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ORIGINAL RESEARCH PAPER

An inventory of buildings in the city of Tunis and an assessment of their vulnerability

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Abstract Tunis is a densely populated city. Its building stock was constructed without any seismic design code and mostly over soft soils. These facts make a seismic risk assessment of the city necessary. To prepare a large-scale vulnerability assessment of the buildings of Tunis, the following methodology was employed: (1) a collection of data based on a rapid visual screening procedure was gathered using an inventory form. These data were composed of files and information placed at the disposal of the authors by the municipality of Tunis. The data also contained information gathered by surveys carried out by engineering departments and information gathered from building owners. (2) A classification of building typologies was carried out considering construction material, structural system, age, height, function and state of maintenance. A measure of seismic vulnerability was assigned to each typology considering the first two parameters. (3) A large-scale vulnerability assessment using two methods was conducted for buildings for which few data were available. Vulnerability methods inspired by the EMS98 concepts and the Italian GNDT concepts were modified and applied to pilot-scale buildings located in the downtown zone (Habib Bourguiba Avenue) and in the old zone (Medina). The data analysis, through the application of the two methods, suggests that the vulnerability of buildings surveyed in Tunis is significant and risk mitigation efforts are necessary.

Keywords Building inventory · Ordinary buildings · Historic buildings · Vulnerability assessment

1 Introduction

Tunis, the capital city of Tunisia since the twelfth century, is located in the northeast of Tunisia. It has a population of over 700,000 people according to the 2004 census.

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Tunis was developed in a basin characterized by poor geotechnical qualities and is built on hills sloping down toward the Lake of Tunis eastward and the Sebkha Sejoumi westward. The city has an area of nearly 21,263 ha. The density of population is over 3,000 persons/km^2.

Tunis has experienced highly productive construction since the French occupation in 1890. This period has been characterized by the creation of a new city (Bab Bhar) juxtaposing an old city (Medina). These two cities differ greatly in their structure and their urban design.

Tunis is characterized by (1) very old buildings constructed without a seismic code and mostly over soft soils, (2) a dense population, and (3) a very active socioeconomic context. The combination of these factors represents an extremely high risk under the effects of even a moderate earthquake. Thus, a seismic risk assessment of the city is necessary.

The seismicity of the Tunisian region is moderate compared to that of other Mediterranean regions such as Algeria and Italy (GSHAP 1999; Jimenez and Garcia-Fernandez 1999; Jimenez et al. 2001; Kacem 2004). Thus, during the twentieth century, a few earthquakes with a maximum intensity of V degrees on the MSK intensity scale were felt in the city. The most significant earthquake occurred on 1st December 1970; with a magnitude of 5.1 on the Richter scale, the earthquake caused great damaged to some buildings in Tunis without any registered fatalities (Ambraseys 1962; Vogt 1993). However, before the twentieth century, two major earthquakes were considered destructive in Tunis. The first one occurred in December 856, with an intensity of IX and a magnitude of 6.2, causing the deaths of 45,000 victims. The second occurred in 1758 with an intensity of IX, destroying a large number of houses and killing several thousands (Ambraseys 1962). A recent seismic hazard analysis of Tunis indicates that the peak ground acceleration (PGA) is 0.22 g for a 475 year return period (Kacem 2004).

Various methods for seismic risk assessment have been implemented in countries with strong seismicity, such as that by the Federal Emergency Management Agency in the United States (ATC21 1988; HAZUS 1999) and that by the Gruppo Nazionale per Difesa dai Terremoti in Italy (Benedetti and Petrini 1984; GNDT 1993; Cherubini et al. 1999). Some of these methods are based on the statistical analysis of the observed damage caused by previous earthquakes. This analysis is carried out by considering the structural characteristics of buildings, which control the seismic behavior of structures. Thus, these methods use very detailed surveys, which are not easy to implement in moderate seismic risk regions such as Tunisia because of their relatively high costs. Moreover, compared to methods used in the USA, European methods (e.g., from France and Italy) are more appropriate because of the similarities in structural and urban organizations between the studied buildings in these countries and those in Tunis (Sebag 1998).

For these reasons, the vulnerability assessment presented in this work was carried out using two methodologies, one inspired by the European project “RISK-UE” (RISK-UE 2003; Lagomarsino and Giovinazzi 2006) and the other by the French project “VULNERALP” (Guéguen et al. 2007). The differences in the results of these two methods will be compared herein and their efficiency evaluated within the context of the country of Tunisia.

The present paper focuses on the large-scale assessment of the seismic vulnerability of existing buildings. The first part of this paper focuses on (1) the methodology used to assess the building inventory from a sidewalk survey inspired by the methodology proposed by the FEMA154 (1988) and the GNDT (1993) projects; (2) the establishment of a building classification system corresponding to that adopted by EMS98 (2001); and (3) the assessment of building vulnerability using two methods based on collected structural information. In the second part, a building typology classification is established for the city. In the last section, the results of the inventory, vulnerability and damage assessment are discussed. Several seismic scenarios are calculated for the Tunis area by considering a range of probable intensities.

The vulnerability and expected damage was evaluated for the surveyed pilot-scale buildings located in the downtown zone (Habib Bourguiba Avenue) and in the old zone (Medina).

2 Vulnerability methodology assessment

In the present study, the methodology used for the vulnerability and damage assessment of buildings in Tunis was implemented in three steps, as described in the following sections.

2.1 Building inventory data collection

The building inventory methodology used in this study involved the following procedures: data collection and an integration of this information into a database for a simplified building classification.

The building information was gathered from a sidewalk survey, using a procedure inspired by that proposed by FEMA154 (ATC21 1988) and EMS98 (2001).

This step was based on a rapid visual screening procedure requiring only external visual evaluation by means of an inventory form.

As shown in Fig. 1, this inventory form gathers (1) general information such as street address, building age, height (number of stories) and building occupancy, (2) structural information such as construction materials and structural system, or typology, which canbe masonry, reinforced concrete, steel, wood or mixed, as well as other building attributes that modify seismic performance, such as roof shape and type, the state of maintenance, the position of the buildings, and vertical and plan irregularities. Possible pounding and retrofit were also included.

The form was designed to allow for a quick data assessment: the time required per building was set not to exceed 30 min. The data survey (of approximately 900 buildings in Tunis) lasted six months.

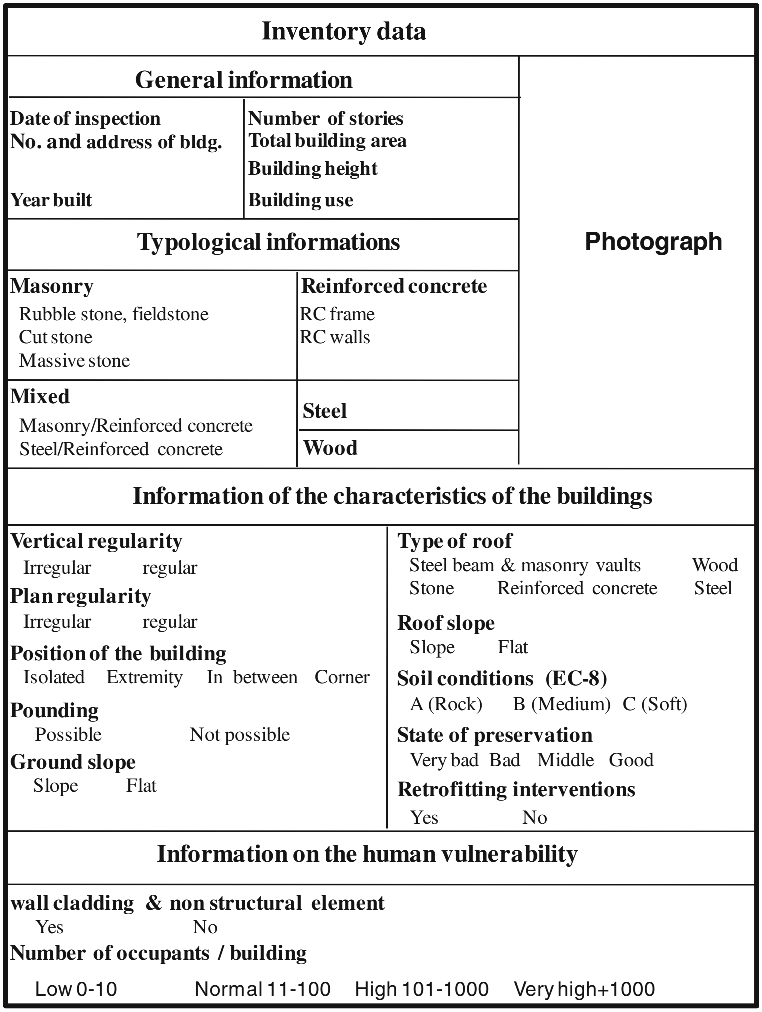
These data are supplemented by (1) archive files and construction plan information from the municipality of the city of Tunis, the Association of Safeguard of Medina (ASM) and the Urban Agency of Large Tunis (AUGT) and (2) a survey carried out in the engineering departments of the ministries of health and education and with the owners of the buildings. The most important feature of this procedure is that it permits a vulnerability assessment of the buildings based only on a sidewalk survey.

All of the collected data and photographs of the façades for each surveyed building were integrated into a database, the analysis of which is described in Sect. 3. The geographic information system (GIS) software program Arcview 3.2 was used to store the inventory database and compile it into several other databases and digital maps.

2.2 Building typological classification

The definition of a classification system is an essential step in vulnerability analysis that ensures a uniform interpretation of data and results. It depends on the availability of building stock and a related database.

Because a full coverage of building stock in the city of Tunis was not possible (because it would cover 30,000 buildings), testing sites were selected prior to the study (Medina and H. Bourguiba). Sites were selected by visual inspection of all city delegations, noting that the buildings in the selected areas are sample buildings of the city of Tunis.



Inventory data

General information

Date of inspection
No. and address of bldg.
Year built

Number of stories
Total building area
Building height
Building use

Photograph

Typological informations

Masonry
Rubble stone, fieldstone
Cut stone
Massive stone

Reinforced concrete
RC frame
RC walls

Mixed
Masonry/Reinforced concrete
Steel/Reinforced concrete

Steel

Wood

Information of the characteristics of the buildings

Vertical regularity
Irregular regular
Plan regularity
Irregular regular
Position of the building
Isolated Extremity In between Corner
Pounding
Possible Not possible
Ground slope
Slope Flat

Type of roof
Steel beam & masonry vaults Wood
Stone Reinforced concrete Steel
Roof slope
Slope Flat
Soil conditions (EC-8)
A (Rock) B (Medium) C (Soft)
State of preservation
Very bad Bad Middle Good
Retrofitting interventions
Yes No

Information on the human vulnerability

wall cladding & non structural element
Yes No
Number of occupants / building
Low 0-10 Normal 11-100 High 101-1000 Very high+1000

Fig. 1 Building inventory form

The main criteria used for this classification are based on structural system and material type. The building classification system established for the city of Tunis is developed in Sect. 3. Nine different building types, based on the materials and types of construction, are most commonly found in Tunis.

2.3 Vulnerability assessment methods

The study presented herein was carried out using the following two methods: the first one is derived from concepts of the GNDT (1993) (VULNERALP 2004; Guéguen et al. 2007). The second one is inspired by concepts of the EMS98 (RISK-UE 2003; Lagomarsino and Giovinazzi 2006).

2.3.1 Vulneralp project based method

This method is a simplified empirical method inspired by the VULNERALP project (VULNERALP 2004). Its goal is to allow for the establishment of a seismic inventory of buildings on a large scale by the simple and rapid recording of structural parameters.

The authors have made some modifications to the methodology developed by Guéguen et al. (2007). The main differences are (1) the introduction of two new parameters called "maintenance" and "modifications". They are deduced from street observations and take account of construction anomalies observed in the city of Tunis. These anomalies will be described in Sect. 3. It is noted that the "modifications" parameter is not included in the original (GNDT 1993) method. (2) The degree of accuracy of the roof parameter is enhanced by introducing roof shape as well as material type.

The vulnerability index is calculated based on nine modification parameters per studied building: (1) material type (masonry, reinforced concrete, wood, steel), (2) age of construction, (3) elevation regularity, (4) building position (sloping or flat site) and foundation (rock or sediments), (5) building position in a block (in a corner, isolated, in-between, at the end), (6) plan regularity, (7) material type and roof shape (masonry or reinforced concrete and flat or sloping), (8) state of maintenance (good or bad), and (9) modifications.

The weights Wi, the average scores IViM and the range of probable values (IVimax and IVimin) are extracted from the vulnerability matrices of the GNDT. We implement the same procedure adopted by Guéguen et al. (2007) (Table 1). The scores used are also in accordance with those applied by Boukri and Bensaïbi (2007) to Algiers (Algeria), particularly for the parameter "modifications". A weight Wi is assigned to each vulnerability parameter, ranging from 0.5 (e.g., plan regularity) for the least important parameters up to 2.5 for the most important ones (Material type and Age of construction). A score IVi is assigned to each vulnerability index of each parameter: from 0 (very low vulnerability) to 45 (high vulnerability). Most of the intermediate scores are equal to 5 and 25.

The IVi values of the material type and age of construction parameters indicate those of material quality, reflecting the evolution of building design codes in Tunisia and the materials used in different periods.

Vulnerability index evaluation (IV)

The median index of vulnerability of each building $\mathrm{IV_M}$ and its lower and higher limits ($\mathrm{IV_{min}}$ $\mathrm{IV_{max}}$) are calculated by the following formula:

$$\mathrm{IV} = \sum_{i=1}^{n} \mathrm{IV_i\, W_i} \tag{1}$$

where

IVi is the partial index of vulnerability

Wi is the weight of each structural parameter

The value of IV is standardized to 100, where 0 represents the least vulnerable buildings and 100 the most vulnerable.

Damage Calculation

According to this method, the relation between the average damage d, the macroseismic intensity $\mathrm{I_{EMS98}}$ and the index of vulnerability IV is also determined by the GNDT method (GNDT 1993) through the following formula:

$$d = 0.5 + 0.45 \arctan\left(0.55\left(I_{EMS98} - 10.2 + 0.05 IV\right)\right) \tag{2}$$

Table 1 Vulnerability index (IV_{imax}, IV_{iM} and IV_{imin}) and weight W_i for each structural parameter (VULNERALP 2004)

Material type and Age of construction IV_1

$W_1 = 2.5$	Before 1945			Between 1945 and 1970			Between 1970 and 2000			After 2000		
	$IV_{1\,max}$	IV_{1M}	$IV_{1\,min}$	$IV_{1\,max}$	IV_{1M}	$IV_{1\,min}$	$IV_{1\,max}$	IV_{1M}	$IV_{1\,min}$	$IV_{1\,max}$	IV_{1M}	$IV_{1\,min}$
M	45	25	15	45	25	15	25	15	5	25	15	5
RC	25	25	25	25	15	5	15	5	0	5	2.5	0

Building position and foundation IV_2

$W_2 = 0.75$	With slope sediments			With slope rock			Without slope sediments			Without slope rock		
	$IV_{2\,max}$	IV_{2M}	$IV_{2\,min}$	$IV_{2\,max}$	IV_{2M}	$IV_{2\,min}$	$IV_{2\,max}$	IV_{2M}	$IV_{2\,min}$	$IV_{2\,max}$	IV_{2M}	$IV_{2\,min}$
M	45	25	5	45	15	5	5	5	5	0	0	0
RC	25	10	5	15	10	5	5	5	5	0	0	0

Building position in the block IV_3

	Corner	Extremity	In between	Isolated
M	1.5	1.3	1	1
RC	1	1	1	1

Elevation regularity IV_4

$W_4 = 1$	Irregular			Regular		
	$IV_{4\,max}$	IV_{4M}	$IV_{4\,min}$	$IV_{4\,max}$	IV_{4M}	$IV_{4\,min}$
M	45	25	15	25	15	0
RC	15	10	5	15	5	0

Plan regularity IV_5

$W_5 = 0.5$	Irregular			Regular		
	$IV_{5\,max}$	IV_{5M}	$IV_{5\,min}$	$IV_{5\,max}$	IV_{5M}	$IV_{5\,min}$
M	45	25	25	5	2.5	0
RC	15	15	10	5	2.5	0

Roof (material type and shape) IV_6

$W_6 = 0.5$	Slope			Flat		
	$IV_{6\,max}$	IV_{6M}	$IV_{6\,min}$	$IV_{6\,max}$	IV_{6M}	$IV_{6\,min}$
M	45	25	15	15	7.5	0
RC	25	20	0	0	0	0

State of maintenance IV_7

$W_7 = 1$	Good			Poor		
	$IV_{7\,max}$	IV_{7M}	$IV_{7\,min}$	$IV_{7\,max}$	IV_{7M}	$IV_{7\,min}$
M	25	15	0	45	25	5
RC	10	5	0	15	10	5

Table 1 continued

Modifications IV_8						
$W_8 = 0.5$	No			Yes		
	$IV_{8\max}$	IV_{8M}	$IV_{8\min}$	$IV_{8\max}$	IV_{8M}	$IV_{8\min}$
M	5	2.5	0	45	25	25
RC	5	2.5	0	15	15	10

Table 2 Equivalence between the damage grade (EMS98) and the average damaged

EMS98 scale	Degree 1 Negligible to slight damage	Degree 2 Moderate damage	Degree 3 Substantial to heavy damage	Degree 4 Very heavy damage	Degree 5 Destruction
Average damaged	[0.0 – 0.2]	[0.2 – 0.4]	[0.4 – 0.6]	[0.6 – 0.8]	[0.8 – 1.0]

This formula, as well as the min, median and max values of IV, allows for the calculation of the min, median and max values ($d_{\min}, d_M, d_{\max}$) of the damage expected for a given intensity.

The average damage ranges from 0 to 1.

This method also suggests an equivalence between the calculated damage d and the level of damage indicated on the European Macroseismic Scale (Table 2).

2.3.2 RISK-UE project based method

This method relies on the evaluation of an index of vulnerability for buildings in terms of the typology IV0 as well as various factors likely to modify its behavior IV_M (plan irregularity, state of preservation, etc.) (Giovinazzi and Lagomarsino 2004). This method is based on the RISK-UE method; however, the survey form of the latter is very detailed. Thus, the structural parameters used in the study herein described were simplified. Only the most important structural parameters considered to be indispensable were used in the method. The selected scores and weights of each RISK-UE structural parameter were used.

The method defines, for each element of the typology, five representative values of IV (Table 3). IV_0 is the most probable value for the typological vulnerability index, which represents the membership of a building to a class of vulnerability (Milutinovic and Trendafiloski 2003). IV_{0-} and IV_{0+} are the probable values for a specific building type, which represent the bounds of the uncertainty range of IV_0. IV_{0--} and IV_{0++} are the unlikely values that correspond to the upper and lower bounds of the possible values of the typological index of vulnerability (Giovinazzi and Lagomarsino 2004). This method thus has the advantage of giving both the limits of the plausible interval of the index of vulnerability (IV_{0-}, IV_{0+}) and the possible limits (min:IV_{0--}, max:IV_{0++}). It is worth noting that the typological vulnerability index has been conventionally defined to range from −0.02 to 1.02 (Table 3).

This index is then modulated in terms of the specific structural criteria of each structure and according to whether it is a masonry or reinforced concrete building, as presented in Table 4 (Giovinazzi and Lagomarsino 2004). The sum of the modulating coefficients $\sum IV_M$ will be added to the basic index IV_0.

$$IV = IV_0 + \sum IV_M \tag{3}$$

Table 3 Example of RISK-UE typology and representative values of IV_0 (Milutinovic and Trendafiloski 2003)

RISK-UE typology	Values of IV0				
	IV_{0--}	IV_{0-}	IV_0	IV_{0+}	IV_{0++}
Rubble stone, fieldstone	0.620	0.810	0.873	0.980	1.020
Simple stone	0.460	0.650	0.740	0.830	1.020
Massive stone	0.300	0.490	0.616	0.793	0.860
RC frame with infill walls	0.140	0.207	0.447	0.640	0.860
RC dual systems (RC frame and wall)	−0.020	0.007	0.402	0.760	0.980
Steel and RC composite system	−0.020	0.047	0.386	0.670	0.860
Steel frame+unreinf. mas. infill walls	−0.020	0.257	0.402	0.720	1.020
Wood structures	0.140	0.330	0.484	0.640	0.860

where

IV = index of vulnerability of the building

IV_0 = typological index of vulnerability

$\sum IV_M$ = scores for behavior-modifying factors

The vulnerability indices IV_-, IV_+, IV, IV_{--} and IV_{++} can be deduced from $IV_{0-}, IV_{0+}, IV_0, IV_{0--}$ and IV_{0++}, respectively, by Eq. 3.

From this index, it is possible to define, according to the macroseismic intensity scale EMS98, the average damage state expressed by the following formula:

$$\mu_D = 2.5\left[1 + \text{tangh}\left(\frac{I + 6.25IV - 13.1}{2.3}\right)\right] \tag{4}$$

$\mu_{D-}, \mu_{D+}, \mu_D, \mu_{D--}$ and μ_{D++} are calculated from IV_-, IV_+, IV, IV_{--} and IV_{++}, respectively.

The value of μ_D varies between 0 (no damage) and 5 (severe damage or destruction). The damage grades are defined using the EMS98 scale.

3 Methodology application

3.1 Description of field survey data

Information about age, condition, use, materials and other parameters (approximately 20 characteristics) was obtained from a street survey modeled after the level 1 form inspired by FEMA154 (1988), GNDT (1993) and VULNERALP (2004).

3.1.1 Medina district: historic buildings

Medina is one of the oldest districts in Tunis, dating back to the sixteenth century (Fig. 2), with 8,265 buildings according to the 2004 census.

This historic city consists of dense residential and commercial districts with narrow streets. Its buildings are typically composed of rubble stone and brick masonry. They are in poor conditions due to degradation over the centuries. Moreover, some old masonry buildings have been demolished and replaced by new reinforced concrete (RC) buildings. Recently,

Table 4 Scores for the vulnerability factors IV_M for masonry and RC buildings

Behaviour modifier	Masonry		Reinforced concrete	
		IV_M	ERD level	Pre/low IV_M
State of preservation	Good maintenance	−0.04	Good maintenance	0
	Bad maintenance	+0.04	Bad maintenance	+0.04
Number of floors	Low (1 or 2)	−0.08	Low (1 or 3)	−0.02
	Medium (3, 4 or 5)	0.00	Medium (4–7)	0.00
	High (6 or more)	+0.08	High (8or more)	+0.04
Soft story	Demolition/transparency	+0.04		
Plan irregularity		+0.04	Shape	+0.04
			Torsion	+0.02
Vertical irregularity		+0.04	Shape	+0.04
			Short column	+0.02
			Bow windows	+0.04
Roof		+0.04		
Retrofitting interventions		−0.08 + 0.08		
Aggregate building: position	Middle	−0.04	Insufficient joints	+0.04
	Corner	+0.04		
	Header	+0.06		
Aggregate building: elevation	Staggered floors	+0.04		
	Buildings of different height	0.04 + 0.04		
Soil morphology	Slope	+0.02	Slope	+0.02
	Cliff	+0.04	Cliff	+0.04

continuous efforts have been aimed at the conservation and renovation of this historic city, with the support of the municipality of Tunis (the Association of Safeguard of Medina (ASM)).

The analyzed data set consists of 553 buildings. It shows that most of the surveyed buildings are commercial and between 1 and 3 stories tall (Fig. 3), with walls built mostly of poor-quality rubble stone and brick masonry in lime mortar. The floors are mostly composed of masonry vault, wood, composite steel and masonry or mixed. Recently, there has been a growing practice of using reinforced concrete.

A Geographical Information System was used to display the data gathered from the street survey (Fig. 4).

3.1.2 Bab Bhar district (Habib Bourguiba): ordinary buildings

The buildings of the downtown area, another focus of the study, date from the nineteenth to twenty-first centuries (Fig. 5). These buildings present some particularities:

1. Extension or retrofitting works can induce very significant modifications to the resistance of structures. The impact of these works depends on their extent. If works consist in adding stories with different structural systems or transforming the ground floor for commercial use (leading to a soft story), the structures can be destabilized.

Fig. 2 View of the medina district

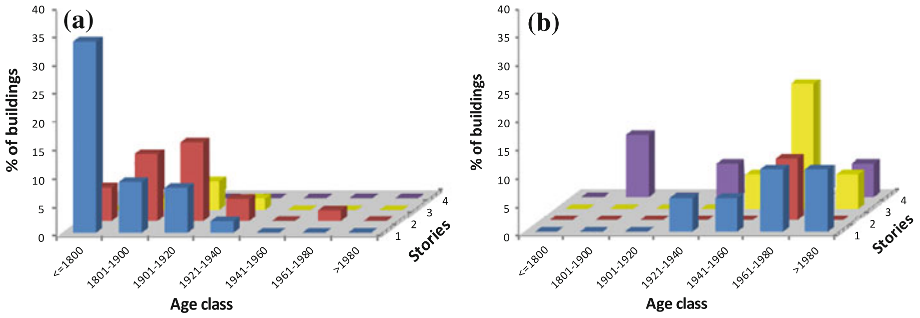


Fig. 3 Distribution of masonry (**a**) and RC (**b**) buildings according to number of stories and year of construction

2. The maintenance of a building can make it appear that there is no degradation, but the construction may actually present potential deficiencies from a seismic point of view.
3. The majority of listed buildings are constructed on soils of poor geotechnical quality. Previous studies in Tunis have shown that (i) a high amplification of ground shaking is expected at the crossing of subsurface layers and (ii) soil liquefaction can occur at nearby foundations within the first 20 m (Anibi and Romdhane 2007).

The case study consists of a survey of 337 buildings. Figure 6 shows the distribution of the buildings according to typology (Fig. 6a), use (Fig. 6b), age of construction (Fig. 6c) and number of stories (Fig. 6d).

From a typology point of view, 50 % of the studied buildings are composed of masonry and 27 % of reinforced concrete. Most masonry buildings have vertical load-bearing elements composed up of rubble stone (98 %). However, most reinforced concrete buildings are frame structures. It should be noted that a typology that is specific to the city of Tunis is mixed system (MRC) (13 %), combining masonry walls at the base and reinforced concrete frames on the upper floors. In addition, a very limited number of steel (6 %) and timber (3 %) buildings exist in the studied sample area.

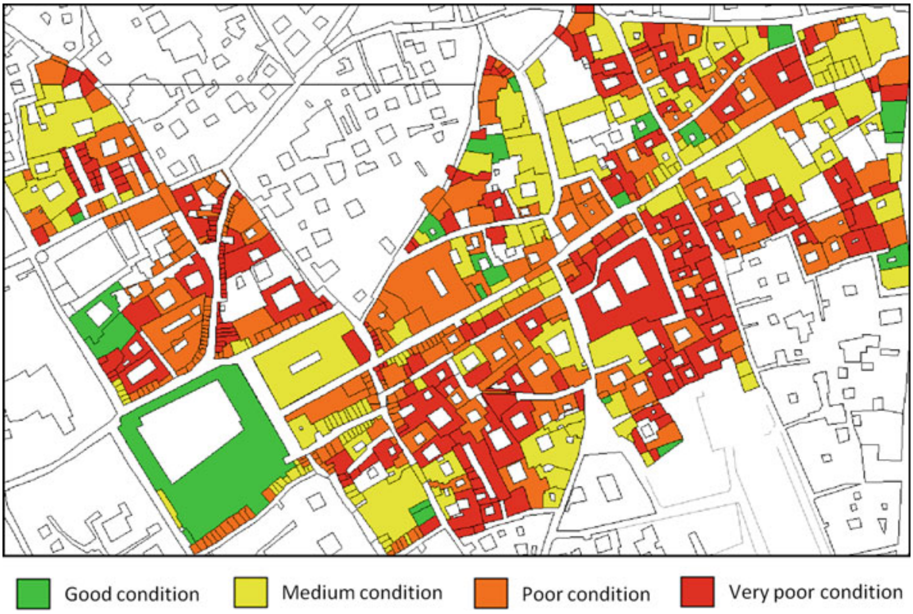


Fig. 4 Reference map of the surveyed area within the medina district and state of conservation

Fig. 5 General view of the Avenue of Habib Bourguiba

Considering the distribution of buildings according to their occupancy, the buildings of multiple use (commercial/residential) and commercial use exist in equal proportions (40 %). Only a few residential (5 %) and public buildings (5 %) were assessed.

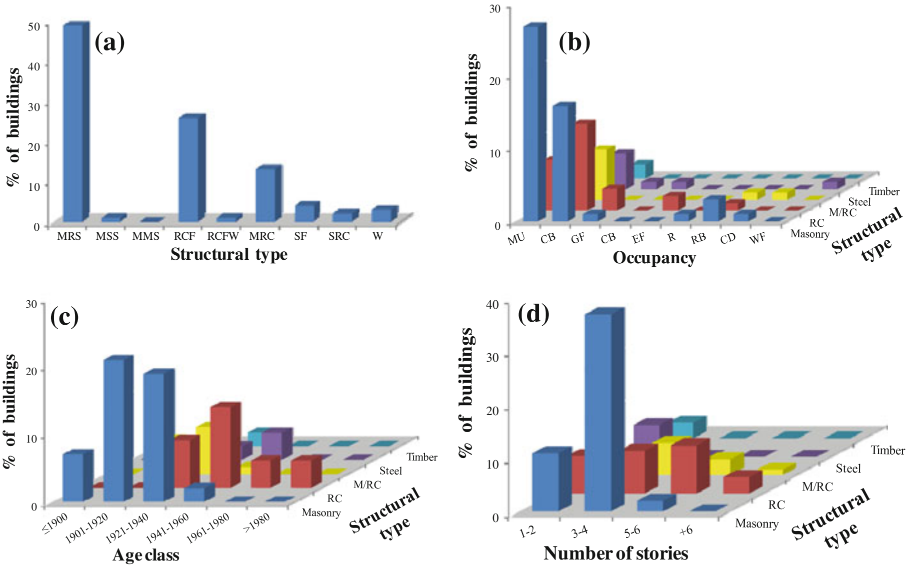


Fig. 6 Distribution of buildings according to **a** typology **b** occupancy **c** age of building and **d** number of stories

Considering the distribution of buildings according to the period of construction, 91 % of buildings were constructed before 1960. This means that they were built by foreign contractors. Only 8 % of the buildings were built after colonization. Of the buildings studied, 82 % of the assessed buildings have less than four floors; only 18 % of them are higher.

3.2 Building typological classification

The classification of the existing building typologies is the most important task for vulnerability analysis. In the present work, the classification of the studied buildings was based on that proposed in the European Macroseismic Scale (EMS98).

Table 5 shows the building typology classification carried out in this study. The buildings are classified into different types according to their construction material and their structural system.

A few varieties of construction types and building materials are used in Tunis. According to the suggested classification, buildings are grouped into the following classes: (1) masonry buildings, (2) reinforced concrete buildings, (3) mixed system buildings (4) steel buildings, and (5) timber buildings. These classes are further divided into nine sub-categories (Fig. 7). A qualitative description of building features is provided in the following sections.

Compared to the existing EMS98 classification, the proposed classification introduces two new typologies. The first one is called a mixed system typology, which features reinforced concrete and masonry structures and is built over a variable period. This type is among the most common in Tunis. The second one is a wood frame building with unreinforced masonry infill, which is less common than other types.

Masonry rubble stone (MRS)

This type of construction is designed for multiple uses (commercial and residential). It represents up to 50 % of the total studied building stock. Buildings of this type were mostly built

Table 5 Proposed classification of existing building in Tunis into 9 typologies

Building type	Type of roof	Structural system	Materials
MRS			
Rubble stone	Shallow arches supported by steel beams	Stone load-bearing walls	Masonry
MSS			
Simple stone	Wood		
MMS			
Massive stone	Reinforced concrete Stone		
RCF			
Reinforced concrete frame with unreinforced masonry infill (brick)	Reinforced concrete	Reinforced concrete frame or frame-wall	Reinforced concrete
RCFW			
Dual reinforced concrete frame and Reinforced concrete shear wall			
MRC			
Mixed system (masonry/reinforced concrete)	Shallow arches supported by steel beams Wood Reinforced concrete Stone	Stone load-bearing walls/reinforced concrete frame	Masonry/reinforced concrete
SF			
Steel frame with unreinforced masonry infill (parpaings, brick)	Steel	Steel frame	Steel
SRC			
Steel and RC composite systems	Steel Reinforced concrete	Steel frame/reinforced concrete frame	
W			
Wood frame with unreinforced masonry infill (rubble stone, parpaings, brick)	Wood	Wood frame	Wood

before 1940 and are typically 1–4 stories high. The statistical data indicate that more than half of the rubble stone structure of the building stock contains shallow arches supported by steel beams. The slabs are also wooden structures, reinforced concrete or stone material. The quality of construction and the building conditions are poor. As a result, these buildings are considered to be highly vulnerable to seismic effects.

Fig. 7 Classification of Tunis buildings into nine typologies

Masonry simple stone (MSS)

This form of construction is typically seen in public buildings under four stories high built prior to 1910. The slabs are formed, in the same frequency of occurrence, by shallow arches supported by steel beams, wooden structures or stone material. The quality of construction varies but is generally poor.

Masonry massive stone (MMS)

The use of massive stone constitutes a large part of religious construction in the Medina (mosques) and the new city (churches) of Tunis. This type of masonry was used both in the large mosque buildings before the French occupation and in the churches since built since one century. The quality of construction is generally good.

Reinforced concrete frames with infill walls (RCF)

A large proportion of commercial buildings in Tunis were constructed using reinforced concrete with masonry infill. Generally, the RC buildings are between 4 and 6 stories tall. More than half of them were built after 1940. They are mostly located in the downtown of Tunis (Habib Bourguiba Avenue). In the medina, there are a small number of reinforced concrete buildings. The quality of the concrete varies with the time of construction. These RC buildings were designed according to different design codes established during difference construction periods. The latest code is the French BAEL 91 (1992), modified in 1999, which is still applied. Before the BAEL 91 (1992), the French CCBA 68 and 70 (1975) codes were also used.

In building design, gravity loads are considered dead or live loads and beams are designed for simple flexure, columns for simple compression (no horizontal load), and slabs are one-way reinforced (T-beams). The materials strength of concrete cores is tested under compression. Other tests are used to test concrete mixtures and reinforcement steel strength but not seismic loads.

Reinforced concrete frames with concrete walls (RCFW)

Dual system buildings represent a small percentage of the existing building stock. They were mostly built after 1988 and are up to 6 stories in height. Walls are often found along the perimeter of the buildings. The floors are usually constructed of reinforced concrete. This construction type is used for commercial buildings.

Mixed system (MRC)

This class includes buildings with unreinforced masonry bearing walls (MRS, MSS) that stop at a certain level of the buildings. The rest of the stories were later built using reinforced concrete (RCF, RCFW). This type of construction is generally used in commercial building measuring 4–5 stories tall.

Steel frames with unreinforced masonry infill (SF)

Numerous steel buildings are generally used as industrial or commercial halls. They are generally single-floor buildings with steel roofs constructed between 1920 and 1940. These buildings were constructed without any design code using very poor materials. This type is absent in the medina building stock.

Steel and RC composite systems (SRC)

These buildings were constructed using composite steel and concrete columns and beams. The structures typically feature non-structural walls composed of a number of materials (brick masonry, concrete utility blocks (parpaings). The codes that were (and still are) applied are the French CM66 (1998) and Eurocode 3 (CEN 1993).

Wood frames with unreinforced masonry infill (W)

This type of construction represents a small percentage of the building stock. These single-floor buildings consist of a wood frame with unreinforced masonry walls (parpaings, brick). Most of them were constructed prior to 1930 for commercial use. The quality of construction and the building conditions are very poor.

4 Damage and vulnerability assessment

A damage and vulnerability assessment was performed using two methods: the first one is the “simplified method” inspired by VULNERALP. The second is the method inspired by RISK-UE; in its original form, the method relies on more information than the former but has been simplified for the purposes of the study presented herein.

4.1 Vulneralp project based method

For each building, the damage values d_{min}, d_M and d_{max} (See section 2.3) were calculated for the corresponding EMS98 intensities, IV_{min}, IV_M and IV_{max}, respectively.

For an intensity level of 7, the value of d_M is greater in masonry buildings ($d_{Mmedina} = 0.25$; $d_{Mh.bourguiba} = 0.19$) than in reinforced concrete ($d_{Mmedina} = 0.06$; $d_{Mh.bourguiba} = 0.1$). According to Table 2, these values are equivalent to damage grades 2 and 1 of the EMS98 scale in masonry buildings and to grade 1 in reinforced concrete.

It is interesting to note that, for an intensity level of 7, the maximum damage levels (d_{max}) are approximately 0.68 in the Medina and 0.45 in H. Bourguiba for masonry buildings because the former buildings are much older and badly maintained. The maximum damage levels are 0.13 and 0.18, respectively, for reinforced concrete. These values are equivalent to grades 4 and 3 of the EMS98 scale for masonry buildings and to grade 1 for reinforced concrete.

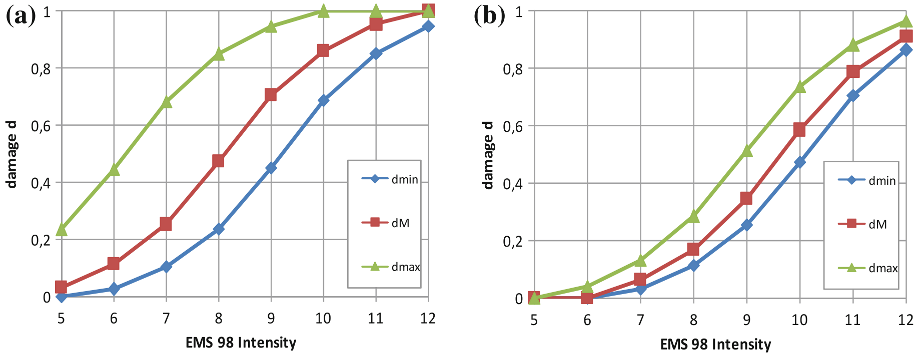


Fig. 8 Vulnerability curves for **a** masonry and **b** concrete buildings in Medina. The expected damage is $d_M = 0.25$ for masonry typology and $d_M = 0.06$ for concrete typology when $I = 7$

Figure 8 shows the results for intensities varying from 5 to 12 of the medina district, and Fig. 9 shows the results of the seismic vulnerability analysis in the GIS format for Habib Bourguiba Avenue for the probable scenario of an intensity level of 7.

4.2 RISK-UE project based method

The aim of this study was to estimate, for the entire group of medina district buildings, relationships defining the proportions of buildings suffering from five degrees of damage as defined in the EMS98 scale (2001) in terms of macroseismic intensity. The scores of the specific behavior modifiers used for masonry buildings in the Medina center have been identified by Balbi et al. (2004).

The vulnerability curves of different typologies are compared in Figs. 10 and 11. These curves show that the average values of the expected damage for the masonry buildings is high, particularly the expected damage of the rubble stone buildings. For the probable scenario of an intensity level of 7, the value of μ_D is 2.41 for the rubble stone typology. This value is equivalent to damage grade 3 of the EMS98 scale, thus corresponding to significant damage.

Figure 12 represents a model of the vulnerability curves (based on Eq. 4) used to evaluate the probability damage distribution of the rubble stone building in terms of the macroseismic intensity I.

5 Conclusion, discussion and outlook

The large-scale assessment of the vulnerability and damage of buildings was carried in this study using two methodologies. These methods were applied to different buildings of the city of Tunis (ordinary and historic buildings) in three steps.

Data collected from the street survey show that masonry rubble stone is the more representative system in the studied building stock. This system is characterized by poor conditions, and its irregularity in elevation is represented mainly by the presence of soft stories due to the transformation of the ground floors for commercial use. Considering the distribution of buildings according to the period of construction, three major periods are distinguished. Before 1920, there was a strong dominance of masonry buildings mainly composed of rubble stone. The period between 1920 and 1960 was reported to have been dominated by masonry

(a) lower: d_{min}

(b) middle: d_M

(c) upper: d_{max}

Fig. 9 Damage level in Habib Bourguiba computed according to the Eq. 2 and corresponding to EMS98 intensity 7

buildings with an appearance of reinforced concrete. The period after 1960 is characterized by an expansion of the reinforced concrete buildings without adhering to any seismic design. The two first periods represent approximately 90 % of the total buildings studied herein; this means that they were built before the colonization by French and Italian construction companies. Because of the similarity of the studied buildings to those found in France and Italy, the methods chosen are entirely based on European methods.

A classification scheme for the buildings in Tunis has been developed, identifying the main typologies and their key characteristics and deficiencies. Despite the use of a few varieties of construction types in Tunis, we proposed two new typologies in addition to those of the EMS98: the first one is called a mixed system typology with reinforced concrete and masonry structures built over a variable period. The second one is a wood frame building typology with unreinforced masonry infill.

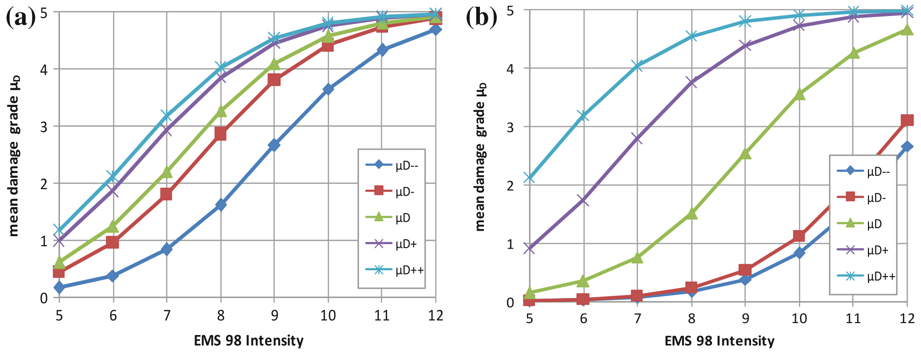


Fig. 10 Vulnerability curves for a) masonry and b) concrete buildings. The expected damage is $\mu_D = 2.21$ for masonry typology and $\mu_D = 0.77$ for concrete typology when $I = 7$

Fig. 11 Mean vulnerability curves for different building typologies; expected damage $\mu_D = 3.4$ for rubble stone typology when $I = 8$

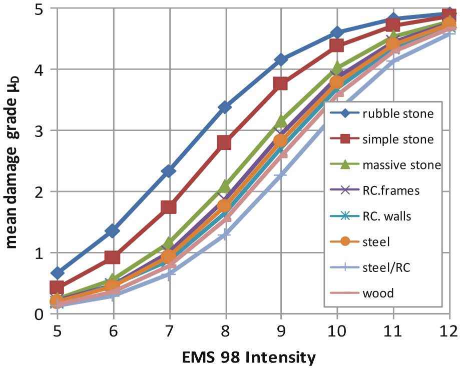
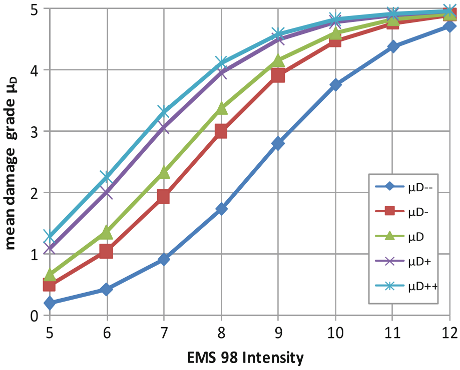


Fig. 12 Vulnerability curves of rubble stone building typology (mean value μ_D, plausible range: μ_{D--}, μ_{D-}, μ_{D+} and μ_{D++})



In the event of the probable scenario of an intensity level of 7, the estimate of the expected damage in Tunis shows that the Medina, the oldest part of the city, mainly composed of masonry buildings, could suffer moderate to substantial damage according to the method used (grade 2–3 EMS98). This is essentially due to the poor quality of buildings in the Medina; meanwhile Bab Bhar, the newest part, would suffer less damage. However, due to the poor geotechnical quality of soil in Tunis, an increase of one degree of intensity was observed, which could make the seismic damage in Tunis substantial to heavy.

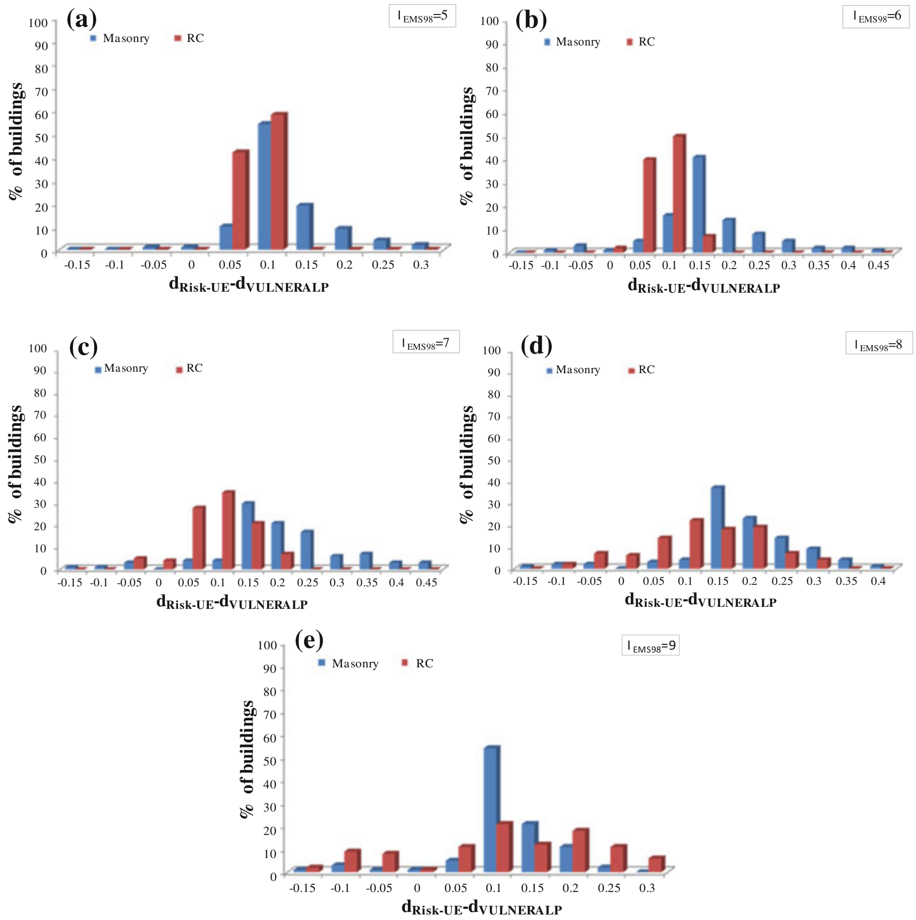


Fig. 13 Graphical representation of percentages of residue D_R ($D_R = d_{Risk-UE-}d_{VULNERALP}$) for masonry and concrete buildings for different EMS98 intensities: **a** $I_{EMS98} = 5$, **b** $I_{EMS98} = 6$, **c** $I_{EMS98} = 7$, **d** $I_{EMS98} = 8$, **e** $I_{EMS98} = 9$

The two methods were compared through the value of the percentage of damage, which corresponds to the most probable value for the VULNERALP project-based method (d) and RISK-UE project-based method (μ_D). The values of comparison (D_R), the residual values, computed as follows: $D_R = d_{Risk-UE}$-$d_{VULNERALP}$, for the majority of buildings were very similar overall ($-0.2 < D_R < 0.2$). The values correspond to less than one degree on the EMS98 damage scale. The residual values are different between the two methods according to the intensity (Fig. 13a–e). For example, for an intensity level of 5, 94 % of masonry buildings and 100 % of reinforced concrete buildings have a residual value of less than 0.2 in absolute values (i.e., an increment of damage on the EMS98 scale) (Fig. 13a). According to the two methods used, the damage is included in the first degree of damage defined by EMS98. The average damage to be expected is slight structural damage. For an intensity level of 7, the percentage of D_R is found to reduce to 64 % for masonry buildings and remains at 100 % for reinforced concrete buildings (Fig. 13c). This could be explained by the fact that masonry construction covers a wide range of vulnerability classes of EMS98. Damage at this intensity level is obviously much greater than that at an intensity level of five. It is noted that according to the method used, the masonry buildings pass from damage grade 2 (based on method VULNERALP) to damage grade 2, 3 and 4 (based on method RISK-UE). The damage for this type of building thus covers three classes, from which a distinction is made between the two methods even if their levels of damage are comparable. For both methods, the reinforced concrete buildings are within the first two degrees of damage (grade 1 for the first method and degree 1 and 2 for the second). Figure 13 compares the values of D_R between the two methods for masonry and reinforced concrete buildings for intensity levels ranging from 5 to 9.

It is noted that the results obtained from the two methods for Tunis, in terms of building damage, are similar overall, though a few slight differences are observed. Thus, for the lowest intensities, the method based on VULNERALP is more conservative compared to the method based on RISK-UE ($D_R < 0$) but is less conservative ($D_R > 0$) for higher intensities; this is due to the statistical law used to calculate damage, which was a binomial distribution for GNDT (and therefore VULNERALP) and β for RISK-UE.

We conclude that the methods applied herein are especially suitable in studying regions where there are no seismic damage data and no complete inventory of buildings, such as Tunis. The results of the simplified vulnerability assessment procedure can be used to determine the potential seismic performance of the selected buildings, to further short-list the buildings requiring detailed vulnerability assessment and to prepare emergency plans for earthquake risk mitigation. These results show a good agreement with the historical evolution and the current state of the city of Tunis. Moreover, to validate the proposed methods, our research team is currently studying the ambient vibrations of selected buildings for each studied typology. This analysis seems to be an alternative way to estimate the vulnerability of buildings in Tunis. Its goal consists in extracting from ambient vibration recordings the modal parameters (resonance frequencies, modal shapes and damping) that would allow us to develop a simplified numerical model of the elastic behavior for each class of studied building. We would then study the response of these models to seismic excitations to determine the threshold acceleration sustained by each class of building, which we would interpret as the first damage level and therefore the building class's vulnerability index.

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References

Ambraseys NN (1962) The seismicity of Tunis. Ann Geophys 15(2–3):233–244

Anibi S, Romdhane NB (2007) Contribution à l'estimation du risque de liquéfaction du sous sol de Tunis. Colloque international "Sols et matériaux à problèmes", Hammamet, Tunisie, Février 2007, pp 163–172

BAEL 91 révisées 99 (1992) Règle techniques de conception et de calcul des ouvrages et constructions suivant la méthode des états-limites. Editions Eyrolles

Balbi A, Giovinazzi S, Lagomarsino S (2004) A vulnerability method for historical centre buildings. In: Proceedings of the 11th Italian conference on earthquake engineering, Genoa, Italy

Benedetti D, Petrini V (1984) On seismic vulnerability of masonry buildings: proposal of an evaluation procedure. L'Industria delle Costruzioni 18:66–78

Boukri M, Bensaïbi M (2007) Indice de vulnérabilité des bâtiments en maçonnerie de la ville d'Alger. Actes du congrès AFPS, France

CCBA 68 révisées 70 (1975) Règle techniques de conception et de calcul des ouvrages et constructions en béton armé. Editions Eyrolles

CEN (1993) Eurocode 3: Calcul des structures en acier. Comité européen de normalisation (CEN), Brussels

Cherubini A, Di Pasquale G, Dolce M, Martinelli A (1999) Vulnerability assessment from quick survey data in the historic centre of Catania. In: Faccioli F, Pessina V (eds) The Catania project: earthquake damage scenarios for high risk area in the Mediterranean. CNR-Gruppo Nazionale per la Difesa dai Terremoti, Roma, pp 213–225

CM66 et additif 80 (1998) Règles de calcul des constructions en acier. Editions Eyrolles

EMS98 (2001) L'Echelle Macrosismique Européenne 1998. Conseil de l'Europe, Cahiers du Centre Européen de Géodynamique et de Séismologie, vol 19

FEMA154 (1988) Rapid visual screening of buildings for potential seismic hazards: a handbook. Federal Emergency Management Agency and applied technology council (ATC-21), Washington DC

Giovinazzi S, Lagomarsino S (2004) A macroseismic model for the vulnerability assessment of buildings. In: Proceedings of the 13th world conference on earthquake engineering, Vancouver, Canada, paper 896 (CD-Rom)

GNDT (1993) Rischio sismico di edifici pubblici—Parte I: aspetti metodologici. Centro Servizi Quasco, Bologna

GSHAP (1999) Global Seismic Hazard Assessment Program (map source: GSHAP Project http://seismo.ethz.ch/GSHAP/)

Guéguen P, Clotaire M, LeCorre L (2007) A simplified approach for vulnerability assessment in moderate-to-low seismic hazard regions: application to Grenoble (France). Bull Earthq Eng 5:467–490

HAZUS (1999) Earthquake loss estimation methodology–technical and user manuals. Federal Emergency Management Agency (FEMA), National Institute of Building Sciences, Washington, DC

Jimenez MJ, Garcia-Fernandez M (1999) Seismic hazard assessment in the Ibero-Maghreb region. Annali di Geofisica 42:1057–1065

Jimenez et al (2001) Seismic hazard in the Mediterranean region Boll. Geof Teor Appl 42:3–18

Kacem J (2004) Etude sismotectonique et évaluation de l'aléa sismique régional du nord-est de la Tunisie: Apport de la sismique réflexion dans l'identification des sources sismogéniques, PhD thesis, University of Sciences of Tunis, 167 pp

Lagomarsino S, Giovinazzi S (2006) Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings. Bull Earthq Eng 4:415–443

Milutinovic ZV, Trendafiloski GS (2003) WP4-Vulnerability of current buildings handbook, RISK-UE project, 110 pp

RISK-UE (2003) An advanced approach to earthquake risk scenarios with applications to different European towns, Projet Européen, EVK4-CT-2000-00014

Sebag P (1998) Histoire d'une ville, Harmattan, 685 pp

Vogt J (1993) Further research on the historical seismicity of Tunisia, Terra motae, pp 475–476

VULNERALP (2004) Projet d'évaluation de la vulnérabilité sismique à Grenoble. http://wwwlgit.obs.ujfgrenoble.fr/~pgueg/VULNERALP