Seismic vulnerability assessment of bridges using analytical hierarchy process

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Abstract. Bridges play an important role in transportation network. After an earthquake, bridges must remain functional. To reach this goal, vulnerability study must be conducted. The aim of this study is to develop a vulnerability index method for bridges. The most important parameters influencing the seismic behaviour of bridges are identified, and a seismic vulnerability assessment model is developed using the analytical hierarchy process (AHP) to quantify the contribution of each parameter. Using the developed model, several bridges are treated and the obtained results show a good adequacy with in situ observations.

1. Introduction

Natural disasters such as earthquakes can cause severe damages to the transportation network, which affect rescue and emergency operations. Therefore, the seismic vulnerability assessment of critical infrastructure in transportation network must be investigated.

In the last decade, different empirical, analytical and hybrid approaches were developed to estimate the seismic vulnerability of bridges and help project managers and decision-makers to intervene in both before and after an earthquake.

The available current procedures in the United States are developed by the Applied Technology Council (ATC) [1], the Federal Highway Administration (FHWA) [2, 3] and The California Department of Transportation (CALTRANS) [4, 5]. We can also mention Nevada and Missouri [6], Washington [7, 8], Illinois [9], New York [10], Tennessee [11], and Oregon [12], procedures for the other states in America.

Further, in Japan, three methods have been used, the approach of "JHPC", "EDMC" [13, 14], and that of KUBO - KATAYAMA [15]. The «OFROU» method is applied in Switzerland [16], "SISMOA" in France, [17, 18], and "MTQ" in Canada (Quebec) [19].

Although various techniques can be developed for decision-making model, the Analytical Hierarchy Process (AHP) method [20] was selected for this study because of the accuracy of the prescribed decision provided, as well as the compatibility and appropriateness of the acquired decision in dealing with the problem. Moreover, it can be used to provide a complete and rational framework for structuring decision-making, representation and evaluation of the elements, and connect them to objectives and evaluating alternatives [21].

In the present study, the seismic vulnerability of bridges is performed using the vulnerability index method. This evaluation procedure is based on the subjective assignation of weighting values
corresponding to different parameters that characterize the seismic behaviour of structures or the influence of these parameters on their environments in order to obtain a global representing value of their vulnerabilities. These parameters are identified from the experience acquired by the analysis of the damages produced by past earthquakes.

This research proposes a model based on Analytical Hierarchy Process (AHP), to determine the weight coefficients of the identified parameters, and evaluate the vulnerability index in order to classify bridges according to their risk degree.

2. Developed approach
The developed process is based on the vulnerability index method, which combines several parameters influencing the seismic behaviour of bridges and allows the assessment of seismic vulnerability index "VI".

2.1. Identification of the parameters
Various parameters are defined from post-seismic observations and seismic experience feedbacks [20, 22-26]. The parameters selected for this model are subdivided into two groups, structural and hazard parameters. The structural parameters serve to distinguish the structural aspects that make systems more or less vulnerable. The aim of hazard parameters is to consider the influence of the seismic area. Selected parameters of the evaluation model are classified into items; each item is divided into a certain number of factors; these factors are also composed of several categories (table 1).

Each parameter, item and factor have a related weight noted as $W_i$, $W_{ij}$ and $W_{ijk}$, respectively, which reflects its importance relative to the other parameters and their factors. The aim is to determine the weight coefficients value.

| Parameter | Item | Factor | Category | Scores |
|-----------|------|--------|----------|--------|
| Girder type | Arch or rigid frame | 10 |
| | Continuous Girder | 30 |
| | Simple Girder | 50 |
| | 1 span | 20 |
| Number of spans | 2 spans or more | 40 |
| | Straight deck (Not skewed) | 10 |
| Skew | Low | 20 |
| | Medium | 30 |
| | High | 40 |
| | Straight deck (No curvature) | 10 |
| Structural | Curvature | Low | 20 |
| | Medium | 30 |
| | High | 40 |
| | Wide 70cm or wider | 10 |
| Min. Bridge seat width | Narrow less than 70 cm | 40 |
| | No. seat: 0 cm | 20 |
| | With specific device | 10 |
| | Bearing (with clear design concept) | 20 |
| Bearings | Bearing type | Movable bearing | 40 |
| | Others (no. bearing, etc) | 20 |
### Table 2

| Parameter       | Item                                      | Factor             | Category      | Scores |
|-----------------|-------------------------------------------|--------------------|---------------|--------|
| Ground and Foundation | Ground type                               | Stiff/Hard         | 0             |        |
|                  |                                           | Medium             | 10            |        |
|                  |                                           | Soft               | 40            |        |
|                  |                                           | Very soft          | 50            |        |
|                  |                                           | Pile Bent          | 40            |        |
| Foundation type |                                           | Others Pile        | 20            |        |
| Max. Height of Abutment / Pier (m) | Expanded |                     | 30            |        |
| Structural       |                                           | Less than 5 m      | 10            |        |
|                  |                                           | Between 5 to 10 m  | 30            |        |
|                  |                                           | More than 10 m     | 50            |        |
|                  |                                          | Expanded           | 40            |        |
| Piers and Abutments | Construction Material of Abutment / Pier | Reinforced Concrete | 40         |    |
|                  |                                           | Masonry            | 30            |        |
|                  |                                           | Others             | 20            |        |
|                  |                                           | No piers for masonry structure | 10            |    |
|                  |                                           | No piers for other than masonry structure | 40         |    |
|                  |                                           | Columns piers      | 20            |        |
|                  |                                           | Massive piers      | 10            |        |
|                  |                                           | Backfilled abutment| 40            |        |
|                  |                                           | Buried abutment    | 30            |        |
|                  |                                           | Abutment Superficially Founded | 20         |    |
|                  |                                           | MMI < VIII         | 10            |        |
|                  |                                           | VII ≤ MMI < IX     | 20            |        |
|                  |                                           | IX ≤ MMI < X       | 30            |        |
|                  |                                           | X ≤ MMIX < XI      | 40            |        |
|                  |                                           | XI ≤ MMI           | 50            |        |
| Hazard           |                                           | No liquefaction    | 10            |        |
|                  |                                           | Low 0 < PL ≤ 5     | 20            |        |
|                  |                                           | Medium 5 < PL ≤ 15 | 30            |        |
|                  |                                           | High 15 < PL       | 50            |        |

#### 2.2. Quantification of the identified parameters

To derive the criterions weighting coefficients, Analytical Hierarchy Process (AHP) method was applied. AHP was developed by Thomas L. Saaty [20] in the 1970s and has been extensively studied and refined since then. It is a robust and flexible multi-criteria decision analysis methodology.

The AHP is a modelling technique which reduces a system to a sequence of pair-wise comparisons of identified components. The AHP has been widely used to quantify intangible factors [27].

Several application models for studying the performance and assessing the seismic vulnerability of infrastructures were developed using the AHP process [28-32].

The model based on the AHP method allowed determining the relative contribution of each parameter. The pair-wise comparisons are entered in a reciprocal comparison matrix for each level of the hierarchy. The obtained weights for each level parameters, items and factors are summarized in table 2.
Table 2. Weighting factors, items and parameters.

| Parameter       | W* | Item                  | W*  |
|-----------------|----|-----------------------|-----|
| Structural      | 0.250 | Superstructure | 0.512 |
|                 |     | Girdertype | 0.574 |
|                 |     | Number of spans | 0.232 |
|                 |     | Min. bridge seat width | 0.667 |
|                 |     | Skew | 0.097 |
|                 |     | Curvature | 0.097 |
|                 |     | Bearing type | 0.333 |
|                 |     | Ground type | 0.750 |
|                 |     | Foundation type | 0.250 |
|                 |     | Max. height of Abutment / Pier (m) | 0.491 |
|                 |     | Construction Materiel of Abutment / Pier | 0.268 |
|                 |     | Pier type | 0.160 |
|                 |     | Abutment type | 0.081 |
| Hazard          | 0.750 | Ground and Foundation | 0.281 |
|                 |     | Bearing type | 0.333 |
|                 |     | Ground type | 0.750 |
|                 |     | Foundation type | 0.250 |
|                 |     | Max. height of Abutment / Pier (m) | 0.491 |
|                 |     | Construction Materiel of Abutment / Pier | 0.268 |
|                 |     | Pier type | 0.160 |
|                 |     | Abutment type | 0.081 |
|                 |     | Seismic intensity | 0.800 |
|                 |     | Liquefaction potential | 0.200 |

*Weight.

After finding the weigh for each level, a numeric worth score $S_{ijkl}$ from 0 to 50 is assigned to every category. This reflects the one-dimensional value of the performance level of each category. The last column of table 1 shows the score values of all categories.

2.3. Determination of vulnerability index

Based on the interaction of all risk parameters and their factors shown in table 1, the vulnerability index "VI" is defined as a function of them and formulated as given in equation (1) below.

$$VI = \sum_{i=1}^{2} W_i \sum_{j=1}^{2or4} W_{ij} \sum_{k=1}^{2or4} W_{ijk} S_{ijkl}$$

(1)

where:

- $W_i$: The weighting coefficient of structural or hazard parameters.
- $W_{ij}$: The weighting coefficient of items.
- $W_{ijk}$: The weighting coefficient of factors.
- $S_{ijkl}$: the score of category.

According to the values obtained for the vulnerability index, and after an analysis and comparison of results, three-risk level is proposed to classify bridges. The three risk levels, low, medium and high and their range are summarized in table 3.
Table 3. Risk levels of bridges.

| Risk Levels | VI       |
|-------------|----------|
| Low Risk    | $0 < VI < 35$ |
| Medium Risk | $35 \leq VI < 50$ |
| High Risk   | $VI \geq 50$ |

3. Case study

3.1. Validation of the proposed approach
To calibrate and investigate the sensitivity of the proposed methodology, to be more confident with its results of evaluation and make it applicable for use, seven different bridges are considered, those bridges samples are as representative bridges.

The considered bridge samples are evaluated by the developed and Kubo Katayama method. This latter is also based on the vulnerability index.

A summary and comparison of the evaluation results obtained by the mentioned evaluation methodologies are presented in table 4. Ratings given in this table are subjective since they represented the same results for both methods. The results obtained are in good agreement.

Table 4. Comparison between the results obtained by Kubo-Katayama and developed methods.

| Bridges                  | Developed Method | Kubo-Katayama Method                |
|--------------------------|------------------|-------------------------------------|
| Damous Bridge (Tipaza)   | High Risk        | High Probability of Damage          |
| Mazafran Bridge (Tipaza) | High Risk        | High Probability of Damage          |
| Bouyaghsane Bridge (Tipaza) | Medium Risk  | Medium Probability of Damage        |
| Fadjana Bridge (Tipaza)  | Medium Risk      | Medium Probability of Damage        |
| Boukadir Bridge (Tipaza) | Low Risk         | Low Probability of Damage           |
| El Harrach Bridge (Algiers) | Medium Risk    | Medium Probability of Damage        |
| Sabdou Bridge (Boumerdes) | High Risk        | High Probability of Damage          |

3.2. Applications of the proposed approach
In order to apply the proposed method, a number of bridges located in Tipaza region have been chosen. Tipaza is situated in the north of Algeria, West of Algiers (capital of Algeria). The road network in this area contained ninety two (92) bridges; Fifty seven (57) of them are studied.

The study area illustrated in figure 1 is located in the south of the seismogenic basin of Mitidja, beside several active faults. The seismic movements caused by those faults can be felt with different intensities. The strongest events are the Chenoua (Tipaza) and Zemmouri (Boumerdes) earthquakes. They were occurred on October 29th, 1989 (6.0) and on May 21st, 2003 (M 6.8) respectively.
The seismic risk assessment was performed for three different scenarios; the distribution of expected risk for the three hazard levels is shown in figure 2.

3.3. Discussion of results
Based on the results obtained from the evaluation of the Tipaza bridges by the proposed method, it can be noticed that the most of studied bridges have a medium risk level. No high risk level was observed for the first and second scenarios. Whereas nearly 40% of studied bridges have a high risk for the third scenario (MMI=X).

According to the above results, it can be confirmed that in addition to structural parameters, seismic intensity has a great impact on the seismic vulnerability. The results of this study are in good adequacy with in-situ observations.

4. Conclusions
To evaluate the seismic vulnerability and risk levels of existing bridges, a new developed method is presented in this paper. This approach is used to calculate vulnerability index for bridges and classify them.
The proposed model was carrying out using AHP procedure through identifying and quantifying the major parameters and factors affecting the seismic vulnerability of bridges. This suggested model adopts AHP for its multiple criteria decision analysis step. It should be noted that the proposed methodology covers most of the important seismic bridge characteristics. However, it can be applied in simple and systematic manner without any complications.

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