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SEISMIC VULNERABILITY ASSESSMENT OF ROAD NETWORKS

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ABSTRACT

Past earthquakes showed the vulnerability of road networks under seismic event and highlighted the necessity to assess this vulnerability.

The aim of this study is to develop a vulnerability index (VI) for road networks. To achieve this goal, the most important parameters influencing the seismic behavior of roads are identified, based on the worldwide seismic feedback experience and data from past Algerian earthquakes (Ain Temouchent 1999 and Zemmouri 2003). A Multi Criterion Decision-Making (MCDM) method is used to define the VI. In the present study, the Analytical Hierarchy Process (AHP) allows the determination of weighting factors for each defined parameter. Two examples are processed and the obtained results show a good adequacy with in situ observations.

INTRODUCTION

Roads play a fundamental role in transportation and during major disasters such as earthquakes, they allow emergency and recovery operations.

The need for studies on seismic vulnerability assessment of road networks was highlighted in (Argyroudis et al., 2005) (Yin and Xu, 2010) (Arsık and Sibel Salman, 2013).

Several studies were conducted on this topic (Berdica and Eliasson, 2004) (Tung, 2004) (D'Andrea et al., 2005) (Jenelius et al., 2006) (Kiremidjian et al., 2007) (Yin and Xu, 2010) (Yang and Qian, 2012) and methods for performing seismic scenarios were developed considering road networks (ATC-13, 1985) (ATC-25, 1991) (RADIUS, 1996) (JICA, 2002) (FEMA-NIBS, 2004) (RISK-UE, 2003) (Werner et al., 2006) (Syner-G D3.7, 2009).

In this study, a seismic vulnerability assessment of roads was performed using the vulnerability index method. For this purpose, the parameters affecting this vulnerability will be identified. Thereafter, the weighting coefficients of these parameters will be determined using the AHP (Analytical Hierarchy Process) method.

VULNERABILITY INDEX METHOD

The approach using the vulnerability index method allows assessing roads vulnerability. It is based on the definition of an index resulting from an analytical expression that combines the main factors influencing the seismic behaviour of roads.

This method consists in gathering quantitative information to identify significant parameters in terms of vulnerability (D'Andrea et al., 2006) and seismic characteristics of the site (Wang and Zhang,

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2013). Thereafter, values are assigned to these parameters. These values can be defined by experts based on feedback from past earthquakes. Therefore, the defined analytical expression generally includes weights. These weighting factors reflect the relative contribution of each parameter in the global vulnerability.

There are several methods for determining the weighting factors. In the present study, these factors will be calculated by applying an MCDM (Multi Criterion Decision Making) method. The use of MCDM responds to the need to take into account many qualitative and/or quantitative criteria with different nature and with unequal importance that differentially affect the vulnerability of road networks.

ANALYTICAL HIERARCHY PROCESS (AHP)

Several MCDM methods do exist. They are all used to aggregate many criterions and assess their relative importance. The AHP is one of the MCDM methods. Many researchers applied this method to assess seismic vulnerability of tunnels (Wang and Zhang, 2013), bridges (Mohammadreza et al., 2012), buildings (Ishita and Khandaker, 2010) (Panahi et al., 2013), buildings construction site (Zahaf and Bensaibi, 2014), lifelines (Qunlin et al., 2013) and of urban areas (Gheitarani et al., 2013).

The AHP method was developed by Saaty (Saaty, 1980). This method uses a hierarchical structure with several levels of objectives, criteria, sub-criteria and alternatives. For each level of the hierarchy, pairwise comparisons are carried out. These binary comparisons allow constructing matrices that are used to obtain criterions weighting factors. These weights are derived by computing the eigenvector W using the following formula:

$$A.W = \lambda_{\max}.W \tag{1}$$

Where:

A is the comparison matrix of rank n, n the number of criteria and $\lambda_{\max}$ the largest or principal eigenvalue of the pair wise comparison matrix.

Such us:

$$\sum_{i=1}^{n} w_i = 1 \tag{2}$$

Saaty proposed to verify the consistency of comparisons in calculating a Consistency Ratio (CR) using formula (3). This ratio must be less than 0.1 (Saaty, 1980).

$$CR = \frac{CI}{RI} \tag{3}$$

With RI the random index defined by Saaty and CI the Consistency Index calculated as follows:

$$CI = \frac{\lambda_{\max} - n}{(n-1)} \tag{4}$$

PRINCIPLE OF THE PROPOSED METHOD

The proposed method follows three steps:

Step 1: Identification of the parameters that affect the vulnerability of roads

Step 2: Quantification of these parameters using the AHP method

Step 3: Definition of a vulnerability index
The description of each step is given here after.

Step 1: Identification of parameters
Vulnerability of roads depends on their geometric and structural characteristics as well as geotechnical and seismic properties of the site. The parameters are defined on the basis of seismic experience feedback over the world (EERI/CTC, 1980) (EERI, 1991) (Erdik, 2000) (JICA, 2002) (Edwards, 2004) (Tung, 2004) (FHWA, 2004) (O'Connor et al., 2007) (Syner-G D3.7, 2009) (Chouw et al., 2011) (Anbazhagan et al., 2011) (Zhang et al., 2012) (Wang and Zhang, 2013) and Algeria observations following Ain Temouchent and Zemmouri earthquakes (CTTP, 1999) (CTTP, 2003). Thus lead to distinguish two types of parameters, Structural and Seismic one. These parameters are divided into items, which in turn are divided into factors and factors into categories. Finally, the aim is to prioritize and to determine a weighting coefficient for each one (Table.1).

Table 1. Proposed Hierarchy

Parameter	Item	Factor	Category
Structural	Pavement	Number of lanes	> 2 lanes
			≤ 2 lanes
		Pavement Type	Paved
			Unpaved
	Embankment	Height	H≤ 2 m
			2m < H ≤ 5m
			5m < H ≤ 8m
			H > 8m
		Compaction quality	Compliant with standards
			Compliant with technical provisions
			Other
		Slope	< 2/3
			= 2/3
			> 2/3
	Ground conditions	Ground Type	Rock
			Hard soil
			Soft soil
			Very soft soil
		Landslides potential	Low
			Medium
			High
	Maintenance conditions	Pavement conditions	High
			Medium
			Low
		Slope protection measures	Compliant with standards
			Compliant with technical provisions
			Without any protections
Hazard	Seismic intensity		MMI < VIII
			VIII ≤ MMI < IX
			IX ≤ MMI < X
			X ≤ MMI < XI
			XI ≤ MMI
	Liquefaction potential		0 ≤ PL ≤ 5
			5 < PL ≤ 15
			15 < PL
	Intersection with Fault		No intersection
			Intersection

Step 2: Quantification of parameters
A score is assigned to each category as given in Table.2.

Table 2. Assigned Scores

Factor	Category	Score
Number of lanes	> 2 lanes	20
	≤ 2 lanes	40
Pavement Type	Paved	20
	Unpaved	50
Height	H≤ 2 m	10
	2m < H ≤ 5m	30
	5m < H ≤ 8m	40
	H > 8m	50
Compaction quality	Compliant with standards	10
	Compliant with technical provisions	30
	Other	40
Slope	< 2/3	10
	= 2/3	30
	> 2/3	50
Ground Type	Rock	0
	Hard soil	10
	Soft soil	40
	Very soft soil	50
Landslides potential	Low	10
	Medium	30
	High	50
Pavement conditions	High	10
	Medium	20
	Low	40
Slope protection measures	Compliant with standards	20
	Compliant with technical provisions	30
	Without any protections	50
Seismic intensity	MMI < VIII	10
	VIII ≤ MMI < IX	20
	IX ≤ MMI < X	30
	X ≤ MMI < XI	40
	XI ≤ MMI	50
Liquefaction potential	0 ≤ PL ≤ 5	10
	5 < PL ≤ 15	30
	15 < PL	50
Intersection with Fault	No Intersection	10
	Intersection	40

The following weights are obtained using the AHP method for each level (parameters, items and factors) (Table.3).

Table 3. Weighting coefficients

Parameter	Weight	Item	Weight	Factor	Weight
Structural	0.250	Pavement	0.108	Number of lanes	0.667
				Pavement Type	0.333
		Embankment	0.283	Height	0.648
				Compaction quality	0.122
				Slope	0.230
		Ground conditions	0.561	Ground Type	0.200
				Landslides potential	0.800
		Maintenance conditions	0.048	Pavement conditions	0.667
				Slope protection measures	0.333
Hazard	0.750	Seismic intensity	0.633	-	-
		Liquefaction potential	0.106	-	-
		Intersection with Fault	0.261	-	-

Step 3: Definition of a vulnerability index VI

Based on the weighting coefficients given above (Table.3) and the assigned scores (Table.2), the vulnerability Index VI is calculated as follows:

$$VI = \sum_{i=1}^{2} W_i \sum_{j=1}^{3 or 4} W_{ij} \sum_{k=1}^{2 or 3} C_{ijkl} \cdot W_{ijk} \qquad (5)$$

With:

W_i the weighting coefficient of structural or hazard parameters,

W_{ij} the weighting coefficient of items,

W_{ijk} the weighting coefficient of factors, where $W_{ijk}=1$ if $i=2$

and C_{ijkl} the score of category, where $l = 2$ or 3 or 4 or 5.

APPLICATION

Two case studies have been treated. The studied roads are located in the town of Ain Temouchent. On 22 December 1999 an earthquake (MMI =VII) occurred and damaged these roads.

Case study 1:

This case study is related to a national road section (RN35) located at Ain Temouchent at the kilometer marker 2+800. This road links Ain Temounchent to Tlemcen a big City in the North-West of Algeria. This road section crosses a soft soil and includes an average embankment (H=5m). Data regarding this road are given in Table.4.

Table 4. Characteristics of case study 1

Factor	Category	Case study 1 characteristics
Number of lanes	> 2 lanes	X
	≤ 2 lanes	
Pavement Type	Paved	X
	Unpaved	
Height	H≤ 2 m	
	2m < H ≤ 5m	X
	5m < H ≤ 8m	
	H > 8m	
Compaction quality	Compliant with standards	
	Compliant with technical provisions	X
	Other	
Slope	< 2/3	
	= 2/3	
	> 2/3	X
Ground Type	Rock	
	Hard soil	
	Soft soil	X
	Very soft soil	
Landslides potential	Low	X
	Medium	
	High	
Pavement conditions	High	
	Medium	X
	Low	
Slope protection measures	Compliant with standards	
	Compliant with technical provisions	X
	Without any protections	
Seismic intensity	MMI < VIII	X
	VIII ≤ MMI < IX	
	IX ≤ MMI < X	
	X ≤ MMI < XI	
	XI ≤ MMI	
Liquefaction potential	0 ≤ PL ≤ 5	X
	5 < PL ≤ 15	
	15 < PL	
Intersection with Fault	No intersection	X
	Intersection	

The obtained vulnerability index (VI) using eq.(5) is equal to 13.011

Case study 2

This case study is related to a national road section (RN35) located in the suburb of Ain Temouchent at the kilometer marker 16+000. This road section crosses a soft soil and includes a high embankment (H=8m). Data are given in Table.5.

Table 5. Characteristics of case study 2

Factor	Category	Case study 2 characteristics
Number of lanes	> 2 lanes	X
	≤ 2 lanes	
Pavement Type	Paved	X
	Unpaved	
Height	H≤ 2 m	
	2m < H ≤ 5m	
	5m < H ≤ 8m	X
	H > 8m	
Compaction quality	Compliant with standards	
	Compliant with technical provisions	
	Other	X
Slope	< 2/3	
	= 2/3	
	> 2/3	X
Ground Type	Rock	
	Hard soil	
	Soft soil	X
	Very soft soil	
Landslides potential	Low	X
	Medium	
	High	
Pavement conditions	High	
	Medium	
	Low	X
Slope protection measures	Compliant with standards	
	Compliant with technical provisions	
	Without any protections	X
Seismic intensity	MMI < VIII	X
	VIII ≤ MMI < IX	
	IX ≤ MMI < X	
	X ≤ MMI < XI	
	XI ≤ MMI	
Liquefaction potential	0 ≤ PL ≤ 5	X
	5 < PL ≤ 15	
	15 < PL	
Intersection with Fault	No intersection	X
	Intersection	

The obtained vulnerability index (VI) using eq.(5) is equal to 13.794

As it can be noticed the second value of the VI is greater than the first one, thus road section 2 is more vulnerable. This is due to the height of embankment and the lack of slope protection measures. Furthermore, the quality of embankment compaction materials is poorly than in the case study 1.
The result of this study is in a good adequacy with in-situ observations. In fact, road section 2 suffered significant damages and great retrofitting activities were necessary after the quake (CTTP, 1999).

CONCLUSIONS

A seismic vulnerability assessment method for road networks has been developed. This method enables computing a vulnerability index for road sections. This index gives an idea about the seismic behavior of the road section under study. Therefore, the method can be used as a diagnosis tool in order to classify roads according to their seismic vulnerability and for prioritizing their retrofitting activities. It can also be used as a tool for emergency management and urban planning.

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