers and represents a part of the strategic bridges. It is a simple and efficient inspection method for the preliminary evaluation of seismic vulnerability of existing bridges. This assessment was conducted based on two earthquake scenarios considering two existing faults that can generate earthquakes with a maximum acceleration of 0.8g. The main findings of this study are summarized in this paper.

Keywords: existing reinforced concrete bridges, seismic vulnerability, earthquake scenarios

1. Introduction

On Wednesday 21 May 2003 at 19h 44mn local time, a destructive earthquake struck Boumerdes region and its surrounding towns causing the death of 2287 people, injuring more than 11000 and making about 100000 homeless. It damaged about 182000 apartments and private houses in the whole affected area, among them, 19 000 dwellings were rendered uninhabitable. It is considered as one of the most damaging earthquake in Algeria. The shallow earthquake of magnitude M6.8 was located offshore, 7 km north of the locality of Zemmouri in the wilaya (province) of Boumerdes and about 50 km of the capital city Algiers. The epicenter was located in the city of Boumerdes, the focal depth of the earthquake was 10 Km and the approximate duration was 35 seconds. The extent of the socio-economic impacts of these events confirmed that Algerian buildings are highly vulnerable to the recurrence of destructive earthquakes. This earthquake caused considerable economic losses to Algeria, had large socio-economic and psychological impacts on the region. The total cost of the damage has been estimated at around 5 billion U.S. Dollars.

Thirty four communes (districts) of fifty seven, the most populated and affected by earthquake damage were considered in this study. Utilizing the field observed damage data and the Japanese Methodology [1], based on Engineering judgments, the seismic vulnerability was evaluated for those bridges with a large number data in order to get a statistically significant sample size.

Expert survey teams investigated the field and conducted post-earthquake evaluation on selected bridges that did not suffer from the event. The data collected were analyzed in order to evaluate the seismic vulnerability of the Reinforced Concrete, RC, bridges that are representative in the capital Algiers. Hereafter, the main results of the study are presented using the Japanese methodology.

2. Description of the urban study area

2.1 Localization

The study area covers almost all the Wilaya of Algiers, capital of Algeria. This is one of the high seismic potential zone with many active faults. Urban development experienced a rapid progress in Algiers without the development of proper disaster prevention systems against potential earthquakes. After the great 2003 Boumerdes earthquake, it became urgent and necessary to prepare a master earthquake disaster prevention plan in order to mitigate possible future seismic damages in Algiers [2]. The seismic micro zoning mapping covers a total area of approximately 225 km^2 and a population of 2 624 428 inhabitants including the surrounding urbanized area. Thirty four communes of fifty seven, the most populated and built areas were concerned in this study. Figure 1 shows the map of the concerned study area delimited by the solid bold black line.

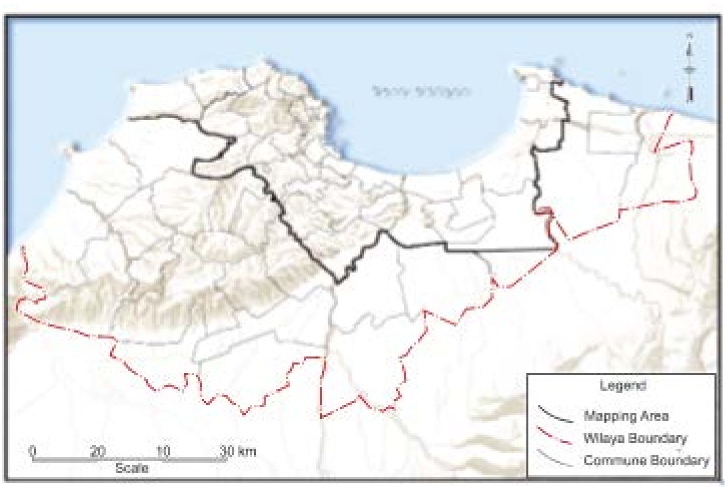

Fig. 1 – Map of the concerned study area

2.2 Seismic hazard assessment

Many seismic hazard investigations and research projects were developed for the northern part of Algeria by the two research centers CRAAG and CGS using the seismic instrumentation network [3]. Based on the observed damage, the post earthquake survey [4], and taking into account the consideration of the current situation and the past experience of Algeria from previous earthquakes, possible scenarios were drawn up. In total, six major active faults have been identified and chosen at the periphery of the region subject to the survey and used to create a seismic scenario so as to estimate magnitudes of possible future earthquakes in consideration of recurrence periods. The Sahel, Chenoua, Blida, Thenia and Zemmouri faults, in addition to Khair Eddine offshore fault were considered in this study. Figure 2 shows the location of each active fault.

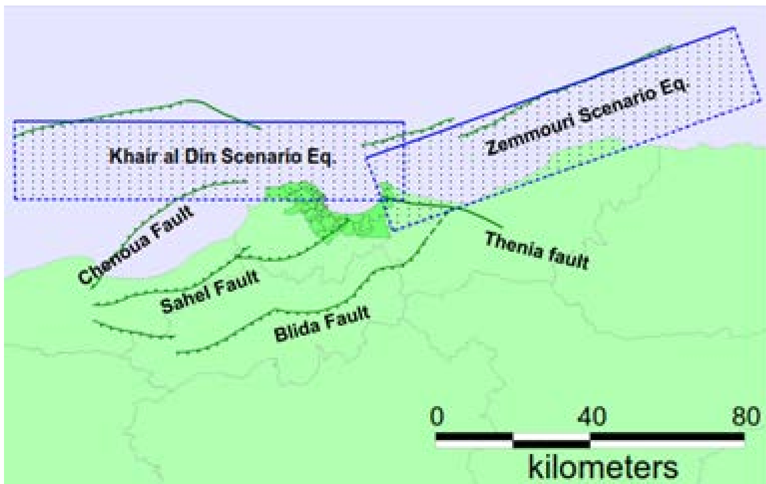

Fig. 2 – Identified active faults around the capital Algiers

2.3 Post earthquake survey

The number of existing RC bridges in the thirty four communes was estimated in accordance with the GIS data and the result of inventory survey. A total sampling number of 148 existing RC bridges were investigated in the whole study area [5]. The bridges inventory was conducted by experts and engineers of CGS. The post earthquake survey was conducted in order to estimate their damage and to develop in the future the seismic risk planning for ordinary bridges in Algiers.

3. Methodology

When bridges suffer heavy damage due to a major earthquake, emergency rescue efforts will be disturbed and various social functions will be frozen for a long time [6]. Failure of a bridge structure can determine an extensive disruption to the traffic system even though each failure is limited to a particular point in the road system. For instance, although the road itself is safe, if some bridges are destroyed, the road network will not function and emergency rescuers will be unable to reach sites where assistance is needed. In addition, the road network in terms of reconstruction will be useless because bridges repair in term of time are extremely long compared to the road repair. Thus, collapse of bridges should be prevented as much as possible [7]. A significant number of existing reinforced concrete bridges require maintenance and a permanent survey [8]. In Algeria, a rapid evaluation procedure for the diagnosis of existing bridges is needed. The seismic damage of bridges is estimated for two earthquake scenarios: “Khair al Din” and “Zemmouri”.

4. Katayama’s Methodology

Various procedures for assessing the seismic vulnerability of existing bridges have been proposed in a wide range from simple to precise inspection [9], the Katayama’s methodology is very effective in evaluating bridges from the viewpoint of falling-off the girders and is used as a first screening. An outline of the inspection method which is capable to assess the seismic vulnerability taking into account the damage features developed in recent earthquakes is shown in Figure 3. The main purpose of the procedure consider five principal factors: The site investigation which consist to conduct a bridge inventory survey in order to get a data basis for the analysis, the inspection of drawings and specifications because seismic design procedures have been reviewed and amended in the light of lessons learned through past seismic damages and development of new seismic design methods. The intensity of earthquake ground motion due to the scenario earthquake is introduced in terms of PGA and converted to MSK intensity. The liquefaction potential due to scenario earthquake is provided from geotechnical expert and hazard map. The scoring by categories which considers the type, materials, shape and slope of the superstructure are included to represent the properties of superstructure. The properties of substructure are represented in terms of type, pier, height of abutment and materials. The type of substructure is taken into account in term of girder type. Vulnerability of bridge depends on properties derived from hazard and resistance. Each property is weighted and then summed up. The relative importance of the different variables on the predicted bridge rate of failure is shown in Table 1. These values were determined from an engineering judgments based on the statistical analysis as well as the past experience of seismic damages.

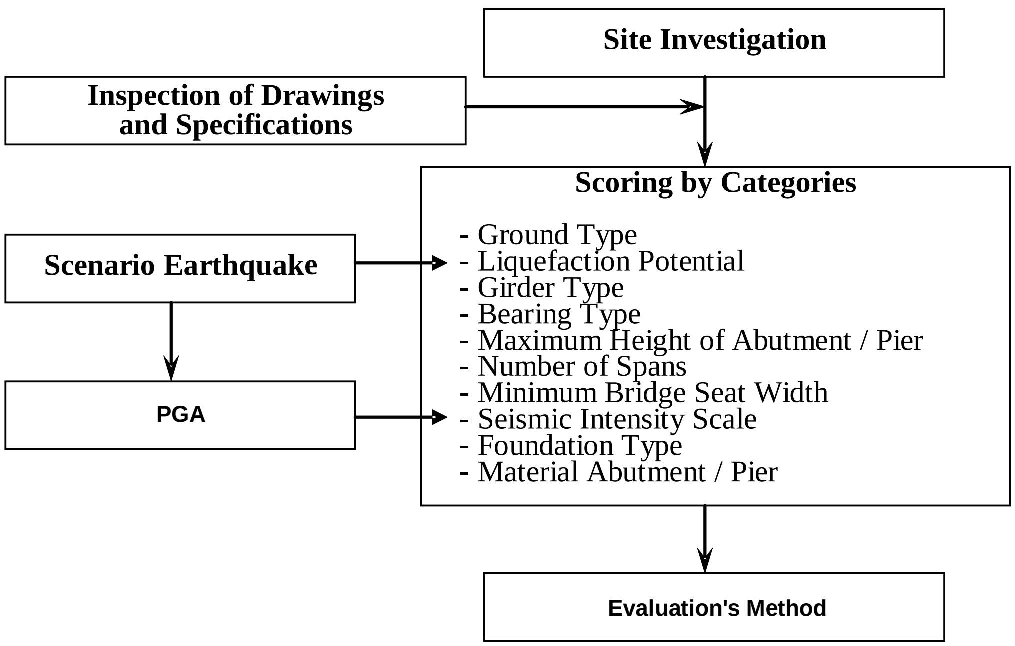

Fig. 3 – Flow chart of seismic vulnerability analysis of bridge

Based on the statistical analyses on the factors which are likely to contribute to the seismic susceptibility of bridges, Katayama's evaluation method is adopted to assess the seismic vulnerability of a number of bridges based on a simple inspection without complex calculation. Furthermore, the method is able to detect the bridges which have possibility for suffering damages in terms of falling off the girders when subjected to the ground shaking due to the earthquake. It should be noted that in Algeria 80% of the existing bridges are multiple simply supported girders. The major cause of damage to this type of bridges from the past earthquakes is attributed to the excessive relative movement between the superstructure and substructure. Hence, the choice of this method is suitable for this study.

Although the accuracy of the adopted method is insufficient for assessing the seismic vulnerability of bridges without complex calculation, it provides a realistic basis for assessing the seismic vulnerability of bridges from which fatal damages such as falling-off superstructure were most likely developed from excessive relative movement between the superstructure and substructure, and from failure of substructures due to inadequate strength. This method is based on regression analysis on bridge damage data, and has many positive aspects since it was essentially elaborated based on common sense and empirical rules: it is physically sound, it may be expeditly employed, it allows detect out the variables that are most likely to affect structural failure.

There are a number of bridge structures which are considered to have lower seismic safety from the view of current design practice [10]. Therefore, it is of considerable importance to retrofit the existing highway bridges which have high vulnerability for seismic damages [11]. The falling of the girders can determine serious impacts to the road system. The methodology adopted in this paper, generally referred to “Katayama’s method” is selected to carry out this study.

This method should allow us to improve the data relative to the considered scenarios of crises, and more globally, to improve the knowledge and the prevention of the seismic risk at the scale of the territories: elaboration of the plans of risk prevention, organization of rescue and planning of the future urbanization such as judicious implantation of strategic buildings and structures.

5. Factor affecting the seismic vulnerability of bridges

For detecting the factors which make bridges susceptible to seismic damage, the degree of seismic damage was evaluated and classified into groups by referring to post earthquake reconnaissance reports and a numerical value was assigned for each sample. A total of eleven (11) items likely to affect the probability of a girder falling are selected and considered as quantity to be analyzed statistically. They characterize the properties of a bridge that are likely to have influenced on the damage degree. These items are shown in the first column of Table 1. Each item is subdivided into several categories; a weighting factor is affected by each of them and shown in the "category score" at the third column of Table 1. Weights are derived from observation of damages from past earthquakes.

Table 1 – Inspection format for seismic vulnerability of bridges in Algiers

Item	Category	Category Score
Ground Type	Stiff / Hard: Slightly / No Weathered Rock	0.5
	Medium: Weathered / Moderately Weathered Rock	1.0
	Soft: Deposited Soil / Diluvium	1.5
	Very Soft: Deposited Soil / Alluvium	1.8
Liquefaction Potential	No Liquefaction	1.0
	Possible Liquefaction: $0 \leq P_L < 15$	1.5
	Liquefaction: $15 \leq P_L$	2.0
Girder Type	Arch or Rigid Frame	1.0
	Continuous	2.0
	Simple	3.0
Bearing Type	With Specific Device (prevent girder from falling)	0.6
	Bearing (with clear design concept)	1.0
	Exist Two Bearing (it can move axial direction)	1.15
	Others (no bearing, etc)	1.1
Max. Height of Abut./Pier	Less Than 5 m	1.0
	5 to 10 m	1.35
	More Than 10m	1.7
Number of Spans	1 Span	1.0
	2 Spans or More	1.75
Min. Bridge Seat Width	Wide: 70 cm or Wider	0.8

	Narrow: Less Than 70 cm	1.2
	No Seat: 0 cm	1.1
Seismic Intensity Scale (MSK)	MSK < 7.885 (JMA: less than 5.0)	1.0
	$VII^{1/2} \leq$ MSK < $VIII^{1/2}$ (JMA: 5.0 to less than 5.5)	2.1
	$VIII^{1/2} \leq$ MSK < $IX^{1/2}$ (JMA: 5.5 to less than 6.0)	2.4
	$IX^{1/2} \leq$ MSK < $X^{1/2}$ (JMA: 6.0 to less than 6.5)	3.0
	$X^{1/2} \leq$ MSK (JMA: 6.5 and more than 6.5)	3.5
Foundation Type	Pile Bent	1.4
	Others	1.0
Material of Abutment/Pier	Plain Concrete or Masonry	1.4
	Reinforced Concrete or Others	1.0

6. Earthquake senarios

Based on the results of damage estimations and according to the ASCE post earthquake investigation report [12], two earthquake scenarios were chosen for the present paper: Khair al Din and Zemmouri. The maximum credible earthquake that can be generated has been derived from their segmentation and down dip geometry of the fault plane, as imaged by the offshore data from the Maradja cruise [13]. Assuming a 100 ±20 km long fault dipping 45° southward to a depth of 20 km, the seismogenic capability of their sources is: $M_w = 7.4 \pm 0.3$, which corresponds to a rupture area of 2830 ± 565 km^2.

The maximum credible earthquake for identified active faults in the Algiers region is summarized in Table 2.

Table 2 – Seismic capability of Khair El Din and Zemmouri active faults

Fault	**Length (Km)**	**Dip Angle (°)**	**Depth (Km)**	**Rupture area (km^2)**	**M_w**
Khair El Din	100±20	45	20	2830 ± 565	7.4 ± 0.3
Zemmouri					

The relationship between the Japanese Meteorological Agency (JMA) scale and the seismic intensity Medvedev–Sponheuer–Karnik scale (MSK) is show in Figure 4.

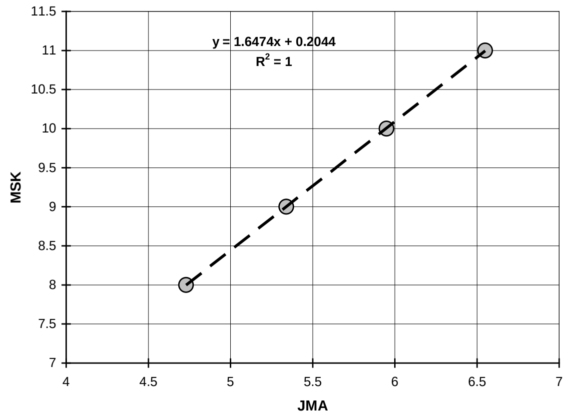

Fig. 4 – Empirical relation between JMA and seismic intensity scale in MSK

The original Katayama's method is based on the MSK scale that was modified to be suitable to the newly adopted JMA scale. In Algeria the used seismic intensity scale is the peak ground acceleration (PGA), hence the need of a relationship between the PGA and the MSK scales in order to be able to use the adopted methodology for this study. The relationship between the PGA and the seismic intensity in MSK scale is shown in Figure 5. The obtained intensities derived from this relation were used in this paper. The JMA-MSK relationship shown at Figure 4 is given just for illustration and to get a rough idea on the values between the different intensities.

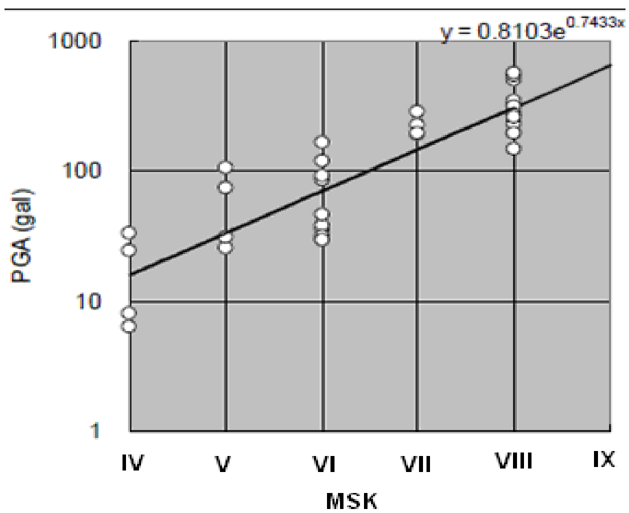

Fig. 5 – Empirical relation between PGA and seismic intensity scale in MSK

7. Analysis of bridges

Hundred forty eight (148) bridges that did not suffer from the Boumerdes earthquake (M 6.8) of 2003 were analyzed. The original values of the predictor, is shown in the second column of Table 3, to estimate the damage rank of bridges was based on 30 damaged bridges selected as samples during the Kanto earthquake of 1923 (M 7.9), the Fukui earthquake of 1948 (M7.3) and the Niigata earthquake (M7.5) of 1964. These values were modified; see the third column of Table 3, to fit the Algerian bridge type and the observed damage after Boumerdes earthquake. Vulnerability of seismic damage was then classified into three groups. The definition of the class of damage rank and the initial value are modified for this study according to damage results from Boumerdes earthquake in one hand and by taking into account the engineering judgement based on experience in the other hand.

Table 3 – definition of damage rank of bridges

Class of damage rank		Original threshold value	Modified threshold value
A	- High probability of girders falling - Generates huge deformation - Impossible to use for long term and requires reconstruction	≥ 30	≥ 30
B	- Moderate probability of girders falling - Generates deformation - Impossible to use temporarily and requires repairing / rehabilitation	26 to less than 30	22 to less than 30
C	- Low probability of girder falling - Generates small deformation - Possible to basically use after inspection	< 26	< 22

8. Evaluation of seismic vulnerability

Falling-off of bridge girders was not observed in the Boumerdes earthquake; however, some bridges suffered damage such as permanent deformations and cracks. The verification of the method and the threshold value is examined through the damage which occurred to the Sebaou Bridge in the city of Boumerdes and El Harrach Bridge in the city of Algiers. The intensity of earthquake ground motion was introduced in the analysis in term of MSK intensity. Because it is apparent from the past damage surveys that bridge damage was most likely developed due to inadequate strength and/or excessive deformation of substructures. The properties of substructure were represented in terms of pier's type, height and material. The mechanical device to prevent the falling-off the superstructure, which is one of the unique features of Japanese seismic design practice for highway bridges, was also considered as an important item. Ground condition was considered in term of ground type, irregularity, and soil liquefaction potential. This latter was evaluated in accordance to geological and site seismic conditions.

9. Illustrative example

9.1 Bridge on Sebaou river

The Sebaou Bridge is made of successive isostatic reinforced concrete beams as illustrated in Figure 6. The result of the proposed method for this bridge is summarized in Table 4. The bridge crosses a river in a region where the soil is alluvial. Liquefaction that occurred at Boumerdes earthquake, as shown in Figure 7, was considered in the analysis. The lateral ground spreading toward the river was observed at many places around the bridge as illustrated Figure 8. The liquefaction potential index (PL) is estimated as more than 15.

Fig. 6 – View of Sebaou Bridge

Table 4 – Analysis results of Sebaou Bridge

Item	**Category**	**Category Score**
Girder Type	Simple	3.0
Bearing Type	Bearing and System for Prevention of Girders Falling	0.6
Max. Height of Abut./Pier	5 to 10 m	1.35
Number of Spans	2 Spans or More	1.75
Min. Bridge Seat Width	Wide: 70 cm or Wider	0.8
Foundation Type	Others	1.0
Material of Abut./Pier	Reinforced Concrete or Others	1.0

Table 5 – Geological and seismic condition of Sebaou Bridge

Item	**Category**		**Category Score**
Ground Type	Very Soft: Deposit Soil / Alluvium		1.8
Liquefaction Potential	Liquefaction: $15 \leq PL$		2.0
Seismic Intensity Scale (MSK)	MSK = IX	Case 1: $VII^{1/2} < MSK \leq VIII^{1/2}$	2.1
		Case 2: $VIII^{1/2} \leq MSK < IX^{1/2}$	2.4
		Case 3: $IX^{1/2} \leq MSK < X$	3.0

Fig. 7 – Observed liquefaction near the Sebaou Bridge

The MSK intensity scale at the site was reported as IX; this value is between the ranges of $VIII^{1/2}$ to $IX^{1/2}$. Hence, 3 categories for the seismic intensity scale called Case 1, Case2 and Case 3 were selected as shown in Table 5. The total score of each case was: 25.7 (Case 1), 29.4 (Case 2) and 36.7 (Case 3). Consequently, the class of damage rank based on Katayama's method is judged as class "B" (moderate probability) or "A" (high probability).

The post earthquake field investigation of the Sebaou Bridge showed that some girders were displaced due to movement of some piers of around 50 cm or less as shown in Figure 8; however, the girders did not fall off. If no prevention system or less seat width was applied and/or a major earthquake occurred, the girders might have fallen down.

Hence, the damage rank of the Sebaou Bridge is evaluated as class "B" (moderate probability) that is very close to class "A" based on the above mentioned damage condition.

Fig. 8 – Girder displacement of Sebaou Bridge

From the field investigation, the authors advise to set a continuous reinforcement in the concrete pavement across the girder joint that may avoid the falling off the girders and contribute to the stability during strong earthquakes. Recently, devise of falling-off prevention of superstructures, which is one of the unique features of the Japanese seismic design practice for highway bridges, was introduced in practice. The device includes stoppers to prevent excessive relative movement between super and substructures, connections either between super and substructures or between adjacent girders, and increase the seat length to prevent falling-off of superstructure from crest and/or abutment.

10. Verification of the method

Table 6 shows the results of the method with modified threshold values and the actual damage to the Sebaou bridge which matched well with the proposed method. This indicates that Katayama's method is suitable for the damage estimation of the Algerian reinforced concrete bridges.

Table 6 – Summary for the Katayama's method verification of Sebaou Bridge

Bridge	Case by MSK Scale	Total Score	Class of Damage Rank		Verification
			Katayama's Method*	**Actual Damage**	
Sebaou	1	25.7	B	B	Falling of the girders did not occur, but displacement was generated. Probability of falling girders is evaluated by the actual damage as class "B" that is very close to class "A". Hence, the result of the method shows a good match for the actual damage.
	2	29.4	B		
	3	36.7	A		

*Threshold value for evaluation of the class applies the modified value

11. Application of the evaluation method

An evaluation method was applied to analyse 148 sample bridges. It should be noted, in this paper, that the evaluation method was used to predict the seismic vulnerability of bridges subjected to two earthquake scenarios: the "Khair al Din" and the "Zemmouri". Table 7 shows a summary of the predicted damage rank of the seismic vulnerability of the 148 selected bridges. The results show that for the Khair al Din scenario, the class of damage rank was 3, 19 and 126 bridges classified in damage rank A, B and C, respectively. For Zemmouri scenario these values were 4, 7 and 137.

Table 7 – Summary of bridge damage estimation

Class of Damage Rank	Number of Bridges [Ratio (%)]	
	Scenario Earthquake	
	Khair al Din	**Zemmouri**
A: High Probability	3 (2.0 %)	4 (2.7 %)
B: Moderate Probability	19 (12.9 %)	7 (4.7 %)
C: Low Probability	126 (85.1 %)	137 (92.6 %)
Total	**148**	**148**

It is important to note that, for the two scenarios, the seismic vulnerability rank is quite small for rank A and B, but high for rank C. This implies that the seismic vulnerability is reasonable for those bridges of rank C which are quite safe against earthquake. We can also note that for damage rank B, the Khair al Din scenario gives a value which is more than two times greater that the one found using Zemmouri scenario.

12. Conclusions

A screening evaluation method to assess the seismic vulnerability of existing bridge structures, which had likely contributed to assess those of the Algiers region, was presented. The adopted method was applied to Algiers, which is a typical Mediterranean city, located in a moderate to high seismic hazard area. Thirty four communes (districts), the most populated of Algiers were considered in this study. The assessment of the seismic vulnerability concerned one hundred and forty eight existing RC bridges. The assessment showed that the damage on the bridges was minor. Three of the bridges were damaged but did not collapse for Khair al Din earthquake scenario. For the two scenarios, the seismic vulnerability rank is quite small for rank A and B, although it is sufficiently high for Rank C. This implies that the seismic vulnerability is satisfactory for those bridges of Rank C which are quite safe against earthquake. We also noted that for damage rank B, the Khair al Din scenario gives a value which is more than two times greater that the one found using Zemmouri scenario.

From the field investigation, the authors advise to set a continuous reinforcement in the concrete pavement across the girder joint that may avoid the falling off the girders and contribute to the stability during strong earthquakes. Generally, in the study area, with the exception of masonry bridges and colonial bridges built before 1962, there is a low probability of the girders falling off, because, in most cases, enough support width has been provided.

Following the damage caused by the Boumerdes earthquake on 21 May 2003 (M 6.8), the Public Works Ministry of Algeria elaborated a specific seismic regulation for design (RPOA-2008) for the first time. From April 2010, all new constructed bridges must be designed and verified using this new bridge seismic code. The obtained seismic damages constitute an excellent information sources and tools for risk managements, emergency planning and also useful for civil protection, prevention and preparedness for the city of Algiers.

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