ROAD PAVEMENTS FRAGILITY TO SEISMIC RISK: AN ASSESSMENT THROUGH FRAGILITY CURVES DEVELOPMENT

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Abstract- Road Pavements are subject to significant deformation due to the heavy traffic they carry. In seismic zones, these deformations are pronounced and can lead to traffic disturbances in case of a seismic event leading to direct, indirect and induced damages. Examples of such damages have been confirmed by past earthquakes in various countries resulting in soil collapse, settlement, subsidence due to ground liquefaction, lateral subsidence.... Aiming to predict the seismic vulnerability degree of these structures, scientists developed several methods based on different approaches, including the analytical approach. This latter consists in developing the fragility curves that reflect the seismic behaviour of these structures. One of these developments is the HAZUS methodology developed by the National Institute of Building Sciences (NIBS-USA) in 2004 and validated by the SYNER-G project for the European typologies in 2013. Thus, this article presents a study that aims to assess the fragility to seismic risk of the national highway *RN4*, linking the Algerian capital Algiers to the western capital Oran in its section crossing *Chlef* city downtown. To calculate the damage probabilities, the medium *PGD* value observed during the 1980 *El Asnam* earthquake (Ms= 7.3, MMI= X-XI) is considered in this study.

Keywords: Road Pavement, Seismic Vulnerability, Fragility Curves, PGD, SYNER-G.

Résumé- Les chaussées routières subissent d'importantes déformations en raison du trafic intense qu'elles supportent. Dans les zones sismiques, ces déformations sont prononcées et peuvent engendrer des perturbations du trafic en cas d'événement sismique, entraînant des dommages directs, indirects et induits. Des exemples de ces dommages ont été confirmés par les séismes survenus dans différents pays entraînant l'effondrement du sol, le tassement du sol, l'affaissement dû à la liquéfaction du sol, l'affaissement latéral, etc. Afin de prédire le degré de vulnérabilité sismique de ces structures, les scientifiques ont développé plusieurs méthodes basées sur différentes approches, dont l'approche analytique. Cette dernière consiste à développer des courbes de fragilité reflétant le comportement sismique de ces structures. L'un de ces développements est la méthodologie HAZUS développée par le National Institute of Building Sciences (NIBS-USA) en 2004 et validée par le projet SYNER-G pour les typologies Européennes en 2013. Ainsi, cet article présente une étude qui vise l'évaluation de la vulnérabilité au risque sismique d'une section de la route nationale *RN4* reliant la capitale algérienne Alger à la capitale occidentale Oran, au niveau du centre-ville de *Chlef*. Pour calculer les probabilités de dommages, la valeur médiane du PGD observe lors du séisme d'*El Asnam 1980* (Ms=7.3, MMI=X-XI) est considéré dans cette étude.

Mots clés : Chaussées routières, Vulnérabilité sismique, Courbes de fragilité, PGD, SYNER-G

1-Introduction

Road transport is the most common transference way, since it serves a variety of functions including passengers' transportation and socioeconomic exchanges. Furthermore, during major disasters like earthquakes, it enables emergency response, repair operations, and recovery activities.

Nonetheless, previous earthquakes have shown that, like other structures, roads can be

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severely damaged, causing delays in rescue process and extensive socioeconomic losses. As a result, conducting risk assessments studies on roadways is crucial for determining earthquake vulnerability of these basic infrastructures.

The concept of fragility curves in earthquake engineering dates at least to the 1980's. It defines a fragility function/curve as a mathematical function that expresses the probability that some undesirable event occurs, and that an asset, a facility, or a component reaches or exceeds some clearly defined limit state, as a function of some measure of environmental excitation; i.e.: a measure of acceleration, deformation, or force in an earthquake, hurricane, or other extreme loading condition [1].

Fragility curves, defining the conditional probability of being in or exceeding a certain damage state ''*ds*'' are a common tool frequently used for this end. Different methods exist to develop road pavements fragility functions/curves, and it is commonly agreed to classify them in four groups: (1) empirical curves based on observations of actual damages and post-seismic surveys, (2) expert opinion-based curves, directly estimated by experts, or based on vulnerability index models that use expert judgment, (3) analytical curves, obtained from the results of static or dynamic analyses of structural models; and (4) hybrid curves, which can combine any of the above-mentioned techniques, in order to compensate for their respective drawbacks [1 - 5].

Numerous studies have been conducted worldwide on seismic risk analysis and damage assessment of structures. However, very few studies have been conducted on the seismic vulnerability of road or transportation networks. Nevertheless, it is claimed that the assessment of the seismic vulnerability of road networks is a crucial step to increase the resilience of infrastructures and to improve emergency accessibility through the implementation of appropriate and effective emergency mitigation measures [6]. Among the rare projects developed, one can cite the model named REDARS (Risk from Earthquake Damage to Roadway Systems) [7]. For road pavement, this model takes the form of a table that, for different ranges of earthquake induced *PGD* (Permanent Ground Displacement), provides default repair procedures and associated traffic states as well as repair costdeveloped methodology for seismic risk analysis of highway systems [5].

In Algeria, more especially this kind of studies turns out to be rather rare. Yet, the northern part of this country is one of the most seismically active areas in the Mediterranean. All the more so since *Chlef* city (formerly *El-Asnam*), the area concerned by this study, is one of the most Algerian provinces that has experienced destructive earthquakes in the past, such as the *El-Asnam* earthquakes of September, 9, 1954 and the October, 10, 1980, characterized by a seismic magnitude *Ms* of 6.9 and 7,3 respectively [8]. Consequently, the likelihood of another earthquake occurring in this zone is greatly elevated at all times, especially due to the continued traffic growth. Therefore, this paper presents a study carried out through the development of fragility curves, and aiming to evaluate the seismic vulnerability of the road pavement of the major transportation lane crossing the city of Chlef from east to west, which is the national highway *RN4*.

2- Road pavement Damages Due to Seismic loading

In addition to damages or pathologies affecting road pavements under ordinary conditions, such as pavement cracking, potholes, depressions, rutting, shoving, upheavals, and ravelling, in seismic zones specific pathologies can occur under a seismic loading. Past earthquakes experiences reveal that the roadway elements are quite vulnerable to seismic loading and may be subjected to serious damages that can extremely affect the transportation of products and people during both short-term (emergency actions) and long-term period. These damages can be direct, indirect, or induced.

2.1- Direct, Indirect, and Induced Damages

Direct damages can be caused by a fault rupture, as it was the case in many past earthquakes that caused fault ruptures and ground failures due to soil liquefaction and/or

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lateral spreading. The literature cites several cases of these kinds of damages [9]. As examples, one can quote the case of complete collapse and extensive damages of road structures engendering traffic disruption, obstruction of aid and rescue actions, infrastructure damage, and high repair and economic costs.

Among others, the earthquakes of Kobe (Japan) that occurred on January 17, 1995 (Mw= 6.9) , Kocaeli (Turkey) in 1999 (Mw = 7.4), Chi-Chi (Taiwan), in 1999, (Mw= 7.6), Ranau (Malaysia), in 2015, (Mw = 6.0), Balakot (Pakistan) that happened on October 8, 2005 (Mw= 7.6), Peru that take place on August 15, 2007 (Mw= 8), Wenchuan (China) that occurred on May 12, 2008 (Mw= 7.9), and the Myanmar (Burma) earthquake that occurred on March, 24,2011 (Mw= 6.8) [6, 10, 11].

Indirect damages undergone by road pavements due to earthquakes can cause a complete or partial blockage due to the risk of collapsed heavily damaged buildings, especially in urban areas (e.g. during an aftershock) or due to restoration or demolishing works. It can origin the interruption of traffic due to landslide debris (mainly in non-urban areas), or landslide debris, a traffic interruption due to collapsed electricity or telecommunication pylons, a complete or partial blockage resulted by underlying pipeline (water, waste water, gas), or other transportation element failures [5].

An earthquake may also induce induced damages to road pavements, such as soil collapse, settlement, subsidence due to ground liquefaction, lateral subsidence...etc. These kinds of damages usually cause important damages to the road pavement and lead to the closure for days till weeks of the road lane. Induced damages can also lead to the closure of the road lane due to restoration works in damaged underlying networks. Furthermore, induced damages of an earthquake may cause the failure of traffic lights and illumination systems because of damages in electric power network [5].

Note that cracks and failures due to soil liquefaction, settlement and lateral spreading or landslide are induced damages caused by earthquakes, which are often very severe and dangerous. Figure 1 illustrates three of these damage types induced by the *El Asnam* 1980 earthquake, including a vertical soil displacement.



Figure 1: Induced Damages Caused by the *El Asnam* 1980 earthquake- from left to right: vertical reject, surface fault, and landslide [8].

Figure 1: Dommages induits par le séisme d'*El Asnam* 1980- de gauche à droite : rejet vertical, faille en surface, et glissement de terrain [8].

2.2- Typologies and Damage States

Concerning typologies of road pavements, the major considered parameter is the road lanes number, such it is the case for the HAZUS/NIBS methodology [12] and the SYNER-G project [3]. However, some authors consider other parameters for assessing a vulnerability index, such as the pavement condition that represents a vulnerability parameter for floods [13] and the pavement type [14]. Although, a specific weight is to be assigned for each used parameter [6].

Regarding the damage states, describing the level of damage to each highway system component, they are defined as follows: none ds_1, minor ds_2, moderate ds_3, and then extensive or complete ds_4 (Tab.1). These damage states are related to a damage ratio defined as the ratio of repair to replacement cost for evaluation of direct economic loss. Component restoration curves are provided for each damage state to evaluate loss of function. Restoration curves describe the fraction or percentage of the component that is expected to be open or operational as a function of time following the earthquake [3].

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Table 1: Damage states for road pavements [3].

Tableau 1 : Etats de Dommages pour les Chaussées Routières [3].

Damage state	Description	Serviceability
None d_{S1}	/	Fully functional
Minor d_{S2}	Slight cracking / offset of pavement surface.	Open, reduced speeds or closed during repair works.
Moderate d_{S3}	Localized moderate cracking / offset of pavement	Closed during repairs (few days)
Extensive/ Complete d_{S4}	Major cracking / offset of pavements and subsurface soil.	Closed during repairs (few days to weeks)

2.3- Ground Motion Measure

Several parameters are used to measure the ground motion during or after an earthquake, such as the spectral acceleration or displacement responses, the peak ground acceleration, displacement, or velocity, the *MMI* or *EMS* intensities…etc. [1]. Among these parameters, the spatial distribution of *PGA* values is easier to be estimated through simple or advanced methods within a seismic hazard study of a specific area.

Note that the selection of a parameter should be based on both the approach used for the derivation of fragility curves, and the typology of element at risk. For example, as the empirical curves relate the observed damages with the seismic intensity; the latter may be described based on intensity of records of seismic motions, and thus *PGA*, peak ground velocity *PGV* or spectral acceleration *Sa* may be suitable intensity measures. When the vulnerability of elements due to ground failure is examined (i.e. Liquefaction, fault rupture, landslides) permanent ground displacement *PGD* is the most appropriate parameter to use [15].

The *PGD* refers to the displacement or failure of ground resulting from seismic effects, be it strong shaking or direct rupture, and remains after the transient loading of the earthquake is removed. Whilst the *PGD* may usually be measured in meters or centimeters (or inches in some regions) it can be attributable to a wide variety of phenomena, including liquefaction, lateral spreading and ground settlement, land sliding and surface fault rupture [16].

3- Study Methodology

The SYNER-G (Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks and Infrastructures Safety Gain) project [3], has made a validation of the existing HAZUS/NIBS fragility functions [12]. This validation, which is based on damage observations on road pavements during past earthquakes in Greece, aimed to propose the most appropriate functions for the construction typologies in Europe. The developed curves resulted from a combination of expert judgmental models and empirical models [3].

Note that the fragility functions given in the HAZUS/NIBS methodology are the only functions available in the literature for road pavements. These have resulted from a combination of expert judgment and empirical models, and have shown to give realistic assessment of the expected damage level. Two different types of curves are given: [3]: for roads with two traffic lanes (urban roads), and for roads with four or more lanes (major/highway roads). They are defined with respect to road classification and *PGD* due to landslides, liquefaction and fault rupture.

The method considers four damage states denoted as: Minor, Moderate, Severe or Extensive, and Complete (collapse). The analytical expression used for the development of the pavements fragility curves, is given by Eq. (1):

$$P(D \geq D_{SK}) = \frac{1}{2}\left[1 + erf\left(\frac{In(PGD) - In(\mu)}{\beta\sqrt{2}}\right)\right] \quad (1)$$

where:

μ and β are the fragility parameters for road pavements, given by Tab.2 and *erf* is the error function.

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Table 2: Road pavements fragility parameters adopted by SYNER-G project [3].

Tableau 2: Paramètres de Fragilité pour les Chaussées Routières considérés dans le projet SYNER-G [3].

Road Typology	Damage state	Fragility Parameters	
		μ	β
Urban Road (2 traffic lanes)	*ds1*	0.15	0.70
	ds2	0.30	0.70
	ds3	0.60	0.70
	ds4	0.60	0.70
Major Road (≥ 4 lanes)	*ds1*	0.30	0.70
	ds2	0.60	0.70
	ds3	1.50	0.70
	ds4	1.50	0.70

4- Presentation of the Studied Case

The national road *RN4* crossing *Chlef* city, from east to west, and which is a major road counting four traffic lanes is considered in this work. More specifically, the segment under treatment is one that is experiencing notable deformations along a length of almost 800 meters (Fig. 2). This is the portion that runs next to the *Cheliff* River and links the *RN4* to the city center crossroads up to the hopper at the meeting point of the *Tsighaouet* and *Chellif* Rivers. It should be highlighted that this road section's proximity to the river raises the possibility of instabilities under both dynamic (especially heavy vehicles) and cyclic loading (in the event of an earthquake) loading scenarios. In addition, the micro-zoning map of this zone, established by the WCC in 1984 [17], Identified it as prone to settlement, liquefaction and landslide risks

On the other hand, the pavement under study suffers from constant lateral and vertical displacements due to dynamic vehicle loads and the very loose nature of the subgrade. In fact, the entire area consists of a layer of soil with low mechanical strength. The latter is a Quaternary alluvial deposit of low compactness, composed mainly of sand, gravel and clay. The surface layers of this deposit have low shear wave propagation: Vs30 = 230~ 350 m/s. In addition, the degree of soil saturation in these soil layers adjacent to the Chellif River is sufficiently high so that the liquefaction and settlement potentials in this section are also significant in the event of a seismic event [18].

The average daily traffic flow at the location of the considered road section is, according to local official sources (Public Works Direction of the Wilaya of *Chlef*), 51401 vehicles per day when considering both directions of traffic and 35893 vehicles per day when considering only one direction [19]. These values were recorded in 2017, which was the last recording survey done for this important traffic lane. It should be noted that the average daily traffic flow value increase continually, therefore, it may currently surpass the recorded values. In both cases, these values exceed 20,000 V/D, so it is indeed a large traffic lane and can be considered as an express one.



Figure 2: Satellite view of the studied road section (modified from Google map)

Figure 2: Vue Satellitaire de la section routière étudiée (modifie de Google map)

5- Results and discussion

The developed fragility curves that highlight the damage probabilities in the studied road section are presented in Figure 3. Table 3 gives either the maximal damage probability values for each damage state (*ds1*, *ds2*, *ds3*, *ds4*). It should be highlighted that parameters β and μ have the same values for extensive and complete damages, which means than the curves will be superposed (Fig. 3). Note that the ds_1 damage state is not assessed in this study, since it causes no damage to the road pavement (Tab.1).

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In addition, as we consider in this study a seismic scenario corresponding to that of 1980 *El Asnam* earthquake (MS =7.3), the damage probability equivalent to a reference *PGD* value of 1 meter is evaluated. This latter corresponds to the medium vertical discharge observed during this earthquake. In contrast, a larger vertical displacement of 1.34 m was observed west of the Ponteba dam in the *Oumdrou* and *Béni Rached* areas during the post-earthquake survey [20]. However, these locations are approximately eight and fifteen kilometers (as the crow flies) northeast of Chlef city, respectively. Nevertheless, this *PGD* value was not recorded in the vicinity of the city center, where the section of road examined in this study is located. For this reason, we prefer to consider the more likely average *PGD* value of 1 meter.

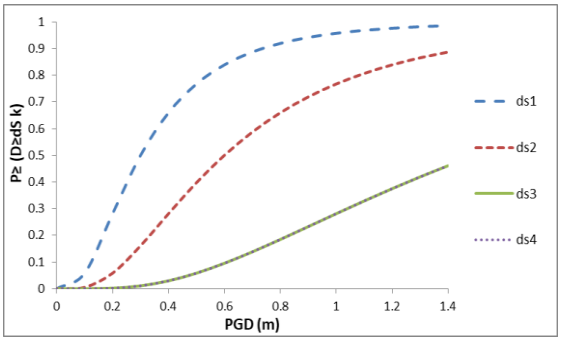


Figure 3: Developed Fragility curves of the studied road section

Figure 3: Courbes de fragilité développées pour la section routière étudiée

Accordingly, from Fig. 3, it is observed that the two damage states minor ds_1 and moderate ds_2 are those reaching the highest percentages of damage probabilities. However, complete and extensive damages are less significant, but remain important as both spread almost below the average probability of damage: i.e. 46% for a maximum PGD value of 1.4 m.

From Table 3, it can be concluded that the maximum probability for ds_2 damage state, reaches 98%, and 96% for the considered *PGD* value (1 meter), respectively. For ds_3 damage state, the maximum probability ranges to 88%, while that corresponding to the considered *PGD* scenario falls to 76%, with a decrease of 20%. Finally, for the ds_4 damage state the maximum probability reaches 46% and that corresponding to the *PGD* scenario is of 28%.

Table 3: Results of the damage probabilities.

Tableau 3: Résultats des probabilités de dommages.

Damage state	Damage probability corresponding to a maximal *PGD* value (%)	Damage probability corresponding to the considered seismic scenario *PGD* value (%)
Minor d_{S2}	98	96
Moderate d_{S3}	88	76
Extensive/ Complete d_{S4}	46	28

It can be noticed that, according to the 1980 *El Asnam* seismic scenario, the highest probabilities of damage are reached for both minor and moderate damage states, i.e. 96 and 76%, respectively. However, a lower damage probability of 28% is reached for extensive or complete damage state ds_4. This result shows that the studied road section will not suffer from major cracking, or offset of pavements and subsurface soil in case of a seismic event. However, it may be subject to slight cracking, and offset of the pavement surface and localized moderate cracking offset of pavement till a percentage of 98% and 88%, respectively. As a conclusion, the serviceability of this road section may undergone a reduced speeds or closed during repair works for few days, depending on the available capacity of the local road rehabilitation companies.

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6- Conclusions

This study focuses on the development of fragility curves to assess the seismic risk to which the major road lane *RN4*, in its section adjacent to *Chlef* River and crossing Chlef city, is exposed. This road section is a good example that required to be studied since it's situated in a high seismic zone (III according to the Algerian seismic codes) [21]. The main obtained results show that the maximum damage probability is recorded for minor damage state ds_2, and then for moderate one ds_3. It is also important to highlight that, in raison to the fact that the considered road pavement is already suffering from serious deformations, these damage probabilities will be actually amplified in case of a seismic event. Finally, it can be said that these results represent an efficient tool to predict the damage level that can be undergone by this important road lane in case of a seismic event, and then might help the local authorities to manage the seismic risk in the city of Chlef.

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