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Development of an integrated approach for Algerian building seismic damage assessment

Mehdi Boukri[*1,2], Mohammed Naboussi Farsi[1a], Ahmed Mébarki[3b] and Mohamed Belazougui[1c]

[1]*National Earthquake Engineering Research Centre (CGS), Rue Kaddour RAHIM, BP 252, Hussein-Dey, Algiers, Algeria*
[2]*Civil Engineering Department, Saad Dahlab University, Blida, Algeria*
[3]*Université Paris-Est, Laboratoire Modélisation et Simulation Multi Echelle, MSME, UMR 8208 CNRS, 5 Bd Descartes, 77454 Marne-La-Vallée, France*

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Abstract. This paper presents a framework for seismic damage evaluation for Algerian buildings adapted from HAZUS approach (Hazard-United States). Capacity and fragility curves were adapted to fit the Algerian building typologies (Reinforced Concrete structures, Confined or Non-Confined Masonry, etc). For prediction purposes, it aims to estimate the damages and potential losses that may be generated by a given earthquake in a prone area or country. Its efficiency is validated by comparing the estimated and observed damages in Boumerdès city, in the aftermath of Boumerdès earthquake (Algeria: May 21st 2003; M_w = 6.8). For this purpose, observed damages reported for almost 3,700 buildings are compared to the theoretical predictions obtained under two distinct modelling of the seismic hazard. In one hand, the site response spectrum is built according to real accelerometric records obtained during the main shock. In the other hand, the effective Algerian seismic code response spectrum (RPA 99) in use by the time of the earthquake is considered; it required the prior fitting of Boumerdès site PGA (Peak Ground Acceleration) provided by Ambraseys' attenuation relationship.

Keywords: Algerian buildings; HAZUS; seismic damage; Boumerdès earthquake; Algerian seismic code

1. Introduction

The historical seismicity (Yelles 2003) shows that Algeria is a country with an important seismic level. It has been shaken by several strong earthquakes during the last three decades.

Since El Asnam earthquake (October 10, 1980, Ms 7.3) which caused more than 2,600 deaths and destroyed or damaged more than 60,000 buildings, several moderate earthquakes (CTC 1981, Bertero and Shah 1983) occurred in Constantine (October 27, 1985, Ms 5.9) (Bounif *et al.* 1987, Ouassadou *et al.* 2013), Chenoua (October 29, 1989, Ms 6.0) (Farsi and Belazougui 1992),

*Corresponding author, Ph.D. Student, E-mail: mehdi.boukri@gmail.com, mboukri@cgs-dz.org
[a]Research Director, E-mail: mnfarsi@cgs-dz.org
[b]Professor, E-mail: Ahmed.Mebarki@univ-mlv.fr
[c]Director, E-mail: mbelazougui@cgs-dz.org

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Mascara (August 8, 1994, Ms 5.6) (Bezzeghoud and Buforn 1996), Algiers (September 4, 1996, Ms 5.6) (Yelles-Chaouche *et al.* 1997), Ain Temouchent (December 22, 1999, Ms 5.6) (Belabbès *et al.* 2009) and Beni-Ourtilane (November 10, 2000, Ms 5.5) (Bouhadad *et al.* 2003). Recently, the region of Boumerdès (50 Km East of Algiers city) was struck by a destructive magnitude Mw 6.8 earthquake on May 21st, 2003, (Belazougui 2008), which caused considerable damages and took lives of more than 2,300 people. The experience of the last earthquakes showed that the elaboration of adequate intervention measures was done after the first in situ inspections, which may take long time to provide information and therefore decreases the chance to find survivors. This delay is due to the lack of different means to locate quickly at the early hours the affected areas and to the uncertain level of alarm to be given.

Shortly after a destructive earthquake occurrence, the decision makers must take urgent decisions to gather the adequate and necessary measures, according to the damage and their geographical distribution. This requires the preparation and the activation of seismic risk reduction strategies, in order to reduce the human and economic losses.

The prior seismic damage estimation studies are very helpful in developing preparation and emergency management plans (Mathur *et al.* 2004). From the historical point of view, the risk assessment methodology has been widely developed since its beginning at the end of the 19thcentury, by the systematic recording and modelling of the weather, stream heights and then earthquakes (Charles 2005). The first who draws up the benefit of the risk reduction studies was John R. Freeman, in his work entitled "*Earthquake Damage and Earthquake Insurance"*, issued in 1932 (Charles 2005), where a state of art of the disasters history was reviewed. During the 1990's, the loss estimation models have been significantly and rapidly developed (Clark 2002), following several storms in Europe, the Andrew hurricane in 1992, the Northridge earthquake (USA, 1994) and Kobe earthquake (Japan, 1995) (Shahriar *et al.* 2012) which caused catastrophic losses to the world insurers and reinsurers who recognized the utility of predictive models development. Indeed, these models allow a better quantification of the covered risks and thus a better knowledge of the exposure.

The developed countries, mainly the United States and Japan, remain active centres of innovation and application of the loss models. Several damage assessment models related on the natural risks and more particularly to the seismic risk have been investigated and continuously improved during the two last decades. These risk estimation methodologies can be classified according to their commercial and non-commercial purposes (Van Westen and Hofstee 2001). The first firms on natural disasters modelling like AIR Worldwide (Applied Insurance Research), EQECAT (subsidiary of the ABS group) and RMS (Risk Management Solution) were created at the end of the 1980's. These firms are world leaders and propose specific models for the countries exposed to the various natural risks (Chiroiu 2004). However, their specific tools are for commercial use and remain therefore private and confidential, and consequently are not public domain: case of EQEHAZARD (EQECAT) and CATMAP (AIR), for instance, as well as commercial methodologies developed by other companies, such as MunichRe, RiskLink (RSM), CATEX (CATEX), EPEDAT (Early Post-Earthquake Damage Assessment Tool), REDARS (Risk from Earthquake Damage to Roadway Systems), etc.

Nevertheless, available and accessible methods are at public disposal without limitation. They are mainly developed by national authorities such as USArmy Corps of Engineers (USACE), Hydrologic Engineering Centres (HEC), Federal Emergency Management Agency (FEMA), and National Institute of Building Sciences (NIBS), for instance. In Canada, the Natural Hazards Electronic Map and Assessment Tools Information System (NHEMATIS) was developed by

Emergency Preparedness Canada. Under the aegis of the United Nations, the secretariat of the International Decade for the Natural Disaster Reduction (IDNDR) launched in 1996 the seismic damage assessment project RADIUS (Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disasters) for developing countries with technical and financial support of the Japanese government (Okazaki and Radius TEAM 2000) and with the assistance of Geo-Hazard International (GHI) in the United States.

HAZUS (Hazard-United States) is the most significant development and innovative methodology in the United States, dedicated initially to the seismic damage assessment of the structures and infrastructures. It was developed in 1997 by the Federal Emergency Management Agency, FEMA, through agreements with the National Institute of Building Science, directed by a multi-field team of experts in seismic damage, geologists, engineers, architects, emergency management experts, economists and sociologists, and released in 1999 (FEMA 2002). The HAZUS methodology was implemented in the form of a public interactive software which uses a Geographical Information System (GIS) for Hazards data input and damage results display. Since 2004, FEMA addressed also other natural risks. These were incorporated into the HAZUS model which became HAZUS Multi-Hazard, in its last update version, HAZUS-MH 2.1, which appeared in February 2012 (NIBS 2012). Up to date, this earthquake loss estimation universal methodology appears to be the most innovating, featuring an easy and friendly use.

Apart from the United States, we may also quote the European project Risk-UE "*An advanced approach to earthquake risk scenarios with applications to different European towns*" developed in 2003 (Milutinovic *et al* 2003), EXTREMUM in Russia (Flavora 2007), GEMITIS model in France (1990-2000) (Chiroiu 2004), the GIS-based model for assessment of seismic vulnerability, seismic damage and seismic risk on a national scale developed and applied to Germany (Tyagunov *et al.* 2006), and Taiwan Earthquake Loss Estimation System (TELES) relying on HAZUS model (Yeh *et al.* 2006). These approaches, using adequate models, estimate direct losses of structures and infrastructures as well as potential indirect economic losses that may be caused by catastrophic potential scenarios defined by the user. Most of these approaches were developed in the United States and are applied all over the world, according to the availability of data.

In the present work, the authors elaborated a seismic damage estimation methodology for Algerian buildings based on HAZUS approach for which capacity and fragility curves of related typologies were adapted in order to fit the Algerian building context typologies. The validity and efficiency of the methodology are investigated on the basis of the observed damages caused by Boumerdès 2003 earthquake and compared to the theoretical prediction of the proposed methodology.

2. Proposal of a seismic damage estimation framework for Algerian buildings

The procedure adopted to estimate the seismic damages caused by earthquake is based on HAZUS methodology, which relies on the capacity spectrum method resulting from various scientific research (Mahaney *et al.* 1993, ATC-40 1996, Comartin *et al.* 1999, Chopra and Goël 1999, Fajfar 1999). The adaptation to the Algerian case relies mainly on the specific soils and their dynamic properties (local and site effects: seismic input) directly used in the damage estimation, as well as the specific material properties and the structural types that govern the structural dynamic response (seismic output). According to the intersecting performance point between the seismic load (reduced response spectrum) and the structural response (capacity curve), see Fig. 1, the

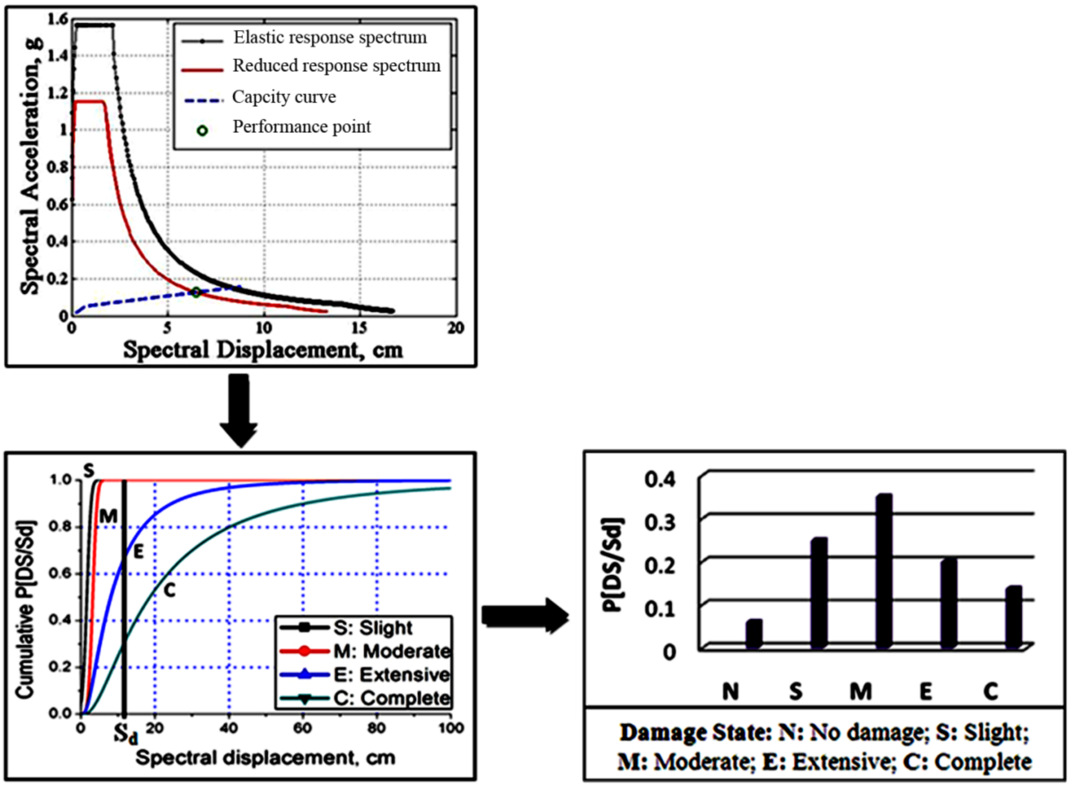


Fig. 1 Seismic damage estimation process

corresponding spectral displacement indicates the level of structural damage, as shown in Table 1. Actually, this spectral displacement provides the probability of damage level occurrence on the fragility curve adopted for the concerned structural typology. Therefore, the probabilities of damage and their category levels are obtained for the considered structure under the given seismic input.

2.1 Detailed flowchart and main steps

Fig. 2 shows the flowchart used to evaluate the damage probabilities. This flowchart consists of seven main steps which are:

• *Step 1*: Choice of the building typology according to the type of building (Reinforced Concrete structures, Steel structures or Non Confined Masonry structures), the height and the corresponding seismic code level.

• *Step 2*: Development of the elastic response spectrum (ξ = 5% : damping) adapted to the concerned site, and transformed into the format “Acceleration-Displacement Response Spectrum” (ADRS) using the following relationship

$$S_{dy}(T) = \frac{S_{ay}(T)}{4\pi^2} T^2 \tag{1}$$

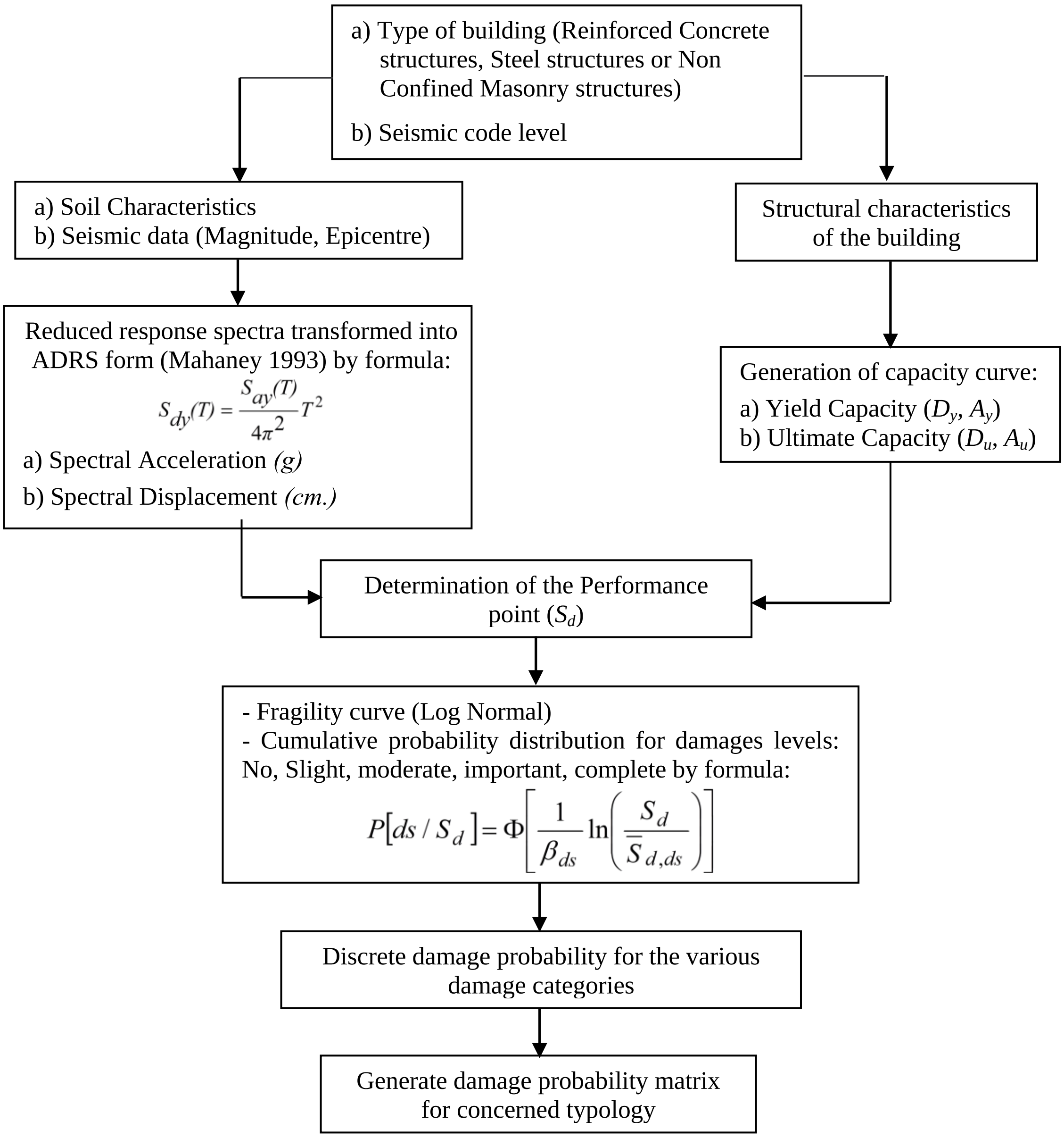


Fig. 2 General flowchart: seismic damage evaluation procedure

where: T [*unit:s*] represents the Period of the building; S_{dy} [*unit:m*] and S_{ay} [*unit:m.s*$^{-2}$] represent the Spectral displacement and the Spectral acceleration, respectively.

• *Step 3*: Generation of the capacity curve

The capacity curve relates the base shear to the top total displacement of the building. The push-over response depends on the geometry, the constitutive materials behaviour considered as linear or nonlinear with possible P-Delta effects (Jerez and Mébarki 2011).

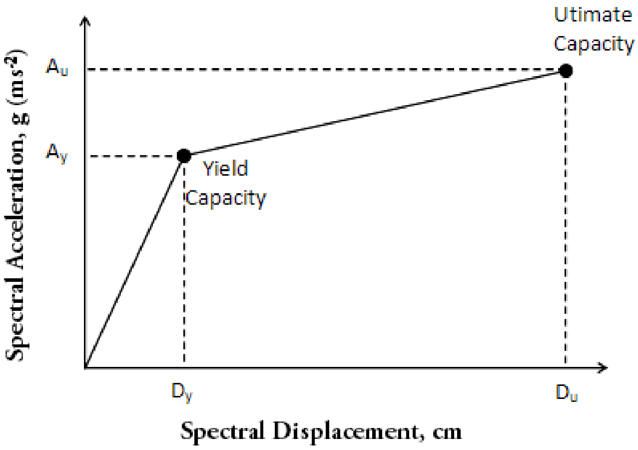


Fig. 3 Idealized capacity curve in ADRS format

This curve is transformed into ADRS format (Pagnini *et al.* 2011) in order to be compared to the reduced response spectrum (see Fig. 3).The main parameters of this capacity curve are:

1) Yield Capacity Point (D_y, A_y)

2) Ultimate Capacity Point (D_u, A_u)

• *Step 4*: Definition of the performance point

The performance point (S_d) represents the performance of the building or generic classes of buildings to a given seismic action level. It expresses the interaction between the capacity curve of the building and the reduced response spectrum for the considered soil conditions (FEMA 2002, ATC-40 1996). Once defined, this point provides the probability of damages occurrence by using fragility curves.

The reduction of the elastic response spectrum (FEMA 2002, ATC-40 1996) is performed in order to take into account the inelastic behaviour.

• *Step 5:* Generation of damage functions

The damage curves are commonly adopted as being lognormal fragility curves that express the probability $P[ds|S_d]$ of reaching or exceeding a given level of structural or non-structural damage (*ds*), for a spectral displacement (S_d) at the performance point. The cumulative distribution for a given damage level (d_s) gives therefore the probabilities for each category of damage $P[N|S_d]$, $P[S|S_d]$, $P[M|S_d]$, $P[E|S_d]$, $P[C|S_d]$ as expressed by Eq. 2 (FEMA 2002)

$$P\left[ds / S_d\right] = \Phi\left[\frac{1}{\beta_{ds}} \ln\left(\frac{S_d}{\bar{S}_{d,ds}}\right)\right] \tag{2}$$

where S_d is the spectral displacement (acting as seismic demand and input); $\bar{S}_{d,ds}$ represents the mean value of the spectral displacement for a given damage level taken equal to "*ds*" ; β_{ds} is the logarithm value of the displacement standard deviation "*d"* for the damage level or category *ds*; Φ is the Cumulative standardized Gaussian distribution; $P[S|S_d]$: Probability of occurrence of a *slight* damage "***S***"; $P[M|S_d]$: Probability of occurrence of a *moderate* damage "***M***"; $P[E|S_d]$*:* Probability of occurrence of an *important and extended* damage "***E***" and $P[C|S_d]$: Probability of occurrence of a *complete* damage "***C***".

Table 1 Damage probabilities matrix

	Damage probabilities matrix				
Damage level	No	Slight	Moderate	Extended	Complete
Probability	P[N]	P[S]	P[M]	P[E]	P[C]

• *Step 6:* Calculation of the specific damage category probabilities

The specific damage category probability, corresponding to each category or level of damage, is then derived from the cumulative probabilities as follows

Complete damage "***C***": $P[\mathbf{C}] = P[C|S_d]$ (3)

Important and extended damage "***E***": $P[\mathbf{E}] = P[E|S_d] - P[C|S_d]$ (4)

Moderate damage "***M***": $P[\mathbf{M}] = P[M|S_d] - P[E|S_d]$ (5)

Slight damage "***S***" $P[\mathbf{S}] = P[S|S_d] - P[M|S_d]$ (6)

No or Very Slight damage "***N***": $P[\mathbf{N}] = 1 - P[S|S_d]$ (7)

• Step 7: Generation of the Damage probability matrix for the considered typology (see Table 1).

2.2 Building classification

The building inventory and its classification into specific typologies is the main and most influent step when aiming to estimate the seismic damage in an urban area (Eleftheriadou and Karabinis 2011). The adopted building classification is based on several parameters: type of lateral-bracing, stories number as well as the period of construction, and constitutive materials. For this purpose, we select the constructions types as they are defined in the Algerian seismic code (RPA99/Version 2003), most widespread in Algeria, i.e. Reinforced Concrete structures and Steel structures (up to or more than eight stories), the Non Confined Masonry structures (up to or more than three stories).

This distinction is roughly homogeneous with the most existing classifications in the world for earthquake loss estimation and particularly with the one that is used by the HAZUS methodology (FEMA 2002). Thus, 11 classes of standard buildings were analysed, representing four categories of lateral-bracing systems as illustrated in Table 2.

2.3 Capacity and fragility curves

In this study, we used capacity and fragility curves developed and used in the HAZUS methodology (FEMA 2002) which take into account the level of the American seismic design code (High-code, Moderate-code, Low-code and Pre-code). The choice to use these capacity and fragility curves is due to the fact that their characteristics are coherent with those of the existing building types in Algeria (see Table 2). Indeed, we used the capacity and fragility curves in accordance with the Algerian building context. Thus, we made a close approach between the application levels of the American seismic code, UBC (FEMA 2002) and of the Algerian code, RPA, in order to use these curves. However, we defined four seismic design levels according to the evolution periods of the various versions of the Algerian seismic code that brought successive changes in the design level, see Table 3.

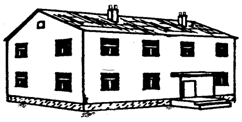
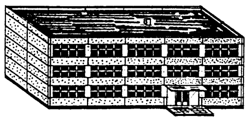
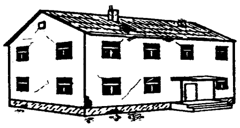
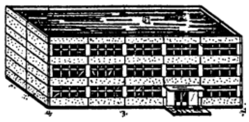
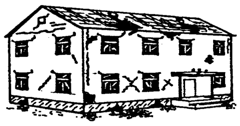
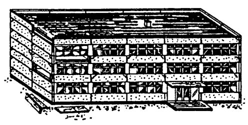
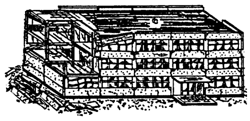
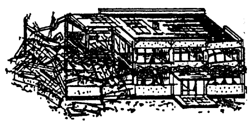
Table 2 Classification of the evaluated buildings according to their typology and stories number

N°	Typology	Type of lateral bracing	Story range	
			Name	Stories
1	RC1-L	Reinforced Concrete Moment Frame (Beam-Columns) structure	Low-Rise	1 – 3
2	RC1-M		Mid-Rise	4 – 7
3	RC1-H		High-Rise	8 and more
4	RC2-L	Reinforced Concrete Shear Walls	Low-Rise	1 – 3
5	RC2-M		Mid-Rise	4 – 7
6	RC2-H		High-Rise	8 and more
7	S-L	Steel Structure	Low-Rise	1 – 3
8	S-M		Mid-Rise	4 – 7
9	S-H		High-Rise	8 and more
10	URM-L	Non Confined Masonry (Bearing Walls)	Low-Rise	1 -2
11	URM-M		Mid-Rise	3 and more

Table 3 Seismic design levels according to the evolution period of the Algerian seismic code versions

Code version	Post-2003	2000–2003	1981-1999	Pre-1981
Code level	High-code	Moderate-code	Low-code	Pre-code

Table 4 Structural and non-structural damages: classification of reinforced concrete and masonry structures according to EMS 98 (Grünthal *et al.* 2001, CGS2003)

Masonry structures	Reinforced Concrete structures	Damage description
		**Level 1: No damage** (none : structural damage)
		**Level 2: Slight damage** (light structural damages, moderate non-structural damages)
		**Level 3: Moderate damage** (moderate structural damages, important non-structural damages)
		**Level 4: Important damage** (important structural damages, severe non-structural damages)
		**Level 5: Severe damage** Collapse or about to (severe structural damages) **Partial or total collapse**

2.4 Post-quake damage evaluation in Algeria: location and evaluation form

In Algeria, the post-seismic damage evaluation form (see Fig. 4), widely used since Chlef

BOUMERDES EARTHQUAKE May, 21 2003
DAMAGE EVALUATION FORM

Investigator Code:
Date:
CONSTRUCTION IDENTIFICATION
Sector Zone
Construction designed for earthquake resistance: Yes – No
Address or identification parameters
Inspected construction: Yes – No

CONSTRUCTION USE (*)
Dwelling School Commercial
Administrative Hospital Industrial
Socio- cultural Sports Water reservoir
Other (precise)

BASIC DESCRIPTION
Approximate age of construction: Under floor space: Yes- No (*)
Number of stories: Basement: Yes- No (*)
Number of separation joints: Independent outside elements
- In elevation: (stairs, canopy, covered crossing)
- Substructure

Soil problems around the construction (*)
Fault : Yes - No - Settlement - Upheaval : Yes-No
Liquefaction : Yes - No - Landslide Yes-No

FONDATIONS – SUB-STRUCTURE (*)
Fondations :
- Fondation type
- damage type
  - Uniform Settlement: Yes - No
  - Sliding: Yes - No
  - Rocking: Yes - No

Infrastructure(Incase of Underfloor space or Basement)
- Continuous R.C Wall : 1-2-3-4-5
- R.C Column with masonry infill : 1-2-3-4-5

RESISTING STRUCTURE (*)
Load-bearing elements (vertical loads)
- Masonry walls 1-2-3-4-5
- R.C Shear walls 1-2-3-4-5
- R.C Columns 1-2-3-4-5
- Steel Columns 1-2-3-4-5
- Wood Columns 1-2-3-4-5
- **Others** 1-2-3-4-5

Floors – Roof terrace
- Reinforced concrete 1-2-3-4-5
- Steel joist 1-2-3-4-5
- Wooden joist 1-2-3-4-5

Lateral bracing elements
- Masonry walls 1-2-3-4-5
- R.C Shear walls 1-2-3-4-5
- R.C frames 1-2-3-4-5
- Steel frames 1-2-3-4-5
- Cross bracing 1-2-3-4-5
- Others 1-2-3-4-5

Tilt Roof terrace
- Steel frame 1-2-3-4-5
- Timber frame 1-2-3-4-5
- Tiled roofing 1-2-3-4-5
- Cement asbestos roofing 1-2-3-4-5
- Steel roofing 1-2-3-4-5

(*) Circle the appropriate description, in case of numbers:
One or several numbers can be circled

(a)

SECONDARY ELEMENTS

Stairs
- Concrete 1-2-3-4-5
- Steel 1-2-3-4-5
- Wood 1-2-3-4-5

External infills
- Masonry 1-2-3-4-5
- Precast concrete 1-2-3-4-5
- Weatherboardings 1-2-3-4-5
- Others 1-2-3-4-5

Other internal elements
- Ceilings 1-2-3-4-5
- Partitions 1-2-3-4-5
- Glass element 1-2-3-4-5

External elements
- Balconies 1-2-3-4-5
- Railings 1-2-3-4-5
- Canopy 1-2-3-4-5
- Acroterion-cornices 1-2-3-4-5
- Chimneys 1-2-3-4-5
- Others 1-2-3-4-5

INFLUENCE ADJACENT CONSTRUCTIONS (*)
- Construction threatens another construction Yes - No
- Construction is threatened by another construction Yes - No
- Construction can be a support for another construction Yes - No
- Construction can be supported by another construction Yes - No

VICTIMS (*)
Yes - No – Maybe If yes, How many ?

COMMENTS ON THE NATURE AND THE PROBABLE CAUSE OF DAMAGE

	Transverse direction (*)			Longitudinal direction (*)		
- In plane symmetry	Good	Moderate	Bad	Good	Moderate	Bad
- Elevation regularity	Good	Moderate	Bad	Good	Moderate	Bad
- Redundancy of lateral-bracing elements	Good	Moderate	Bad	Good	Moderate	Bad

OTHER COMMENTS:

FINAL EVALUATION (*)

General damage level **Colour to be assigned**
1 - 2 - 3 - 4 - 5 **GREEN - ORANGE –RED**

IMMEDIATE DECISIONS:

(b)

Fig. 4 Post-quake damage evaluation form for Algeria: (a)-General data and structural components damage; (b)-Non-structural elements damage and global evaluation

earthquake (1980, Algeria), gathers information of each inspected construction (Bertero *et al.* 1983, CTC 1981, CGS 2003). It results in indicating, after inspection, the corresponding observed damage level among five (05) damage categories classification (Meslem and Yamazaki 2011, Meslem *et al.* 2012) as described in the European Macroseismic Scale, EMS 98, (Grünthal *et al.* 2001, CGS 2003): **1: Light Green** for no damage; **2: Dark Green** for slight damage; **3: Light Orange** for moderate damage; **4: Dark Orange** for important and major damage and **5: Red** for severe damage, as shown in Table 4.

Actually, qualified civil engineers and trained technical staff acting, as inspectors, follow the guidelines of the existing evaluation form available at national level for this purpose. This form results from preliminary expertise and rigorous development by the scientific and engineering community, at Algerian level. It is assumed that all the involved inspectors have already been trained and prepared for the post seismic damage evaluation.

3. Application of the methodology in the case of Boumerdès city (Algeria)

In order to study its efficiency and calibrate the seismic damage estimation methodology elaborated for

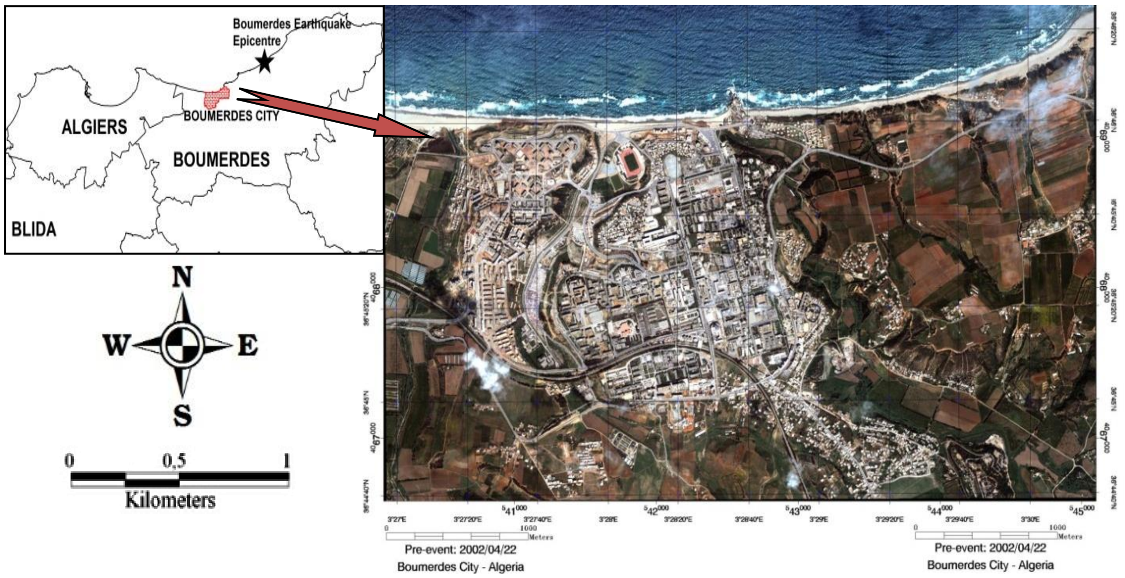


Fig. 5 Right: Quick-bird satellite image of the Boumerdès urban area before the earthquake (April 22, 2002) provided by OYO corp.--Left: Location of the May 21st, 2003 Boumerdès earthquake epicentre (see Black star location) (Bounif *et al*. 2004)

Algerian buildings, we implemented it to the urban area of Boumerdès city (see Fig. 5), which has been struck on May 21st, 2003 by a severe earthquake (M_w = 6.8) (Boukri and Bensaibi 2008, Mehani *et al.* 2013).

The building seismic damages in Boumerdès city are estimated theoretically by using the methodology proposed above, with the May 21st, 2003 Boumerdès earthquake considered as the input. The elastic response spectrum of the site is represented, built on the basis of the real accelerometric signals recorded during the main shock, as shown in Fig. 6. The second theoretical damage estimation was carried out by using, as alternative input, the Algerian seismic code response spectrum in use before the earthquake (RPA 99). These two evaluated seismic damages are compared to those observed in the field after the real inspection campaign; see Tables 6 to 8 and Fig. 9.

3.1 Post-earthquake damage evaluation: observed results and categories of damages

The database used in this study consists of 3,663 inspected constructions or blocks in the city of Boumerdès, distributed into residential, industrial, commercial, educational, administrative constructions and other uses. The reinforced concrete constructions are prevalent and represent the major part of the total buildings in the city. This kind of constructions, built after 1962, are mostly concentrated in the Western part of the city, located between the two rivers crossing the city, respectively the Corso and Boumerdès Rivers. Buildings with the "beam-column" frame system (RC1) represent approximately 71% (2,596 constructions), while those with the reinforced concrete shear walls system (RC2) represent 3.66% whose majority are buildings for residential, commercial or administrative use. Nevertheless, masonry structures mostly erected during the colonial period (before 1962) represent approximately a quarter of the total number of inspected

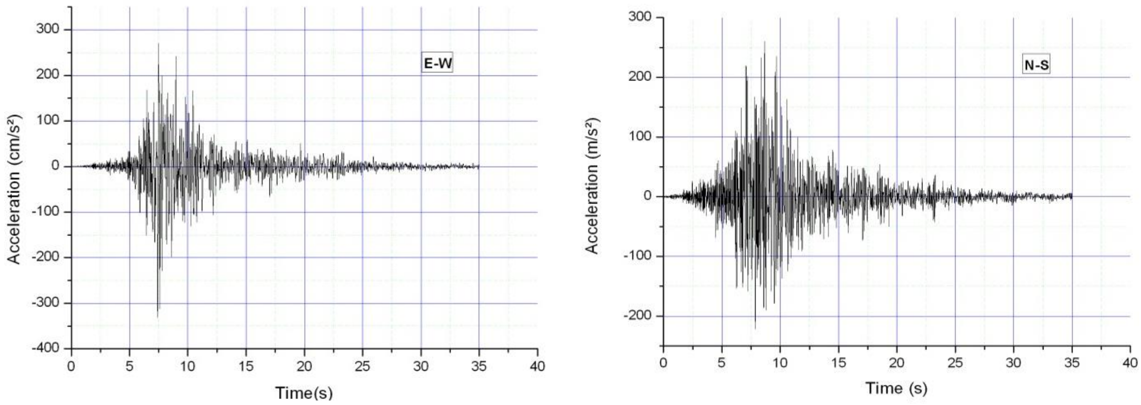
Table 5 Classification of the observed buildings according to their typology and the damage degree

Typology	Damage degree					Number of constructions
	N	**S**	**M**	**E**	**C**	
RC1	54	1,293	675	437	137	2,596
ratio	*2%*	*50%*	*26%*	*17%*	*5%*	
RC2	0	87	30	17	0	134
ratio	*0%*	*65%*	*22%*	*13%*	*0%*	
URM	3	386	270	204	70	933
ratio	*0.5%*	*41%*	*29%*	*22%*	*7.5%*	
Global	57	1,766	975	658	207	3,663
ratio	*2%*	*48%*	*27%*	*18%*	*5%*	

constructions, located mainly in the Eastern and Southern parts of the city and which are mainly individual constructions. There are also some steel (for industrial use) and wood constructions (12 and 15 constructions respectively, which are not included in the 3,663 constructions). Both categories (steel and wood) represent together less than 1% of the Boumerdès buildings and are therefore excluded from the data base for the sake of simplicity. All constructions have been classified according to the constructive system, number of stories, construction period and damage level caused by the May 21st, 2003 earthquake. This classification follows the seismic damage evaluation procedure in use in Algeria.

However, some typologies such as RC1-H, RC2-H and URM-M (Pre-code), RC2-L, URM-M (Low-code) and RC1-H (Moderate code) (see Table 2) do not exist in Boumerdès city. For the construction period before 1981, the number of constructions is about 1,443, and half of them correspond to the masonry system. During this period, Boumerdès city was still a small village depending on the municipality of Thénia (Dunand 2005), as the urban expansion started with the territory-planning management plan of 1970. The number of constructions is more significant (1,866 units) for the low-code period (1981-1999), since nearly 90% are Reinforced Concrete made. During this period, Boumerdès urbanization has been strongly extended since it became Wilaya (province) in 1984, and was transformed at the same time into an industrial pole represented by the Algerian oil company SONATRACH, and an academic pole with the construction of a new university containing various faculties and institutes. For the 3rd period (2000-2003), all the constructions were built using the RC1 or RC2 systems with various heights, but their number is less significant considering the short duration of this period before the earthquake occurred.

The analysis of the observed damages in Boumerdès city as illustrated in Table 5 and Fig. 9, shows that a significant percentage of masonry buildings have suffered several (extended and complete) damages, because these constructions (unreinforced masonry) were built without any design standard and their majority have been built by unqualified workers using poor quality materials. Concerning the RC1 structures, which are prevalent in Boumerdès city, even though half of them were only slightly damaged, the rest represents the largest number of severely damaged structures (574 units classified between *E* and *C* damages). The Damage is due also to the poor quality of concrete and to the lack of column-beam joints reinforcement (inadequate or weak stirrups). The building system described previously could have been appropriate for low or moderate seismicity zones. Following the updated version of the Algerian seismic code (RPA) in 1999, the RC1 system was limited to 6 stories for the area of Boumerdès classified as zone II (moderate seismicity zone), but, after the May 21, 2003 earthquake, the new version of the RPA in



(a) East-West component (b) North-South component

Fig. 6 Horizontal accelerogram components recorded during Boumerdès earthquake main shock (Keddara ST)

2003 limited this system to 2 stories in Boumerdès area, which was classified in zone III (high seismicity zone). RC2 system buildings behaved much better; they represent, essentially, buildings belonging to the public heritage, such as the dwelling residences "Cité 800 logements". This system seems more appropriate for high seismicity zones if it is well designed and well casted in situ.

The global classification of Boumerdès buildings according to their typology and their damage degree are shown in Table 5.

3.2 Probabilistic framework for post-quake damage evaluation

3.2.1 First theoretical case: theoretical simulation using the site response spectrum

Accelerometric records provided from Keddara station (36.65N, 03.41E), located at the south-west of the strong motion area (epicentral distance of 29 km), were used to build the elastic response spectrum for this study. This choice is due to the fact that the station is the closest to the epicentre in Boumerdès and the area under study. This response spectrum was built by taking into account the site effect. The H/V spectral ratios measurements (Farsi and Bard 2004) performed by Meslem *et al*. (2010) show the existence of hard surface layers at the Keddara station site, which corresponds to the absence of site amplification.

• *Development of the elastic response spectrum used as input (ξ = 5%)*

The mean elastic response spectrum used in this case is built on the basis of two (02) horizontal components (E-W and N-S) of the accelerogram recorded at Keddara station, see Fig. 6.

From this response spectrum, we extracted the limit characteristic periods of the constant spectral acceleration branch T_1 and T_2 which have as respective values (0.088s and 0.227s). These two periods are used to build the corresponding elastic response spectrum (see Eq. 8 and Fig. 7) similar to the form used by the Algerian seismic code (RPA99/version 2003).

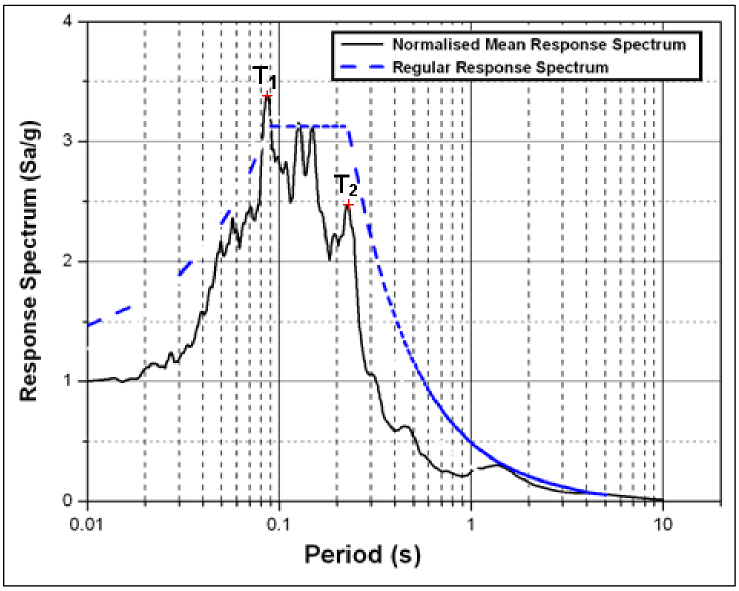


Fig. 7 Normalized elastic response spectrum for 5% damping

$$\frac{S_a}{g}=\begin{cases}1.25A_c\left(1+\frac{T}{T_1}\left(2.5\eta\frac{Q}{R}-1\right)\right) & 0\le T\le T_1\\ 2.5\eta(1.25A_c)Q/R & T_1\le T\le T_2\\ 2.5\eta(1.25A_c)\left(\frac{Q}{R}\right)\left(\frac{T_2}{T}\right)^{5/4} & T_2\le T\le 3s\\ 2.5\eta(1.25A_c)\left(\frac{Q}{R}\right)\left(\frac{T_2}{3}\right)^{5/4}\left(\frac{3}{T}\right)^{5/3} & T\ge 3s\end{cases} \tag{8}$$

where A_c is the Acceleration coefficient (A_c=*1*), T_1 *and* T_2 [unit: s] represent the lower and upper limits of the period range defining the constant spectral acceleration branch, *Q* is the quality factor (*Q=1*), *R* represents the behaviour factor (*R=1*) and η is the damping correction factor given by Eq. 9

$$\eta=\sqrt{7/(2+\xi)} \tag{9}$$

ξ is the Viscous damping ratio percentage of the structure, (taken as ξ = 5%)

• *Site acceleration*

The horizontal acceleration in Boumerdès city was estimated according to the two horizontal components records (EW: 0.34g and NS: 0.26g) at Keddara station and using the Ambraseys PHGA attenuation relationship developed by Ambraseys *et al.* (2005) among other possible existing models (Mébarki 2009). This attenuation relationship (Eq.10) is adopted in this study as it was established on the basis of 595 strong motion records from Europe and the Middle East including 3 records from Algeria caused by shallow crustal earthquakes with magnitudes *M*w ≥5

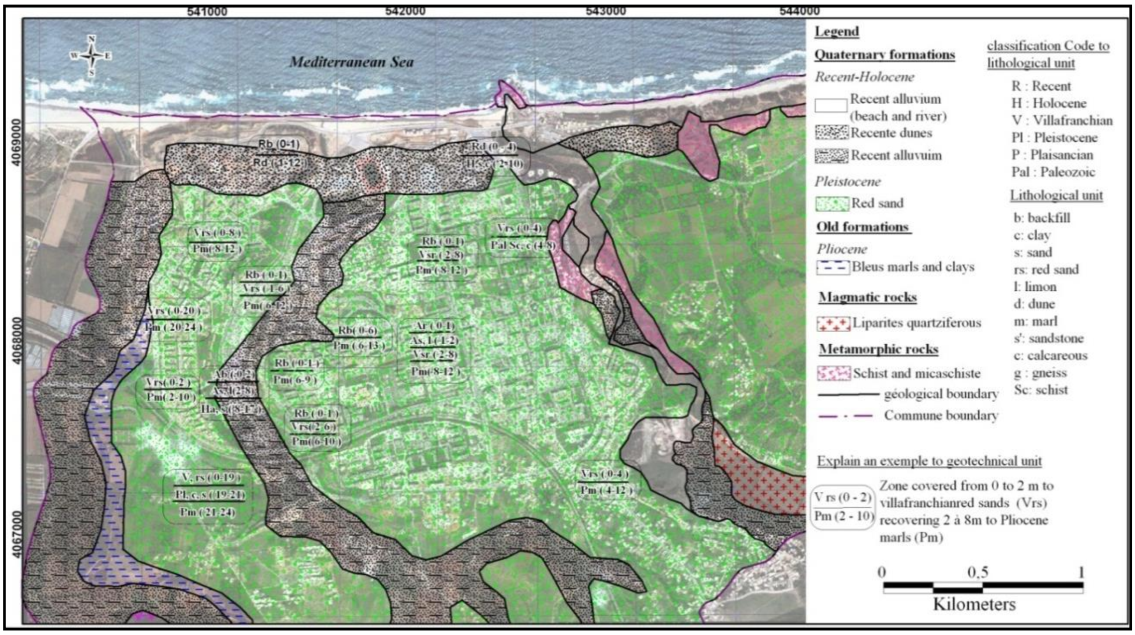


Fig. 8 Geological and geotechnical map of Boumerdès city (CGS, 2009)

and distance to the surface projection of the fault less than 100 km. This attenuation is appropriate to the characteristics of Boumerdès earthquake. Therefore, the horizontal peak ground acceleration value A_h calculated in Boumerdès city is about 0.5g.

$$\log A_h = a_1 + a_2 M_W + (a_3 + a_4 M_W)\log\sqrt{d^2 + a_5^2} + a_6 S_S + a_7 S_A + a_8 F_N + a_9 F_T + a_{10} F_0 \tag{10}$$

where A_h represents the horizontal PGA [unit: ms^{-2}], S_S=1 for soft soil sites and 0 otherwise, S_A=1 for stiff soil sites and 0 otherwise, F_N=1 for normal faulting earthquakes and 0 otherwise, F_T=1 for thrust faulting earthquakes and 0 otherwise and F_0=1 for odd faulting earthquakes and 0 otherwise. a_1 up to a_{10} are coefficients fitted to evaluate the horizontal peak ground acceleration and the spectral response acceleration for 5% damping, *d* [unit: Km] represents the epicentral distance.

• *Geological and geotechnical context of Boumerdès city*

The geological and geotechnical context of Boumerdès city, as illustrated in Fig. 8, shows a firm soil type (S2) according to the Algerian seismic code classification, where the shear velocity (Vs) must be ranging within the interval (400m/s≤Vs≤800m/s). Moreover, the H/V spectral ratios measurements carried out in Boumerdès urban area (Guiller *et al.* 2004) indicate that Vs≥500m/s. Other recent geophysical study performed by the National laboratory of habitat and construction gives mean values of Vs≥490m/s.

The H/V spectral ratios measurements performed in the same area (Guillier *et al.* 2004, Hellal *et al.* 2010 and Meslem *et al.* 2010) show that the site amplification effect can be neglected. This allows the calculated acceleration value (A = 0.5g) for Boumerdès station to be used in order to determine the elastic response spectrum (5% damping) for the whole Boumerdès city.

3.2.2 Second theoretical case: simulations and prediction using the Algerian seismic code response spectrum

In this second case, the theoretical damages are predicted under the hypothesis that the elastic response spectrum (ξ = 5%) corresponds to the regulatory spectrum adopted by the Algerian seismic code version (RPA 99), that was in use until the Boumerdès' earthquake occurrence. This input spectrum is given by (Eq. (11)) with the following data

$$\frac{S_a}{g} = \begin{cases} 1.25A\left(1+\frac{T}{T_1}\left(2.5\eta\frac{Q}{R}-1\right)\right) & 0 \le T \le T_1 \\ 2.5\eta(1.25A)\,Q/R & T_1 \le T \le T_2 \\ 2.5\eta(1.25A)\left(\frac{Q}{R}\right)\left(\frac{T_2}{T}\right)^{2/3} & T_2 \le T \le 3s \\ 2.5\eta(1.25A)\left(\frac{Q}{R}\right)\left(\frac{T_2}{3}\right)^{2/3}\left(\frac{3}{T}\right)^{5/3} & T \ge 3s \end{cases} \tag{11}$$

where A represents the site ground acceleration (A= 0.5g) as discussed in section 3.2.1.

As shown previously, the soil type of the urban site of Boumerdès city is classified as S2 (firm soil) according to the Algerian seismic code, with the vibration periods limiting the horizontal part of the spectral acceleration branch, T_1= 0.15 s and T_2 = 0.40 s.

3.2.3 Damage estimation and analysis

The predicted damages for Boumerdès city buildings, provided by the theoretical methodology developed above, are compared to the damages observed in the aftermath of the quake, see Tables 6 to 8 and shown in Fig. 9.

Table 6 Damage probabilities according to the building typology

Typology	Case	Damage probability					
		PN	PS	PM	PS+PM	PE	PC
RC1	D_{rs}: 1st Simulation	**2%**	30%	49%	**79%** (30+49)	**15%**	**4%**
	D_{obs}: Observed	**2%**	50%	26%	**76%** (50+26)	**17%**	**5%**
	D_{ds}: 2nd Simulation	**1%**	10%	57%	**67%** (10+57)	**22%**	**10%**
RC2	D_{rs}: 1st Simulation	**4%**	51%	37%	**88%** (51+37)	**7%**	**1%**
	D_{obs}: Observed	**0%**	61%	25%	**86%** (61+25)	**14%**	**0%**
	D_{ds}: 2nd Simulation	**0.1%**	12%	60%	**72%** (12+60)	**21%**	**6.9%**
URM	D_{rs}: 1st Simulation	**6%**	24%	40%	**64%** (24+40)	**20%**	**10%**
	D_{obs}: Observed	**0.3%**	41%	29%	**70%** (41+29)	**22%**	**7.7%**
	D_{ds}: 2nd Simulation	**0.0%**	0.01%	40.5%	**40.5%** (0.01+40.5)	**28.5%**	**31%**

PN: No damage probability, PS: Slight damage probability, PM: Moderate damage probability, PE: important or extensive damage probability and PC: Complete damage probability

Table 7 Damage probabilities according to the successive versions of the Algerian seismic code, i.e., period of construction for the buildings under study

Typology	Case	Damage probability					
		PN	PS	PM	PS+PM	PE	PC
Pre-code	D_{rs}: 1st Simulation	**1%**	26%	49%	**75%** (26+49)	**17%**	**7%**
	D_{obs}: Observed	**3%**	40%	28%	**68%** (40+28)	**22%**	**7%**
	D_{ds}: 2nd Simulation	**0.1%**	1%	61%	**62%** (1+61)	**23%**	**14.9%**
Low-code	D_{rs}: 1st Simulation	**4%**	37%	45%	**82%** (37+45)	**11%**	**3%**
	D_{obs}: Observed	**0.4%**	57%	25%	**82%** (57+25)	**14%**	**3.6%**
	D_{ds}: 2nd Simulation	**1%**	22%	55%	**77%** (22+55)	**15%**	**7%**
Moderate-code	D_{rs}: 1st Simulation	**4%**	48%	37%	**85%** (48+37)	**10%**	**1%**
	D_{obs}: Observed	**0%**	34%	28%	**62%** (34+28)	**25%**	**13%**
	D_{ds}: 2nd Simulation	**0%**	0%	54%	**54%** (0+54)	**32%**	**14%**

Table 8 Global damage probabilities comparison for the whole buildings by merging all the typology categories

Case	Damage probability					
	PN	PS	PM	PS+PM	PE	PC
D_{rs}: 1st Simulation	**3%**	38%	43%	**81%** (38+43)	**12%**	**4%**
D_{obs}: Observed	**1.5%**	48%	27%	**75%** (48+27)	**18%**	**5.5%**
D_{ds}: 2nd Simulation	**0.5%**	9%	56%	**65%** (9+56)	**23%**	**11.5%**

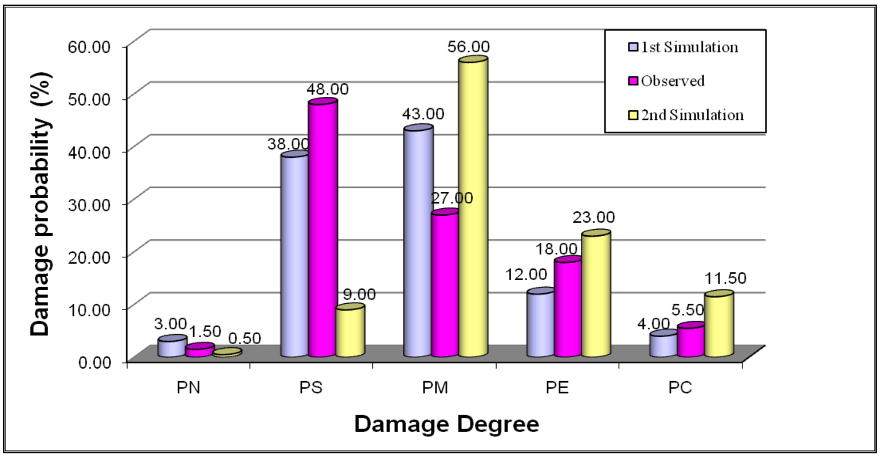


Fig. 9 Histogram of the damage for 3,663 existing buildings in Boumerdès city: observed D_{obs} (CGS in situ evaluation), and theoretical simulations according to the spectrum (Real spectra: 1st case simulation D_{rs}**,** Design spectra: RPA -2nd case simulation D_{cs})

where:

- D_{obs}= observed damage collected by the inspectors during their on-site campaign
- D_{rs}= theoretically predicted damage while considering the so-called "real site effect" and the corresponding elastic response spectrum, i.e., real site spectrum
- D_{ds}= theoretically predicted damage under the hypothesis of regulatory code elastic spectrum: design spectrum

The Boumerdès buildings were classified according to the first 3 periods of the Algerian seismic building code versions: Pre-code, Low-code and Moderated-code, because the High code relates to constructions built according to the version published after 2003 (i.e., RPA 99 version 2003).

The theoretical seismic damages provided by the two input options (1st and 2nd simulation depending on the input spectrum, i.e., real site or regulatory) compared to the observed damages, according to the building typologies and the seismic code periods, are in good accordance and close in most cases, when the input is the real site spectrum. However, they provide almost the same values if the damage categories 2 (*S*) and 3 (*M*) are merged as illustrated in Figs. 10 up to 12. The on-site diagnosis and classification of these 2 categories require some qualification and experience that, unfortunately, some inspectors did not have at that time; for instance, it was not easy to decide rigorously whether the damage should be category 2 or 3 by quick visual inspection. Many cases are at the frontier between two neighbour categories. This non-homogeneity in evaluators' abilities caused different results between the observed damage and that predicted, mainly when it was required to differentiate the two damage categories: 2 and 3, as shown by Fig. 9 for PS and PM distribution.

The observed damages according to the existing typologies in Boumerdès city (RC1, RC2 and URM) compared to those simulated by the real site spectrum are in good accordance in most of damage level cases, obviously by merging the two damage categories *S* and *M* (see Fig. 10). This observation is well-suited for RC1 and URM, but not for RC2, where the Extensive damage level "*E*" observed is somehow higher than those simulated. This difference is explained hereafter.

Concerning the Pre-code and Low-code periods, i.e., the various periods of the Algerian seismic building code evolution, we should notice the good adequacy and coherence between the observed and theoretical (1st case simulation) results in most of damage level cases. However, the case of Moderate-code period presents significant differences for damage levels "*E*" and "*C*", this period being short (2000-2003) and concerning 354 constructions among the 3,663 units erected within Boumerdès city. Actually, more than 90% are RC1, and essentially 3 to 5 stories buildings, which suffered the most severe damage, due to the fact that, according to issued research studies (Laouami *et al.* 2006), the frequency contents in close field starts at 3Hz with a central frequency around 8Hz. This frequency band contains Eigen frequencies of these constructions, erected in the epicentral zone.

The differences between the observed and estimated damages may also be partly originated in the adoption of American capacity and fragility curves for the case of Algerian buildings, even though a great attention has been devoted to establish the adequate correspondence between American and Algerian building typologies. Other possible sources of results differences might be related to the elastic response spectrum built according to the recorded signal from Keddara station distant from 12 km of the defective accelerometric station located at Boumerdès city (36.75N, 03.47E), 18 Km from the epicentre, when the main shock occurred, and which could represent better the characteristics of the earthquake at the damage origin. Furthermore, the poor quality of execution and of constitutive structural material, the inadequacy or lack of structural engineering design (Belazougui 2008) and the effect of aftershocks, reaching a magnitude Mw = 5.8 on May 27, 2003, as well as the effect of building orientation relatively to the fault, the directivity effect, as it was the case of Ibn-Khaldoun-1,200 logements district (Dunand 2005), the presence of many soft stories at ground floor may have greatly influenced the effective damages suffered by the buildings in the city. Furthermore, recent study performed by (Meslem *et al.* 2012) in Boumerdès city shows the relationship between the vulnerability of buildings and the topographical effects.

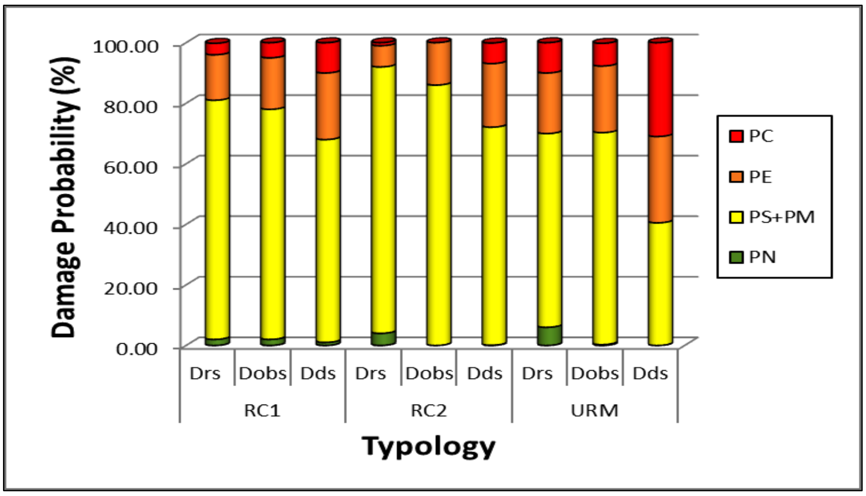


Fig. 10 Observed building damages and theoretical simulations in Boumerdès city according to their typology (Real spectra: 1st case simulation D_{rs}, Design spectra: RPA -2nd case simulation D_{cs})

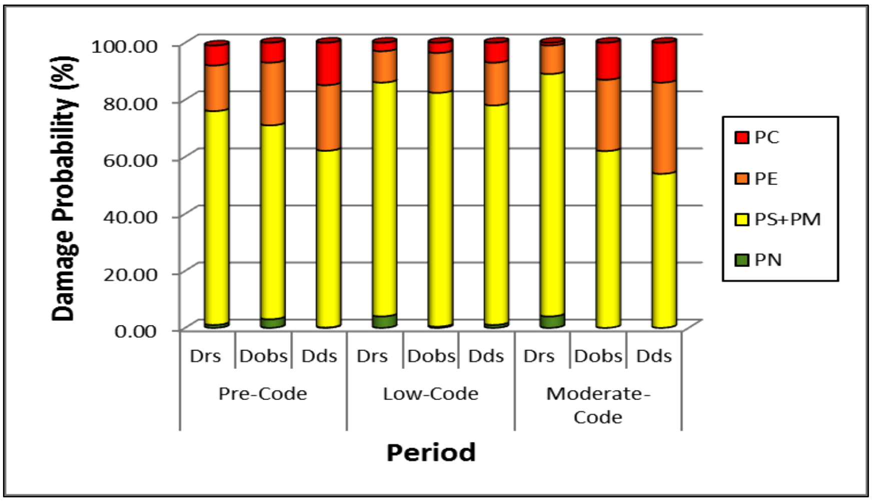


Fig. 11 Observed building damages and theoretical simulations in Boumerdès city according to their seismic code period (Real spectra: 1st case simulation D_{rs}, Design spectra: RPA -2nd case simulation D_{cs})

Many of the differences between theoretical and observed damage category may be due to the effect of these parameters that are not completely taken into account in the theoretical procedures, which still need improvements in order to describe better the intrinsic properties of the existing buildings.

The simulation performed using the RPA99 elastic response spectrum over-estimates slightly the probability of the extensive and complete damages. This is due to the fact that the Algerian seismic code response spectrum takes into account the Algerian building context and its characteristics: a set of partial factors are considered in order to provide acceptable safety margins as it can be noticed in the case of the damage "E" and "C" of the moderate-code (see Table 7).

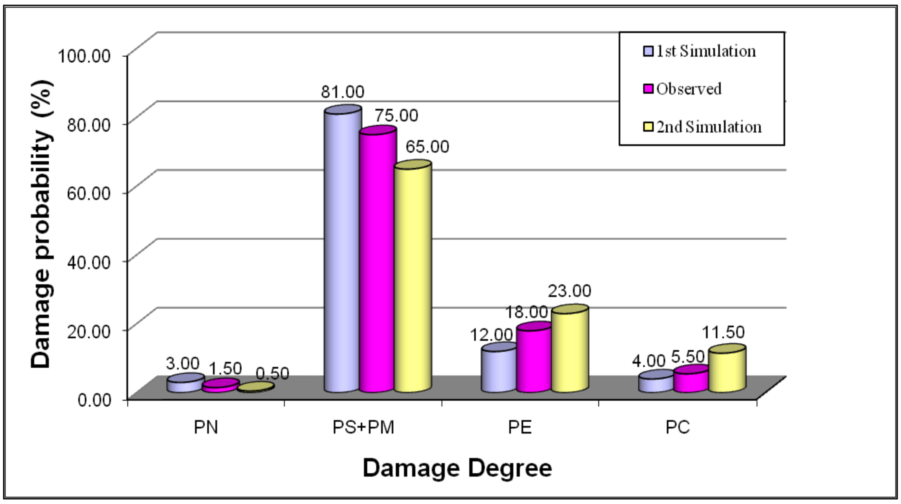


Fig. 12 Observed building damages and theoretical simulations in Boumerdès city (Real spectra: 1st case simulation D_{rs}, Design spectra: RPA -2nd case simulation D_{cs})

4. Pre-disaster predictions and post-disaster analysis

The theoretical methodology developed and presented herein is also calibrated according to real damages observed during past earthquakes. It is useful and powerful regarding various aspects:
- The quick evaluation, in the early hours and days after the earthquake occurrence, of the damage caused to the existing buildings and facilities, reported on a GIS maps with GPS location, allow easily to have a real time mapping of the damages and their socio-economic consequences. It allows to set up a helpful building database interactively updating. This is crucial for fast recovery and emergency measures in the impacted regions.
- The preparation of the expected structural damages and socio-economic consequences regarding possible upcoming earthquakes, for instance, allows the preparedness and disaster mitigation. Such simulations are part of on-going research devoted to sensitive zones such as megacities.
- The prior simulations of various possible hazards in order to elaborate the early alert systems and emergency preparation.
- The prior simulations of expected structural damages in order to help the authorities to focus their efforts in the early hours and days after the earthquake towards the zones supposed to be the most affected. Satellite images and social networks may corroborate quickly the theoretical predictions.

5. Conclusions

In this paper, a seismic damage estimation methodology for Algerian buildings based on HAZUS approach (Hazard-United States) is elaborated. Adequate capacity and fragility curves were adapted to fit the Algerian building typologies. This probabilistic methodology was calibrated in the case of Boumerdès city buildings that have been struck by a strong destructive earthquake on May 21st, 2003.

The methodology calibration was performed in a first approach with the seismic input of the Boumerdès' earthquake represented by an elastic response spectrum based on the real accelerometric records obtained during the main shock. The damage results were compared to the observed damages in the affected Boumerdès urban area: the theoretical and observed damages are mostly close, i.e., with small differences. Furthermore, the results become almost the same when the damage categories 2 (S) and 3 (M) are merged. The differences can be explained by: 1) the adaptation process of American capacity and fragility curves to the Algerian building typologies, 2) the use of a response spectrum derived from seismic records of free field Keddara station located at 12 km distance from Boumerdès, 3) the non-homogeneity in the training level of the on-site inspectors, 4) the intrinsic earthquake characteristics itself, 5) the location of Boumerdès city in the epicentral zone (strong ground motion zone), 6) the poor quality of execution and constitutive structural materials, 7) inadequate or lack of structural engineering design, 8) the aftershocks effect reaching a magnitude M_w = 5.8, 9) the buildings orientation effect relatively to the fault (directivity effect), 10) the presence of many soft stories (Ground floor), 11) the topographical effects, etc. These parameters may have greatly influenced the effective damages suffered by the buildings in the city. It is not always easy to find, by quick visual inspection, the adequate damage category as the damages are close to the upper limit of one category and also close to the lower limit of the following category. Improvements of the evaluation form developed after El Asnam earthquake (1980) are still required in order to solve rigorously these limit cases. Obviously, the local soil conditions should be known completely in order to provide accurate risk assessment.

In the second option, the theoretical damages are predicted under the hypothesis that the seismic input corresponds to the regulatory seismic spectrum provided by the Algerian code RPA 99. The theoretical results show an over-estimation of the damages, since the code takes into account the effective Algerian building context and its characteristics: partial factors are actually considered in order to provide large safety margins by the design code. The simulation using the RPA 99 response spectrum aimed to show its utility in case of a lack of suitable response spectrum for the studied site, which can give acceptable results.

As the methodology is now tested and calibrated on real earthquakes, it is integrated within a data-processing code developed for this purpose.The automatic probabilistic processing method provides the results within GIS tools and GPS location, in order to be helpful for decision, even at the early hours after a disaster occurrence as they allow a quick and easy real time survey of the disaster extends.

Obviously, the theoretical results accuracy depends intimately on the adequate development of capacity and fragility curves that should reflect better the Algerian building context.

Acknowledgements

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