Structural Engineering and Mechanics, Vol. 42, No. 5 (2012) 609-629
DOI: http://dx.doi.org/10.12989/sem.2012.42.5.609

Vulnerability curves of masonry constructions Algiers case study

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(Received April 18, 2011, Revised November 23, 2011, Accepted April 24, 2012)

Abstract. This study deals with the assessment of low and mid rise multi-story buildings made of stone and/or brick, composite steel and masonry slabs from the sixties, known to be vulnerable to seismic hazard using the "vulnerability index" method based on buildings survey following Ain Temouchent (1999) and Boumerdes (2003) earthquakes, from where vulnerability curves are constructed using the translation method. The results obtained for the case study confirm what has been observed in situ.

Keywords: Unreinforced masonry (URM); earthquake; vulnerability curves; vulnerability index; Algeria

1. Introduction

Unreinforced low and mid rise multi storey masonry buildings are typical structures constituting most of the Algerian cities. Dating from the sixties, they are known to be vulnerable to seismic hazard. The post-seismic investigations following the 1999 and the 2003 earthquakes have shown extensive damages to such masonry structures.

In order to undertake any reinforcement actions to lower the seismic risk of such structures, it is essential to estimate at a large scale their seismic resistance capacity. One of the methods used to perform this task is the method of the seismic vulnerability index. Within this method, the vulnerability index is established individually for each construction to indicate its state. This allows knowing the seismic capability of the constructions of a given area to withstand the seismic forces and consequently classify them.

One of the first studies carried out on vulnerability index was initiated by the GNDT (Group of National Defense against earthquake) (Corsanego and Petrini 1994, Riuscetti *et al*. 1997), named as the methodology of level II, based upon observations and given data relative to the constructions. The structural and non structural parameters playing a significant role in the seismic response of the structure should belong to one of the four vulnerability classes (A, B, C or D) (Benedetti and Petrini

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1984, Benedetti *et al*. 1988, Parisi and Chesi 2006). The authors reported that the damage description using the vulnerability index increases with the severity of ground shaking. However, this method was modified in order to be applied to confined masonry buildings in southern Europe (Franch *et al*. 2008). In addition, a guide giving the evaluation of the seismic vulnerability of buildings based on the same principles was written by the AFPS group (Jacquet and Souloumiac 1999).

Nevertheless, in the same context other methods have been developed recently such as the RISK-UE method (RISK-UE 2003, Giovinazzi *et al*. 2003), the Rapid Visual Screening (RVS) (Srikanth *et al*. 2010), the modified vulnerability index Vicente *et al*. (2008) and the method given in the ReLUIS Project (Lagomarsino and Magenes 2009).

In Algeria, work relating to the assessment of the masonry constructions vulnerability using vulnerability index was undertaken (Bensaibi *et al*. 2003, Boukri and Bensaibi 2006, 2008, Djaalali and Bensaibi 2009, Bensaibi *et al*. 2011). These studies allowed the classification of buildings in vulnerability class. Each class of vulnerability is consequently associated to a relation between the seismic intensity and the damage rate which a structure can undergo. This relation is known as the vulnerability function, generally developed from the "Damage Probability Matrix" (DPM) (Whitman *et al*. 1974, Braga *et al*. 1982, Coburn and Spence 1992, Cole *et al*. 2008). Several DPM and vulnerability functions were used or developed throughout the world by different authors (ATC-13 1985, Guagenti and Petrini 1989, Chavez *et al*. 1998, Compos *et al*. 1998, Cherubini *et al*. 1999, D'ayala 2005, Lagomarsino and Giovinazzi 2006, Karimi and Bakhshi 2006, Belmouden and Lestuzzi 2007, Kappos *et al*. 2008, Park *et al*. 2009, Ruiz-Garcìa and Negrete 2009, Saeidi *et al*. 2009, Rota *et al*. 2010, Senel and Kayhan 2010, Mitropoulou and Papadrakakis 2011, Pagnini *et al*. 2011).

Damage scenarios have been also developed for different cities like Potenza (Dolce *et al*. 2003, Dolce *et al*. 2006), Celano (Martinelli *et al*. 2008), Barcelona (Barbat *et al*. 2008), Marmara Sea region (Turkey) (Ansal *et al*. 2009), Granada (Spain) (Vidal *et al*. 2010) and Istambul (Ansal *et al*. 2010, Erdik *et al*. 2011).

The aim of the present work is to use the principle of vulnerability index to develop vulnerability curves specific to the city of Algiers and takes into account, the characteristics of masonry constructions and the seismic experience feedback.

2. Vulnerability index method

The method consists in attributing a numerical value to each building representing its "seismic quality". This number is called vulnerability index (VI); it is obtained by a weighted sum of the numerical values expressing the "seismic quality" of the structural and non structural items which are deemed to play a significant role in the seismic response of the building. According Benedetti (Benedetti *et al*. 1988) the numerical values are chosen by the operator during the field investigation following detailed rules and instructions aimed at minimizing the differences among surveyors. For each item, the numerical values (Table 1) may be ranged in four classes. Class A (numerical value 0) refers to situations which may be considered conform to the Italian seismic code, whereas class D (max. num. value 45) refers to unsafe configurations.

As it can be seen from Table 1, the elements taken into account in the survey are partly of descriptive nature, such as type of walls, and partly of an evaluative nature, such as wall

Table 1 Parameters values for vulnerability index evaluation according Benedetti *et al.* (1988)

Element	Class				Weight Factor
	A	*B*	*C*	*D*	
1. Connection of walls	0	5	20	45	1.00
2. Type of walls	0	5	25	45	0.25
3. Soil condition	0	5	25	45	0.75
4. Total shear resistance of walls	0	5	25	45	1.50
5. Plan regularity	0	5	25	45	0.50
6. Elevation regularity	0	5	25	45	(*)
7. Horizontal diaphragms	0	5	25	45	(*)
8. Roof	0	15	25	45	(*)
9. Details	0	0	25	45	0.25
10. General maintenance conditions	0	5	25	45	1.00

connections. The total shear strength of the walls is estimated by an approximate formula. 'Weights" are also assigned to each element, those marked (*) are fixed by the operator, while the others are predetermined. The vulnerability index is the sum of the partial parameters times the relevant weight factor.

Some difficulties can occur when using this method this is due to:

(1) The "Details" element is not specified, so the operator may consider everything he judges, some items can be missed.

(2) Weighted factor marked (*) need a skilled operator to fix them.

(3) The interpretation of the obtained VI is not easy. A great index indicates a structure with low seismic resistance while a small one indicates a high seismic resistance, but the boundary between great and small index is not evident to know.

In order to avoid these difficulties, the "Details" element was specified and the weighted factors were fixed and incorporated in the parameter value. To improve the method, two additional elements were added and then a building classification was proposed in order to make the vulnerability index interpretation easy.

The "Details" element was specified as follows: studwork, dividing walls, balconies, railing, cornices, chimneys, ventilation space, electrical network, gas network, water network and sewage network.

The two added elements are:

- The element "Pounding effect" expresses that two adjacent structures can suffer damage if the gap is not wide enough. This allows treating a non isolated construction.
- The element "Modification" expresses all addition or subtraction observed on the original structure (balcony transformed on a room, room transformed on a water storage zone, suppression of wall). These modifications affect the value of the seismic effort and the position of the centre of mass.

Each considered element can belong to one of the four defined categories C1, C2, C3 and C4. These categories are declined as follows:

C1 expresses that considered element reflects a good resistance, C4, expresses that considered element reflects a bad resistance, C2 and C3 represent intermediate situations.

Table 2 Parameters values for vulnerability index evaluation

Element	Coefficient k_i			
	C1	C2	C3	C4
1. Total shear resistance of walls	0	0.05	0.12	0.21
2. Plan regularity	0	0.01	0.04	0.07
3. Elevation regularity	0	0.01	0.04	0.07
4. Walls connection	0	0.03	0.07	0.10
5. Walls type	0	0.01	0.03	0.05
6. Floor	0	0.01	0.03	0.05
7. Roof	0	0.01	0.03	0.05
8. Soil conditions	0	0.02	0.06	0.10
9. Pounding effect	0	0.01	0.04	0.07
10. Modifications	0	0.01	0.04	0.07
11. Details	0	0.00	0.02	0.03
12. General maintenance conditions	0	0.03	0.08	0.13

For each considered element and category, a coefficient (k) is identified expressing its seismic quality based on the feedback of seismic experience and statistical data from past earthquakes in Algeria (Ain Temouchent 1999 and Boumerdes 2003), Table 2. The feedback of seismic experience was prevailing in the sense that a statistical analysis relative to 617 buildings in the case of Ain Temouchent Earthquake (1999) and 768 buildings in the case of Boumerdes earthquake (2003) was performed, this allow to provide the coefficients given in Table 2.

The vulnerability index, VI, of a construction will be expressed according Eq. (1)

$$VI = \sum_{i=1}^{12} k_i \tag{1}$$

According to the value obtained for the vulnerability index, three vulnerability ranges P1, P2 and P3 are proposed, Table 3.

The P1 range associated to the green colour classifies the construction to be resistant with no requirement to any repairs. The P2 range associated to the orange colour classifies the construction to be moderately resistant which require reinforcement. The P3 range associated to the red colour classifies the construction to be weak with low resistance which requires demolition. The zero value, expresses a building with good seismic resistance (green) and the value one, express a building with a bad seismic resistance (red).

The correlation coefficients between the single parameters and the total VI for both Ain Temouchent and Boumerdes earthquakes are given in Table 4.

Table 3 Vulnerability index ranges

Ranges	P1	P2	P3
VI	0-0.20	0.20-0.60	0.60-1
Colour	Green	Orange	Red

Table 4 Correlation coefficients of total VI to partial VI of single parameters

Element \ Earthquake	Ain Temouchent (1999)	Boumerdes (2003)
1. Total shear resistance of walls	0.64	0.66
2. Plan regularity	0.17	0.21
3. Elevation regularity	0.14	0.22
4. Walls connection	0.42	0.51
5. Walls type	0.15	0.23
6. Floor	0.18	0.20
7. Roof	0.15	0.18
8. Soil conditions	0.37	0.49
9. Pounding effect	0.15	0.27
10. Modifications	0.12	0.18
11. Details	0.08	0.10
12. General maintenance conditions	0.46	0.53

Table 4 shows that for both data sets the Total shear resistance and the Maintenance play an important role upon the vulnerability index. The total shear resistance is the most important. The items Elevation regularity, Pounding effect and Modifications have quite the same predominance. Since the Elevation regularity element has been established as a significant item (Benedetti and Petrini 1984), so the addition of the Pounding effect and the Modifications elements is justified. The non structural (Details) elements seem to be of less importance.

3. Development of vulnerability functions

The vulnerability curves express the average damage rate which a stock of buildings belonging to various vulnerability classes with respect to various seismic intensities could undergo. These curves are function of the constructive system, the site as well as certain numbers of local parameters. So each city has its own vulnerability curves. The methodology defined in (Huo *et al*. 1998) allows the translation of the buildings vulnerability functions from region to region by systematically considering the differences in buildings design codes. This methodology was adopted in order to determine the vulnerability functions of masonry building of Algiers. They will be deduced from those obtained from damage matrices after Friuli earthquake (courtesy - of Pr. D. Benedetti). This area in Italy has the same kind of masonry structures, similar to those present in the capital Algiers.

3.1 Principle of the translation method

In this method, the difference between earthquake vulnerability curves of a particular building type in two regions can be considered through combination of a translation and a rotation from a reference curve. The values of the translation and the rotation are quantified based on the differences between building codes (Huo *et al*. 1998). For convenience, the vulnerability function to be determined for a region is referred as “target”, while the one used as a basis for translation is referred as “reference”. The design base shear which is a function of the structural system type, fundamental period, site conditions and seismic zone coefficient, controls the structure behaviour in the elastic range until the beginning of the inelastic response for the intensity I, defined by $I_{Inelastic}$. However both the base shear and the ultimate displacement capacity of the building control the translation of the vulnerability functions.

In buildings code, the design base shear (V) is proportional to the peak of the ground acceleration (PGA). The PGA can be related to MMI through an empirical relation. The relation established by Murphy and O'Brien (Log(PGA) = 0.25 + 0.25 MMI), (Murphy and O'Brien 1977) was adopted. So that the shift along the MMI axis of the vulnerability functions is

$$\Delta I = \left(\frac{\mathrm{Log}_{10}(V_C/V_R)}{0.25}\right) \tag{2}$$

ΔI is the MMI shift, V_C and V_R represent the target and the reference design base shear respectively. This will produce an intermediate curve. In addition, starting from $I_{Inelastic}$, the intermediate curve will be rotated with a (θ) angel to obtain the target curve, (Fig. 1).

The difference between MDR's of the reference and the target buildings at I_{severe} is given by

$$\Delta MDR(I_{Severe}) = \left(K_2\frac{\delta_R}{\delta_C} - 1\right) \cdot MDR_R(I_{Severe}) \tag{3}$$

Where: K_2 is the coefficient depending on the relationship of MDR with ultimate deformation capacity of a building. In practice, the inter-story drift or roof drift can be used as a measure of deformation capacity of the building. Due to the lack of detailed experimental data, K_2 is simply taken as 1 (Huo *et al*. 1998).

δ_R and δ_C represent the reference and target ultimate displacement capacities of the building respectively. I_{Severe} is the intensity reflecting that severe damage is observed in the building. According to seismic code, the inelastic behaviour of the buildings starts at about MMI 7 and severe structural damage at about MMI 10.

In order to determine the vulnerability curves for Algiers, the Italian and Algerian seismic codes are used. The parameters relate to the fundamental period of the structures, the behaviour factor and

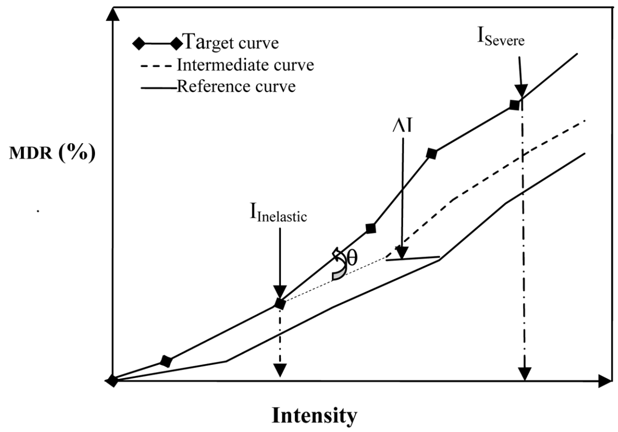

Fig. 1 Vulnerability translation sketch

ultimate displacement are necessary. To properly implement the methodology, the construction practices related to the buildings where the vulnerability functions are taken as references should be consistent with the effective edition of the code in the reference region. The 1986 edition of the Italian building code is used as reference code for translation from Italy; while the 1988 Algerian seismic code (RPA88) is used for the target region. This choice is made because the two seismic codes are close, they have quite the same level of knowledge and philosophy in their specification.

3.1.1 Italian seismic code (1986)

In this code, the design base shear is defined by

$$V = \frac{S-2}{100} R.\varepsilon.\beta.I.W \tag{4}$$

where, W is the weight of the structure, ε is the foundation factor which takes value 1 in the usual cases and value 1.3 for the compressible soils, β is the structural factor (for masonry buildings $\beta = \beta_1 \beta_2 . \beta_1 = 2$ accounting for ductility, $\beta_2 = 2$ design for the ultimate states), I is the factor of importance of the building and R is the response factor defined by

$$R = \begin{cases} 0.862.T_0^{2/3} & T_0 > 0.8 \text{ s} \\ 1.0 & T_0 \leq 0.8 \text{ s} \end{cases} \tag{5}$$

If the fundamental period T_0 of the structure is not available R is supposed to be equal to 1.0 and S is the seismicity index depending on the seismic zone (Table 5).

The seismic design base shear of the building in the reference area is written

$$V_R = C_R W \tag{6}$$

$$\text{with } C_R = \frac{S-2}{100} R.\varepsilon.\beta.I \tag{7}$$

3.1.2 Algerian seismic code (1988)

In the Algerian code (RPA88), the design base shear was defined as

$$V = (A\ B\ D\ Q).W \tag{8}$$

Where, W is the total weight of the structure, A is the coefficient of zone acceleration given on Table 6 and depending on the importance of the structure.

B is the structure behaviour coefficient. B takes value 2.5 for reinforced masonry construction and takes value 1 in the case of unreinforced masonry structure.

The average dynamic amplification factor D (Table 7) is given by the spectrum response which depends on the soil classification and building period T.

Table 5 Seimicity index

Seismic zone	S
I	12
II	9
III	6

Table 6 Coefficient A of zone acceleration

Importance of the structure	Zone I	Zone II	Zone III
1	0.12	0.25	0.35
2	0.08	0.15	0.25
3	0.05	0.10	0.15

Table 7 Dynamic amplification factor

Soil	D
Soft soil	$\frac{1.26}{\sqrt[3]{T^2}}$
Stiff soil	$\frac{0.896}{\sqrt[3]{T^2}}$

The period T is calculated using the following formula $T = 0.09H/\sqrt{L}$, with H the height of the building and L his length in the seismic direction.

The construction quality factor Q, is related to parameters such as plan regularity, elevation regularity, the control of the execution quality etc.

The seismic design base shear of the building in the target area is written

$$V_C = C_C W \tag{9}$$

$$\text{with } C_C = A.B.D.Q \tag{10}$$

3.2 Translation control parameters

The parameters governing the translation vulnerability curves are summarised in Table 8.

Since ten vulnerability curves were deduced from Friuli earthquake, ten vulnerability curves were obtained, they are plotted in Fig. 2.

These ten vulnerability curves belong to vulnerability index classes varying from 0 to 1 (CL1 to CL10) by a step of 0.1.

To be in accordance with Table 3, three sets of curves can be identified. A polynomial interpolation was performed in order to obtain a representative curve for each range. The obtained curves are plotted on Fig. 3.

The interpolations have a correlation of 0.971 for P1, 0.966 for P2 and 0.979 for P3.

Table 8 Control parameters for the translation of the vulnerability curves

Construction	Shear base coefficient C		MMI difference ΔI	Ultimate displacement δ Italian Code 86	Ultimate displacement δ Algerian Code 88
	Italy C_R	Algiers C_C	Algiers-Italy		
Masonry	0.28	0.30	0.12	1.5%	1%

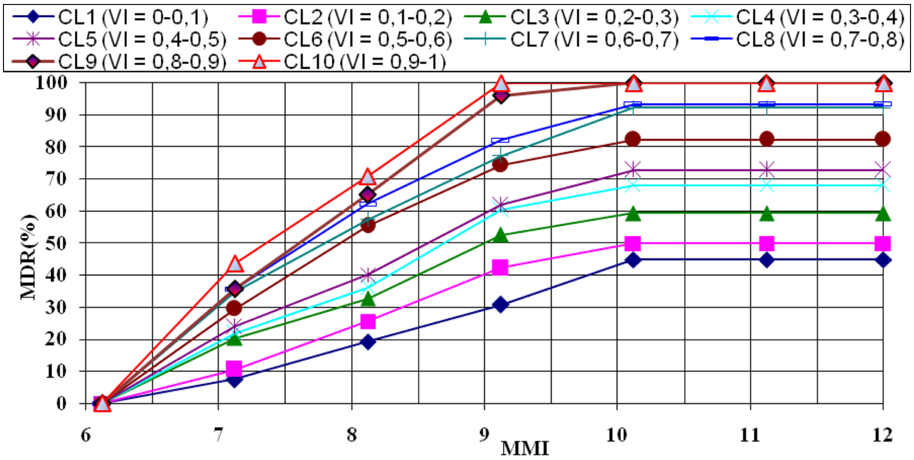

Fig. 2 Vulnerability translated curves

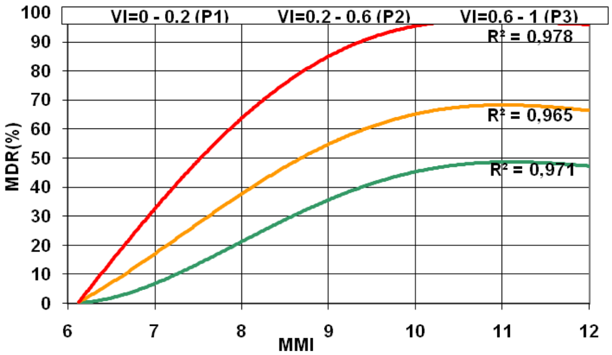

Fig. 3 Algerian vulnerability curves

4. Application

As an application, the district of Belouizdad has been considered. This district is located East of Algiers. The number of inhabitant is of 59248 people according to the census of 1998 (RGPH 1998) and the number of masonry buildings is about 643. These buildings are made of stone and/or brick and composite steel and masonry slabs. The average thickness of walls is about 60 cm. For these masonry constructions, the vulnerability index (VI) and their classification will be determined. A validation was performed through a specific survey. Then the mean damage ratio (MDR) of a set of buildings stroked by the Boumerdes earthquake will be compared to the assessment MDR given by the developed vulnerability curves. A data base is established and managed by a Geographical Information System (GIS).

4.1 Vulnerability index

In situ observations on structures are important information required to assess the vulnerability of structures. An investigation chart for a survey and a computer program were elaborated.

4.1.1 Developed computer program

A program called Vulnerability Index Program "VIP" using Delphi was elaborated providing the vulnerability index values for structures. It uses the elaborated chart in order to estimate the coefficient of the different elements and classify the structures.

The chart contains: a) General data, b) Geometric characteristics, c) Information on the structural system, d) Information on the ground, e) Details on the non structural elements, f) General maintenance conditions.

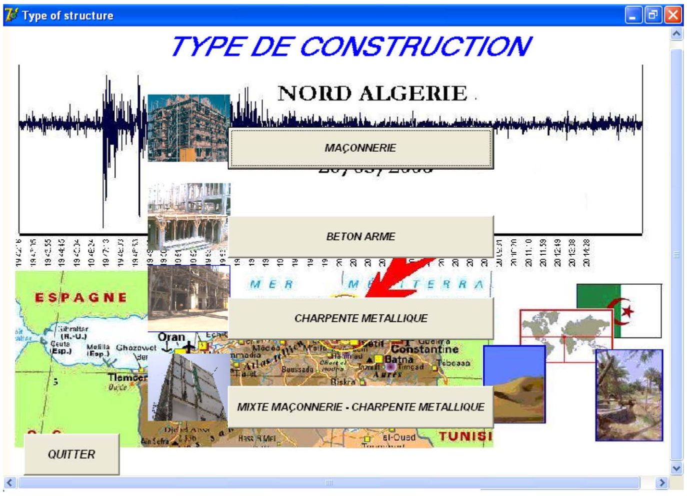

Fig. 4 Front page of the VIP

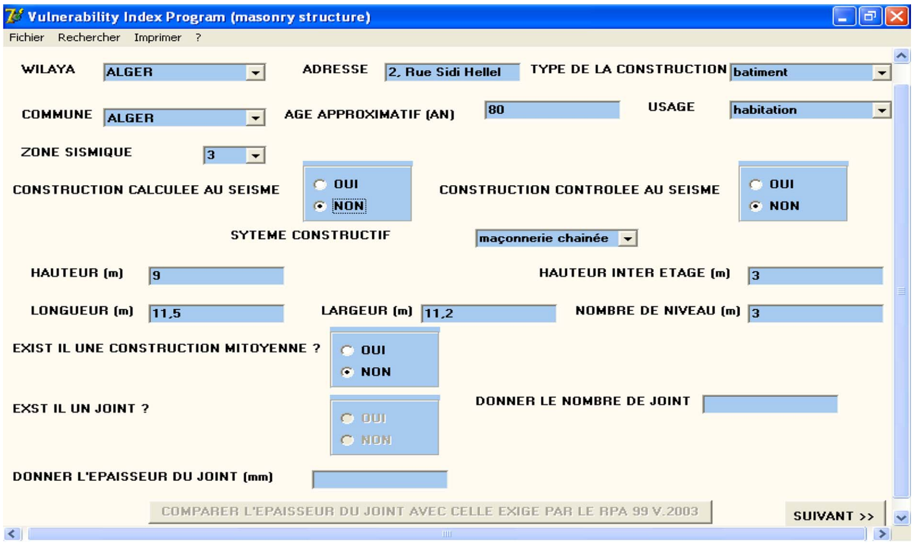

Fig. 5 VIP page for Masonry structure

The front page of the program is given on Fig. 4. A displaying window for masonry structure is shown as a sample on Fig. 5.

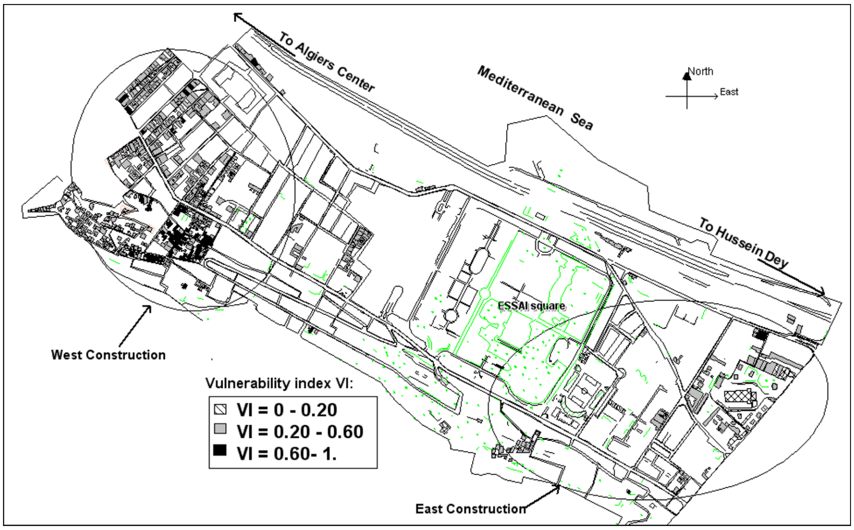

Fig. 6(a) General view of masonry construction for Belouizdad district according their vulnerability index

Fig. 6(b) Zoom view of west constructions

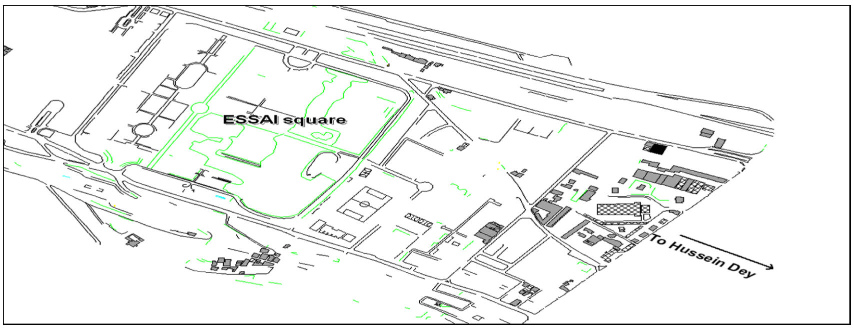

Fig. 6(c) Zoom view of east constructions

4.1.2 Vulnerability index for the study area

The vulnerability index calculated for the 643 buildings of the data base, enabled to have the results given in Fig. 6.

The results show that more than 80% of masonry constructions of the Belouizdad district have an average seismic quality. Indeed the vulnerability index for 508 buildings is included in P2 range which shows an average vulnerability and about 10% of the buildings are very vulnerable to the seismic action. As a result, 90% of the buildings of Belouizdad district are vulnerable and require an intervention for reinforcement or replacement (Fig. 7).

These results can be explained by the age of constructions (Fig. 8), the lack of maintenance of the buildings and the modifications made to the structures, increasing their vulnerabilities.

As can be seen from Fig. 8, most of the structures are more than one hundred years old and belong to P2 class. This makes them more vulnerable as the constituent material have undertaken with times many degradations under the aggression of the atmospheric conditions leading to an alteration of their mechanical characteristics.

4.1.3 Validation of the vulnerability index

In order to show the validity of vulnerability index values, the results are compared with those provided by the Structural Engineering Control (CTC: official organization in charge of control in Algeria) following the survey carried out on 179 buildings of Belouizdad district. The CTC survey

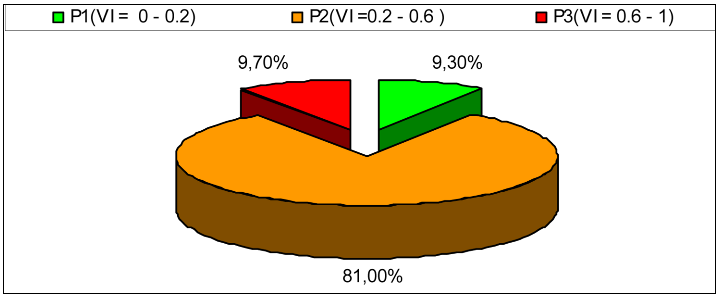

Fig. 7 Vulnerability buildings distribution

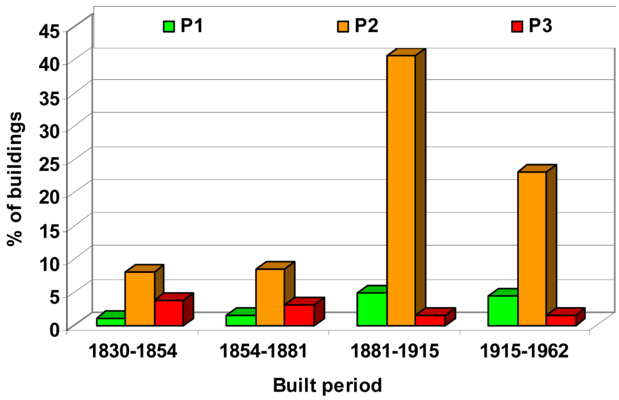

Fig. 8 Vulnerability buildings according the built period

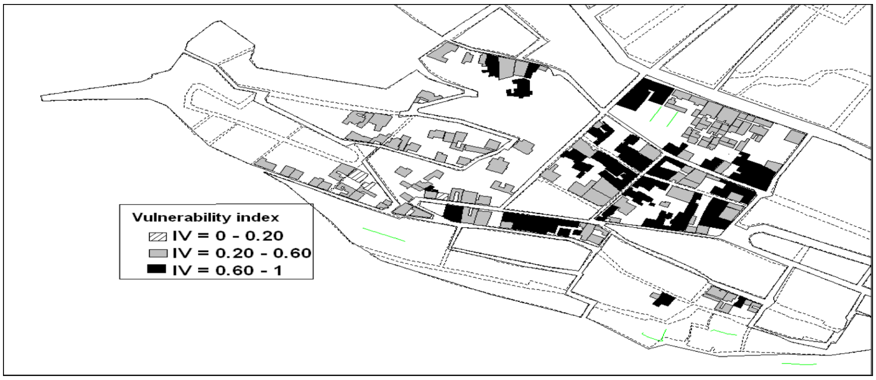

Fig. 9 Vulnerability index obtained by the VIP

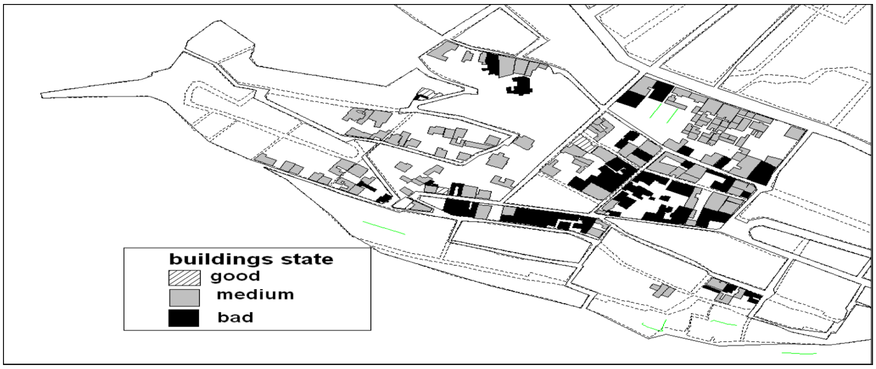

Fig. 10 CTC survey

is done according to the engineer's experience. The main observed damages are listed and the reasons might be also given. Then an opinion on the state of the construction is given which led to its classification according appendix 1.

The results given by the VIP and managed in the GIS are given in Fig. 9 while the results given by the CTC survey are given in Fig. 10.

The vulnerability index calculated provide an estimate of the buildings state with a difference of 9% compared to the one given by the CTC survey. So the results given by the VIP are correct.

4.2 Vulnerability curves validation

A set of buildings at Belouizdad district was considered to validate the determined vulnerability curves. The MDR obtained for this set of buildings is compared to post earthquake survey carried out after Boumerdes (2003) earthquake. This earthquake had a magnitude of 6,8 on Richter scale. The Acceleration (PGA) recorded at Hussein Dey district, East Belouizdad reached 0,27 g. The empirical relation of Murphy and O'Brien (Murphy and O'Brien 1977) which provides a link between the PGA and the MMI, gave an equivalent MMI of 8,7.

The results of the study for the considered set are given in Fig. 11.

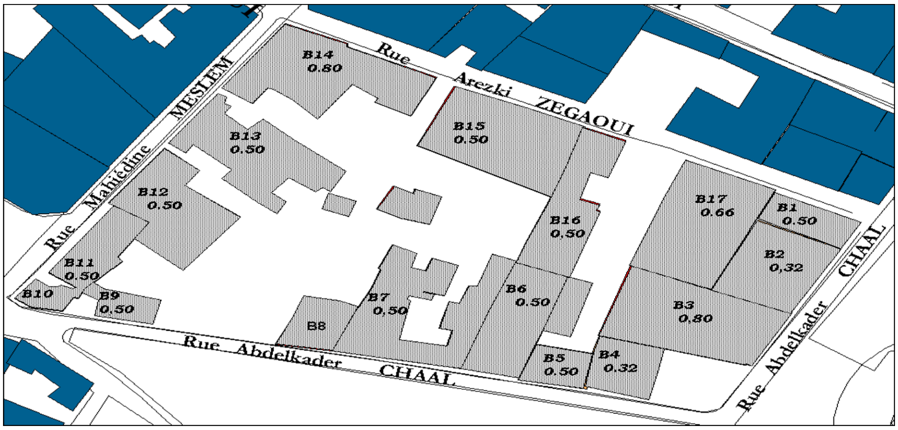

Fig. 11 Mean damage ratio estimation

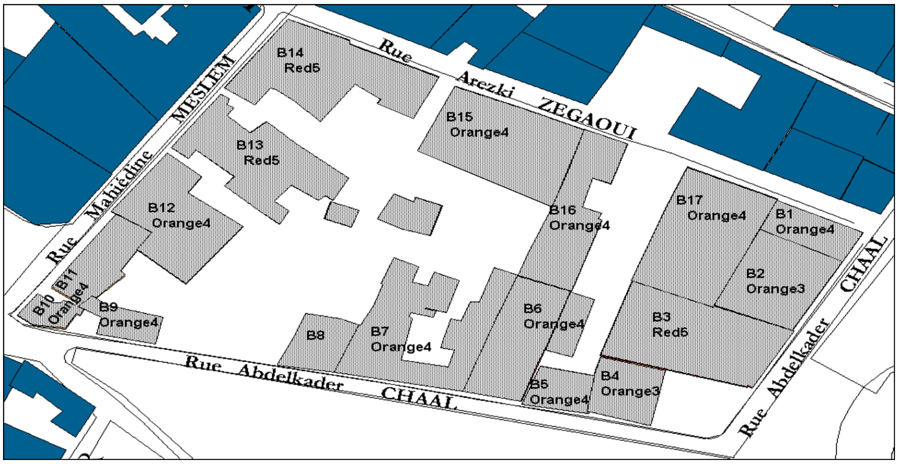

Fig. 12 Post seismic survey

Table 9 MDR for the studied set of building

Set of Buildings	MDR estimated according to Vulnerability curves	MDR Interpretation (Park and Ang)	Post seismic survey results (2003earthquake)	damage level (Park and Ang.)
B1, B5, B6, B7, B8, B9, B10, B11, B12, B15, B16, B17	0. 50	Moderate	Orange4	1. Non structural = 0.01-0.1 2. Light structural damage = 0.1-0.2 3. Moderate structural damage = 0.2-0.5 4. Severe structural damage = 0.5 – 0.85 5. Collapse = 0.85-1.
B13	0,5	Moderate	Red5	
B2,B4	0. 32	Moderate	Orange3	
B3, B14	0.80	Severe	Red5	

Fig. 12 shows the results given by the CTC. The constructions are classified green1, green2, orange3, orange4 and red5 according to the evaluation of Algeria damage levels (appendix 1).

The damage levels given by Park and Ang (Williams and Sexsmith 1995) made it possible to link the post earthquake survey results to the mean damage ratio given by the developed vulnerabilities curves; this was done in Table 9.

Building B8 is of reinforced concrete so it is not concerned by the study.

As can be seen, the results given by the developed curves are similar to those carried on by the survey after the earthquake. So the damage assessment is in accordance with the in situ observation, indeed except for building B13, all the other buildings had the MDR estimated by the developed vulnerability curves. Note that most of these constructions were strengthened after the 2003 earthquake, and buildings B3 and B14 have been rebuilt.

5. Analytical proposal for a damage-intensity function

The analytical representation of the vulnerability curves allows the link between the mean damage ratio (MDR), the intensity and the vulnerability index (VI). These analytical functions are obtained by interpolation of established vulnerability curves (Fig. 13).

To each vulnerability class, a relation, damage rate/seismic intensity is associated, the following analytical functions are proposed

$$\begin{cases} MDR(VI,I) = (-3.65VI - 0.56)[I + 1.52Ln(VI) - 15.77][I + 0.11Ln(VI) - 6.11] \\ I = 6.3, 11 \end{cases} \quad (11)$$

$$MDR(VI,12) = MDR(VI,11) \quad (12)$$

With VI = 0.2 for P1, VI = 0.6 for P2 and VI = 1 for P3.

These analytical functions are implemented in a GIS to perform seismic scenarios.

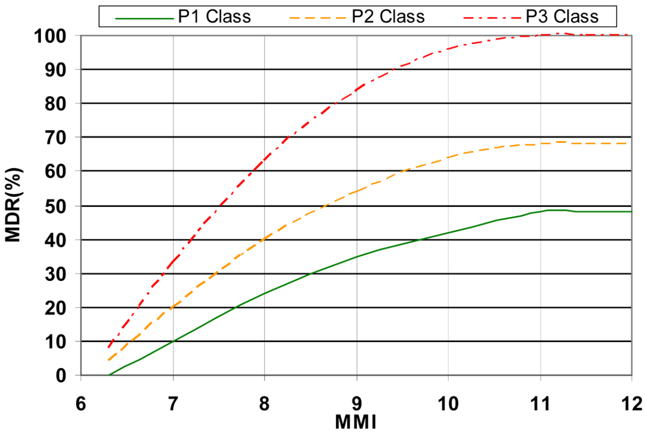

Fig. 13 Analytical functions of Algiers vulnerability curves

6. Discussion

In the case of European program RISK-UE, LM1 method was mainly developed to assess the vulnerability of European structures. It is a method which is largely based on statistical FM/DPM method, (i.e., statistical correlation between the macroseismic intensity and the apparent (observed) damage from past earthquakes) and derived from the European Macroseismic Scale (EMS-98). The LM1 methodology recognizes no-damage state labeled None, and five damage grades termed as Slight, Moderate, Substantial to Heavy, Very Heavy, Destruction.

Building Classification Matrix (BTM) systemize the distinctive features of European current building stock comprises 23 principal building classes grouped by: 1) Structural types; and 2) Material of construction.

The LM1 method is used to define vulnerability classes, vulnerability indices and to develop DPMs pertinent to RISK-UE BTM.

Vulnerability Index (VI) is introduced to represent and quantify the belonging of a building to a certain vulnerability class. The index values are arbitrary (range 0-1) as they are only scores to quantify in a conventional way the building behavior.

The LM1 method defines mean semi-empirical vulnerability functions that correlate the mean damage grade Éþ$_D$ with the macroseismic intensity *I* and the vulnerability index VI.

$$\mu_D = 2.5\left[1 + \mathrm{Tan}h\left(\frac{I + 6.25\,V_I - 13.1}{2.3}\right)\right] \tag{13}$$

When a building typology is directly identified within BTM, the vulnerability index values (VI*, VI-, VI+, VImin, VImax) are univocally attributed according a proposed table. Then a VI is calculated by adding coefficients (Regional Vulnerability Factor ΔV_R and Behavior Modifier ΔV_m) increasing or decreasing the vulnerability of the structure depending on the considered parameter.

In this study, the VI is determined by in situ observed parameters, except one parameter (Total shear resistance of wall). This one need calculation and considers numbers of factors (weight, dimensions, and shear resistance), so it takes into account implicitly the rise of the building under study. In this method the typology of the building is not considered directly.

The present work deals with unreinforced masonry structures (URM), the most found typologies in Algeria belong to buildings with stone and/or brick and composite steel and masonry slabs i.e.

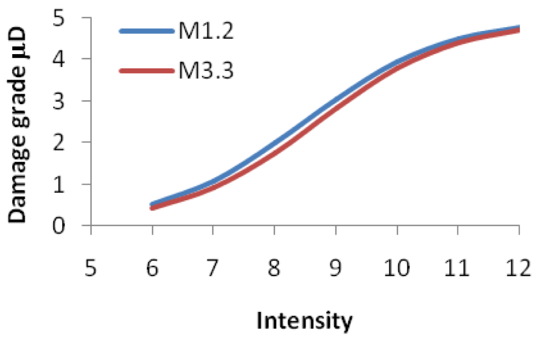

Fig. 14 Mean semi-empirical vulnerability functions

Table 10 Damage grading and loss indices for URM structures

Damage state	Damage state label	Range of loss Index-URM	Central index
0	None	0	0
1	Slight	0-0,04	0,02
2	Moderate	0,04-0,20	0,12
3	Substantial to heavy	0,20-0,40	0,30
4	Very heavy	0,40-0,70	0,55
5	Collapse	0,70-1	0,85

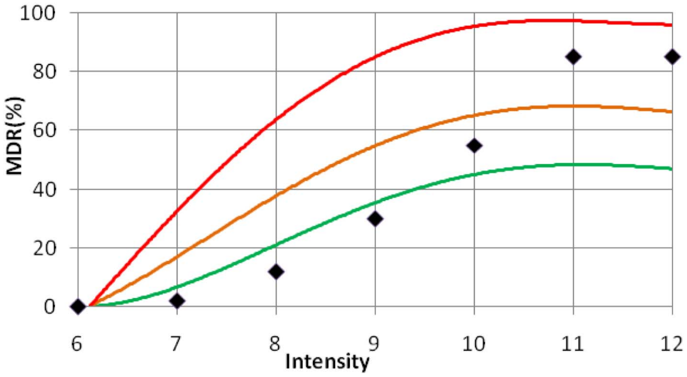

Fig. 15 Mean Damage Ratio for M1.2 and M3.3 RISK-UE buildings typology

M1.2 and M3.3 RISK-UE classification. So in order to compare the vulnerability functions of these two classifications, the Mean Damage Ratio (MDR) will be derived using the LM1 method.

Considering VI* the most probable value of the Vulnerability Index VI and applying Eq. (13) the mean damage grade is obtained for the two typologies (Fig. 14). As it can be seen the two curves are very close so the mean damage grade will be considered as the same for the two typologies.

Then using Table 10, the MDR for M1.2 and M3.3 using the central index is obtained and represented on Fig. 15 (assuming a perfect correspondence between the scales MMI and EMS-98 (Musson *et al*. 2010)).

On Fig. 15 are also represented the vulnerability functions derived in this study.

As it can be observed the developed vulnerability curves are more conservative than RISK-UE vulnerability function. This can be justified by the lack of maintenance and the intensive use of the buildings due to grow of population in Algeria.

7. Conclusions

The vulnerability assessment of existing structures using the vulnerability index is an efficient method which has been largely used in surveys in order to have an idea upon the damage undertaken by structures before and after a seismic event.

In this study, an assessment tool, simple for application even for unskilled personnel was developed and vulnerability curves for unreinforced masonry constructions were established. The obtained curves were validated by considering the results of Boumerdes post earthquake survey. This shows a good correlation between the damage estimated using vulnerability functions and those provided by the CTC survey. A comparison with LM1 (RISK-UE) method shows also that there is a good correspondence between the two approaches.

Acknowledgements

The authors acknowledge Pr. D. Benedetti, from Polytechnic of Milan, for his kindly help.

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Appendix1: Evaluation of the damage levels

Construction classified green (Good)

Level 1: No apparent damage.

Level 2: Light damage having no effect on the structural system.

Construction classified orange (Medium)

Level 3: Moderate damage i.e. significant damage on non structural elements and light damage on structural elements.

Level 4: Significant damage i.e. heavy damage on non structural elements and significant damage on structural elements.

Construction classified red (Bad)

Level 5: collapse construction and construction suffered heavy damage on their structural elements.