The Effects of Building Characteristics and Site Conditions on the Damage Distribution in Boumerdès after the 2003 Algeria Earthquake

Abdelghani Meslem,[a] **Fumio Yamazaki,**[a] **Yoshihisa Maruyama,**[a]
Djillali Benouar,[b] **Abderrahmane Kibboua,**[c] **and Youcef Mehani**[c]

This study highlights the major contributing factors to the observed damage distribution in the city of Boumerdès after the 2003 Algeria earthquake. The results of field investigations and statistical analyses show that a majority of the damaged buildings, mostly mid-rise reinforced concrete (RC) moment-frame systems, were located on steep slopes and small hilltops, along river valleys. The horizontal-to-vertical (H/V) ratios from free-field microtremor measurements at these sites did not show clear results. In contrast, buildings with the same structural characteristics located on flat ground did not suffer much damage, and clear peaks were observed from the H/V ratio curves. The amplification effects of topography have not been incorporated into the revised Algerian seismic code, but the results from this study show the importance of considering this factor when designing new buildings for earthquake resistance. [DOI: 10.1193/1.3675581]

INTRODUCTION

Following the 21 May 2003, M_w 6.8 Algeria earthquake (EERI 2003, Meslem et al. 2010), the damage distribution observed by the survey mission in Boumerdès, the most severely affected city, showed that in some zones buildings were completely destroyed, while in other zones buildings with similar characteristics suffered only slight damage or none at all (Dunand et al. 2004, Hellel et al. 2010). Furthermore, in Boumerdès, which is characterized by rugged topography, field observations have noted increased damage to buildings, mostly to the mid-rise reinforced concrete (RC) moment-frame systems with four or five stories located on hilltops or close to the edges of steep slopes.

Besides the structural characteristics of the affected buildings and the geological conditions of the bedrock and overlying stratum, topographical features can also play a significant role in the damage distribution resulting from an earthquake. Instrumental and theoretical investigations following several worldwide earthquake events have shown that the amplification potential of ground motion can be strongly influenced by effects generated by the

---

[a] Department of Urban Environment Systems, Graduate School of Engineering, Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan
[b] Built Environment Research Laboratory (LBE), Faculty of Civil Engineering, University of Bab-Ezzouar (USTHB), BP32 El-Alia, Bab-Ezzouar, Algiers 16111, Algeria
[c] National Research Center of Earthquake Engineering (CGS), 1 Rue Kadour Rahim BP 252, Hussein-Dey, Algiers 16040, Algeria

Earthquake Spectra, Volume 28, No. 1, pages 185–216, February 2012; © 2012, Earthquake Engineering Research Institute

topographical features of the site and that these features have a significant influence on damage level (Boore 1972, Ashford et al. 1997, Chávez-García et al. 1997, Gazetas et al. 2002, Havenith et al. 2003, Assimaki et al. 2005, McCrink et al. 2010). More precisely, numerous studies have revealed that damage is more significant in buildings on hilltops, ridges, and steep slopes, indicating the amplification of ground motions at these locations (Ċelebi 1987, Kawase and Aki 1990, Hartzell et al. 1994, Bouchon and Barker 1996, Bouckovalas and Papadimitriou 2005).

In this study, the analysis of the damage distribution following the 2003 Algeria earthquake was conducted considering the aforementioned factors, i.e., the structural characteristics of the buildings, the geological conditions of the bedrock and overlying stratum, and the topographic position of the buildings. To estimate the importance of the possible effects of these factors during the earthquake, a statistical analysis was conducted for each factor individually, and then all the factors were examined simultaneously for a correlation.

For typical Algerian buildings, especially in Boumerdès, the principal parameters considered to have a significant impact on seismic resistance are structural materials, construction category (a building versus a house), and height (low-rise, mid-rise, or high-rise). Accordingly, various building classifications were compared in this study to evaluate their seismic resistance based on the actual damage caused by the earthquake.

Due to a lack of P-S log data in the study area, an examination of the site response for damaged and undamaged zones, considering their geology and strata, was carried out using data from microtremor observations in order to document whether site conditions contributed to the observed damage. In addition, a statistical analysis of the topographical features of Boumerdès in relation to the damaged and undamaged buildings was carried out. Supported by field observations and using a digital elevation model (DEM) with cell dimensions of 15 m^2 extracted from satellite imagery from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), the topography of the city was simplified into three possible terrains: small hilltops, steep slopes, and flat ground. Furthermore, the resulting free-field microtremor measurements were also considered with respect to topographic features.

THE 2003 ALGERIA EARTHQUAKE

Historically, the northern part of Algeria has suffered a large number of seismic events. Some recent examples are the September 1954 Orleansville earthquake ($M_s = 6.7$), which caused over 1,200 deaths and damaged over 20,000 buildings, and the October 1980 El-Asnam earthquake ($M_s = 7.2$), which caused over 2,640 deaths and damaged more than 20,000 buildings.

The Algerian Council of Ministers reported that the 2003 earthquake caused 2,278 deaths and 11,450 injuries, and left an estimated 250,000 people (i.e., about 40,000 families) homeless (DLEP 2004). In terms of building damage evaluation, the Ministry of Housing conducted a damage assessment mission the week after the earthquake, covering all affected areas in the provinces of Boumerdès and Algiers (Belazougui 2008b). This mission, which lasted until 30 June 2003, employed five levels of damage classification that corresponded very closely to the European Seismological Commission's guidelines, EMS-98 (ESC 1998), ranging from none/slight damage (Grade 1) to very heavy damage/collapsed (Grade 5), as presented in Table 1. Accordingly, 17,000 structures were demolished and 116,000 were repaired. The resulting direct economic loss was estimated to be U.S. $5 billion (Ousalem and Bechtoula 2005).

In terms of seismology, the epicentre of the main shock, which was felt within a 250-km radius from the epicenter (Laouami et al. 2006), was at 36.91° N and 3.58° E, as provided by the Algerian Research Center of Astronomy, Astrophysics, and Geophysics (CRAAG). However, Bounif et al. (2004) determined that the epicenter was at 36.83° N and 3.65° E (Figure 1), at a depth of 8 to 10 km. The rectangle in Figure 1 shows the focal plane projected to the surface, as proposed by Delouis et al. (2004). The source model runs for an eastern distance of 55 km (3.4°–4.0°E). According to Meghraoui et al. (2004), the model fault (reverse-faulting mechanism) has a strike of 54° to the northeast and a dip of 50° to the southeast, and it extends 1 to 15 km below the ground surface.

AREA OF STUDY: BOUMERDÈS

The city of Boumerdès is the capital of Boumerdès Province, located in the north-central part of Algeria, about 50 km east of Algiers along the Mediterranean coast. Its previous name, before Algerian independence in 1962, was *Rocher Noir*, which, translated from French, means Black Rock. The city of Boumerdès became the capital of the province of the same name as a result of an administrative division that took place in 1984. In 1998, the population was estimated to be 33,646 inhabitants. Figure 2 shows the location and administrative boundaries of the city of Boumerdès. The urban area is concentrated in the western part of the city. The eastern part of the city is mainly agricultural land. A high-resolution satellite image captured by QuickBird (DigitalGlobe 2003) on 23 May 2003, with a spatial resolution of 0.6 m, shows the urbanized area of Boumerdès (Figure 2).

In Boumerdès, 1,382 people were killed and 3,442 were injured in the 2003 earthquake. Based on the results of a macroseismic survey conducted by CRAAG, Boumerdès, which is located at a hypocentral distance of 21 km from the causative fault, was estimated to have an intensity of X according to EMS-98 (Harbi et al. 2007).

The only seismic station in Boumerdès could not record the main shock because it was out of order as a result of instrumental/technical problems during the event, as was later

Table 1. Damage grades for buildings according to a damage survey conducted by CGS following the 2003 Boumerdès earthquake

Damage	Description
Grade 1	None or negligible-to-slight damage to nonstructural elements, and no damage to structural elements
Grade 2	Moderate-to-slight damage to nonstructural elements, and slight damage to structural elements
Grade 3	Heavy-to-slight damage to nonstructural elements, and moderate damage to structural elements
Grade 4	Very heavy-to-slight damage to nonstructural elements, and heavy damage to structural elements
Grade 5	Very heavy structural damage, with part of building collapsed, or total collapse

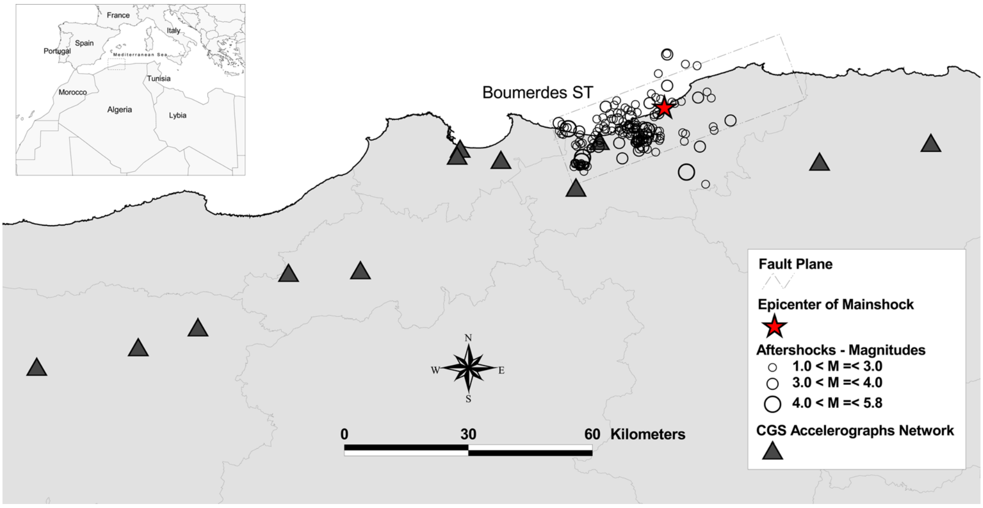


Figure 1. The epicentral area and the epicenter of the main shock (star) of the 2003 Algeria earthquake. The rectangle represents the estimated fault plane (reverse-faulting mechanism). The graduated circles correspond to the 167 aftershocks between May 25 and May 30. The triangles represent the CGS accelerograph network stations located in the central part of northern Algeria (Meslem et al. 2010).

stated by the Algerian National Research Center for Earthquake Engineering (CGS). But the main shock was soon followed by many aftershocks, which were mostly observed by the Boumerdès station (Figure 1). Table 2 shows the ten largest peak ground acceleration (PGA) and peak ground velocity (PGV) values for the aftershocks recorded by the Boumerdès station. The strongest aftershock was recorded on 27 May 2003 at 17:11:40 GMT ($M_s = 5.8$) at 36.78° N, 3.60° E with a PGA of 441.5 cm/s^2 and a PGV of 23.6 cm/s. The results of a study conducted by Meslem et al. (2010) on the impact of the local site effects on the values recorded by the Boumerdès station have shown the presence of firm deposits in the soil layers under the station. The resulting H/V spectral ratio curves from seismic-motion dataset of the 2003 Algeria earthquake showed insignificant shifts in amplitude for different levels of excitation. In addition to the Boumerdès station, the study looked at several other stations selected from different cities located along the fault trace. Details of the methodology used and the results obtained can be found in Meslem et al. (2010).

FACTORS INFLUENCING DAMAGE DISTRIBUTION

BUILDING STRUCTURAL CHARACTERISTICS

In Algeria, masonry was the predominant form of construction during the first half of the 20th century. After the 1960s, the construction of RC moment frames (consisting of columns and beams) with unreinforced hollow brick infill walls and RC shear walls became more typical (Benouar and Meslem 2007). According to data collected for this study, the total number of buildings in Boumerdès before the earthquake was 2,794. Ninety-two percent were RC structures built between 1969 and 2003. The existing masonry buildings

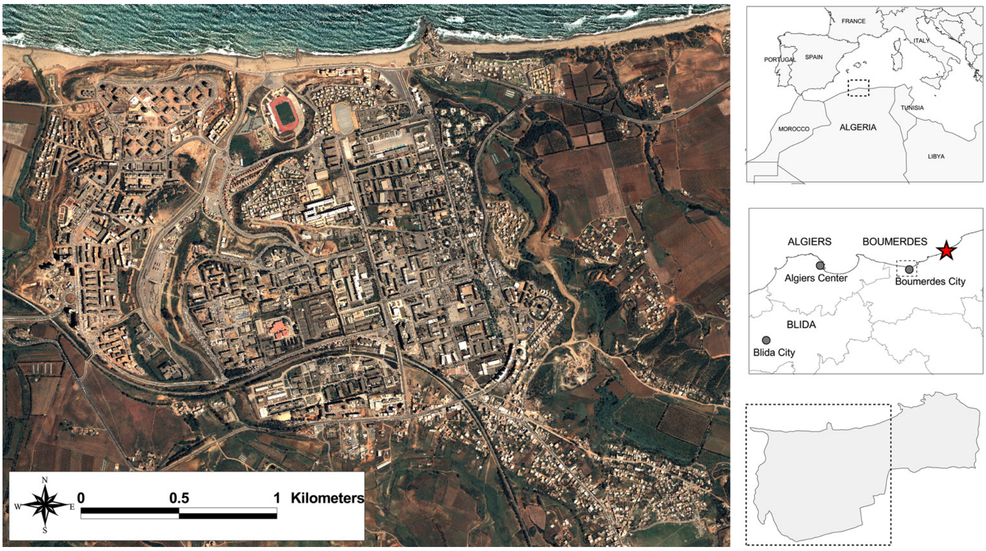


Figure 2. Location and QuickBird satellite image of Boumerdès. The red star indicates the epicenter of the main shock of the 2003 Algeria earthquake.

were built before 1962 and represented only a small fraction (4%) of the total. There were very few steel or wooden buildings (2% and 1%, respectively), and these were mostly for industrial use. Figure 3 shows the distribution by material type from geographic information system (GIS) data for the 2,794 buildings in Boumerdès before the earthquake. In this study, only RC structures will be considered because the number of buildings in the study area constructed using other materials is almost negligible.

Before the 2003 earthquake, the existing seismic design codes in Algeria were only required to be applied to public buildings, and not to private houses. In fact, most private houses were built without following any seismic code or using any quality control measures, and are therefore generally considered to be nonengineered buildings. Soft stories, undersized sections, insufficient longitudinal reinforcement, and weak concrete strength have been shown to be the cause of the majority of earthquake damage in nonengineered buildings (Belazougui 2008b). In response to this situation, beginning in September 2004, all newly built private houses were, for the first time, required to comply to seismic design codes in order to obtain building insurance.

Before the earthquake in Boumerdès, 43% (1,097) of the RC structures were publically owned buildings for residential use, industrial or commercial activities, offices, education, etc. The number of stories in this type of RC building ranged from one to ten. In this study, RC buildings were divided by height into three classes: low-rise (buildings with one to three stories), which represented 30% of the total (332 buildings); mid-rise (buildings with four to six stories), which represented 61% of the total (663 buildings); and high-rise (buildings with seven or more stories), which represented the remaining 9%.

Table 2. Ten largest peak ground acceleration and velocity values of seismic motions recorded by Boumerdès station during the 2003 Algeria earthquake.

					Acceleration (cm/s^2)			Velocity (cm/s)		
Date	Time (GMT)	Depth (km)	Magnitude	Epicentral Distance (km)	PGA NS	PGA EW	PGA Resultant	PGV NS	PGV EW	PGV Resultant
27/05/2003	17:11:40(*)	9.4	5.8	12.1	288.8	397.61	441.5	17.38	16.11	23.59
27/05/2003	17:33:34	5.5	3.8	9.7	38.84	52.49	65.29	0.66	1.23	1.36
28/05/2003	06:58:44	10.3	5.2	8.1	61.91	49.45	61.92	1.30	1.86	1.90
29/05/2003	02:15:07(*)	7.4	5.8	5.1	257.08	310.61	310.88	9.68	11.96	12.23
02/06/2003	08:20:25	-	3.6	7.8	64.23	46.28	64.31	1.43	0.85	1.44
21/07/2003	11:36:13	-	3.7	19.7	61.44	83.89	93.67	1.08	1.10	1.32
11/08/2003	20:03:53(*)	-	3.6	12.0	87.85	119.67	125.95	1.75	2.42	2.44
10/01/2004	18:38:15(*)	-	4.5	12.0	238.55	560.05	575.53	6.68	15.92	16.75
01/12/2004	17:42:49(*)	-	4.5	11.2	285.78	378.27	405.89	8.25	6.79	9.23
05/12/2004	08:31:24(*)	-	4.5	14.1	290.07	370.13	413.94	7.14	6.45	8.77

[*] records considered for computing the average of the H/V ratios for seismic motions in Figure 10.

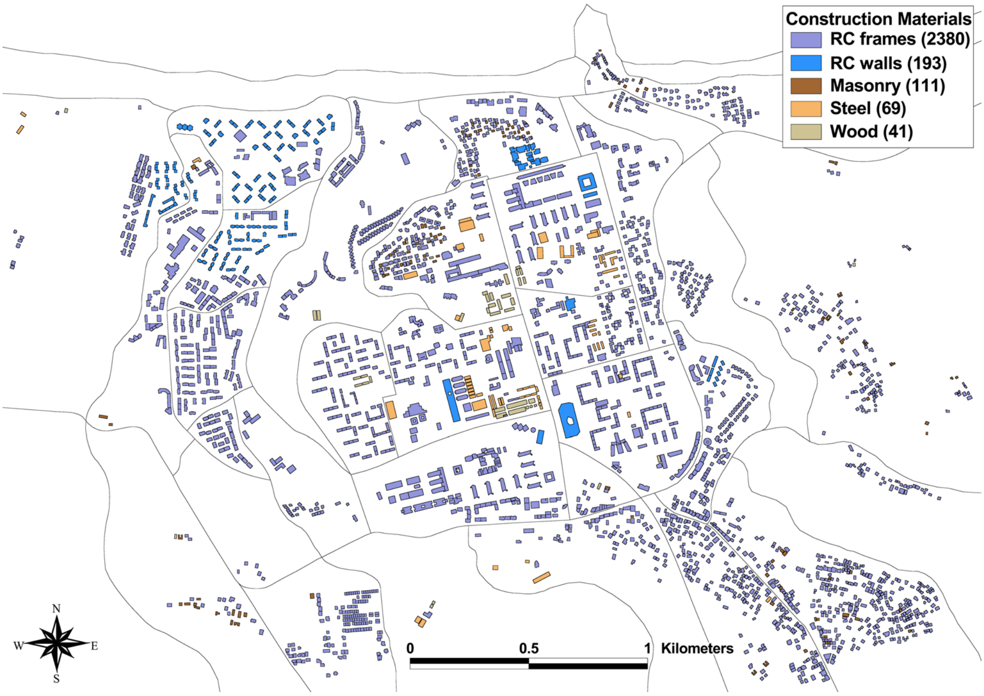


Figure 3. Distribution of buildings by material type in Boumerdès.

The other 57% (1,476) of the RC structures in Boumerdès were privately owned houses for residential use, some of which housed commercial activities (shops) on the ground floor. These houses ranged from one to three stories.

SEISMIC DESIGN CODES

Until the 1980s, there was no official seismic design code for building construction in Algeria. Only guidelines and recommendations for the design of buildings had been introduced up until that point, for example, Règles Anti-Sismiques in 1955: AS55, Règles Para-Sismique in 1962: PS62, and in 1969: PS69 (Belazougui 2008a). In 1972, the government established the Organization for Construction Technology Control (CTC) for the inspection of public buildings. In 1981, with international help, particularly from Stanford University in the United States, the first official Algerian seismic design code, Règles Parasismiques Algériennes: RPA81 (CTC 1981), was published. The document consists of four main parts: definitions and technical rules, seismic zoning and soil categories, constructions grading and process, and finally, computation methods and safety validations. Revisions were made based on further research and lessons learned from earthquake events in Algeria and abroad, resulting in a subsequent version, RPA83, which was published in 1983 (CTC 1983). After the establishment of the Algerian National Research Centre of Earthquake Engineering (CGS) in 1987 these efforts underwent a second revision in 1988 (CGS 1988) and a third in 1999 (CGS 1999). The version published in 1999 was the last version to be published before the 2003 earthquake.

Table 3 presents a summary of applied seismic design loads for existing buildings in Boumerdès for the seismic design codes RPA81 (revised in 1983), RPA88, and RPA99. In all three versions, there were three seismic zones: Zone I (low seismicity), Zone II (moderate seismicity), and Zone III (high seismicity), as well as Zone 0 (no seismicity) in the desert. Boumerdès city had always been classified as Zone II, with 0.15 g as the PGA for the design of apartment buildings. All three versions of the code specified a minimum column size of 25 cm for RC structures in Zone II. RPA83 specified that the main reinforcing bars must constitute a minimum of 1% of the total cross-sectional area of columns. This was changed to 0.8% in RPA88 and RPA99. In all versions published before the earthquake, 15 cm was specified as the minimum interval of hoop reinforcing at the top and bottom of columns for buildings in Zone II. Figure 4 shows photographs and plan views of typical buildings with RC moment-frame and shear-wall systems in Boumerdès. After the 2003 earthquake, RPA99 was revised and the new seismic design code, RPA99'03 (CGS 2003), was published. In this version of the code the city of Boumerdès was upgraded to Zone III, with 0.25 g as the PGA for the design of apartment buildings. Table 3 shows a comparison between earlier versions of the seismic code and RPA99'03. As mentioned previously, in this new version, application of the seismic design code became obligatory for private house owners.

DAMAGE-RESISTANCE CLASSIFICATION

A comparison of the various seismic codes does not show any important differences regarding the damage-resistance characteristics of RC structures located in Zone II. Therefore, in the first stage, we assume that the version of the seismic code used does not have much of an effect on the damage distribution observed in RC buildings in Boumerdès after the earthquake. Based on this assumption and the background information provided in the previous section on Algerian building characteristics, our examination of the distribution of observed damage takes the following points into account: (a) differentiate between houses and buildings as a variable parameter for RC structures, since they may respond differently under the same seismic excitation, and (b) consider the height classes for RC buildings in the examination of the damage distribution. As mentioned before, all the existing RC houses were low-rise structures. Figure 5 shows the final classification of RC structures according to their categories and height classes.

LOCAL SITE CONDITIONS

H/V SPECTRAL RATIOS

To estimate the site effects resulting from the geological conditions of bedrock and overlying stratum, Nakamura (1989) proposed a well-known horizontal-to-vertical (H/V) spectral ratio technique, which uses the ratio of the horizontal and vertical Fourier spectra of microtremors recorded at a site, as soil profiles and PS logging data are not always available. Several researchers have attempted to apply this technique to earthquake records (Yamazaki and Ansary 1997, Rodriguez and Midorikawa 2003).

In this technique, two period parameters are generally evaluated: the fundamental period and the predominant period. The fundamental period (or natural period) corresponds to the

Table 3. Summary of design loads for RC buildings as recommended by Algerian seismic codes for different time periods according to seismic zoning of Boumerdès

Years	Code	Static Seismic Load: V	Zone	Acceleration Coefficient: A	Dynamic Amplification Factor: D	
1983–1988	RPA83	$V = ADBQW$	II	Group1: 0.25 Group2: 0.15 Group3: 0.10	$D = \begin{cases} 2 & 0 \le T \le 0.3 \\ 2\sqrt{0.3/T} & 0.3 \le T \le 2.0 \end{cases}$ (Firm) $D = \begin{cases} 2 & 0 \le T \le 0.5 \\ 2\sqrt{0.5/T} & 0.5 \le T \le 2.0 \end{cases}$ (Soft)	Period for max value of D $(=2)$ for Firm: $0 < T < 0.3$ for Soft: $0 < T < 0.5$
1988–1999	RPA88	$V = ADBQW$	II	Group1: 0.25 Group2: 0.15 Group3: 0.10	$D = \begin{cases} 2 & 0 \le T \le 0.3 \\ 0.896/\sqrt[3]{T^2} & 0.3 \le T \le 2.0 \end{cases}$ (Firm) $D = \begin{cases} 2 & 0 \le T \le 0.5 \\ 1.260/\sqrt[3]{T^2} & 0.5 \le T \le 2.0 \end{cases}$ (Soft)	Period for max value of D $(=2)$ for Firm: $0 < T < 0.3$ for Soft: $0 < T < 0.5$
1999–2003	RPA99	$V = (ADQ/R)W$	II	Group1A: 0.25 Group1B: 0.20 Group2: 0.15 Group3: 0.1	$D = \begin{cases} 2.5\eta 0 \le T \le T_2 \\ 2.5\eta(T_2/T)^{2/3} T_2 \le T \le 3.0 \\ 2.5\eta(T_2/3.0)^{2/3}(3.0/T)^{5/3}\mathrm{T} \ge 3.0 \end{cases}$	Period for max value of D $(= 2.5)$ for S1: $0 < T < 0.3$ ($T_2 = 0.3$ s) for S2: $0 < T < 0.4$ ($T_2 = 0.4$ s) for S3: $0 < T < 0.5$ ($T_2 = 0.5$ s) for S4: $0 < T < 0.7$ ($T_2 = 0.7$ s)
2003– present	RPA99'03	$V = (ADQ/R)W$	III	Group1A: 0.40 Group1B: 0.30 Group2: 0.25 Group3: 0.18	$D = \begin{cases} 2.5\eta 0 \le T \le T_2 \\ 2.5\eta(T_2/T)^{2/3} T_2 \le T \le 3.0 \\ 2.5\eta(T_2/3.0)^{2/3}(3.0/T)^{5/3}\mathrm{T} \ge 3.0 \end{cases}$	Period for max value of D $(= 2.5)$ for S1: $0 < T < 0.3$ ($T_2 = 0.3$ s) for S2: $0 < T < 0.4$ ($T_2 = 0.4$ s) for S3: $0 < T < 0.5$ ($T_2 = 0.5$ s) for S4: $0 < T < 0.7$ ($T_2 = 0.7$ s)

Table 3. *Continued.*

Years	Code	Static Seismic Load: V	Zone	Acceleration Coefficient: A	Dynamic Amplification Factor: D

where

V: total static seismic load
A: zone acceleration coefficient
W: total weight of the structure
Classification of construction:
Group 1A: vital importance
Group 1B: high importance
Group 2: moderate importance
Group 3: low importance

Q: quality factor $Q = 1 + \Sigma P$ (P: penalty)
R: behavior factor
B: structural component factor
T: natural period in s.
T_2: period associated to site category
η: correction factor of damping ($\eta = 1$ for damp. of 5%)

Classification of soil
S1: rocky
S2: firm
S3: soft
S4: very soft

Figure 4. Photographs and plan views of reinforced concrete (RC) systems (moment-frame and shear-wall systems) in Boumerdès. (For Zones 1A, 1B, and 2, see Figure 6): (a) RC moment-frame system for a four-story building built in Zone 1A in 1996, (b) RC moment-frame system for a five-story building built in Zone 1B in 1970, and (c) RC shear-wall system for a five-story building built in Zone 2 in 1986.

first mode of vibration of the soil system, and has been used by several authors as a microzoning parameter (Bour et al. 1998, Chávez-García and Cuenca 1998). The predominant period, which is defined as the period in which the maximum soil amplification (the highest peak amplitude of the H/V ratio curve) occurs, is used as a significant parameter in the assessment of building damage (Fallahi et al. 2003, Gosar 2007, Chatelain et al. 2008). Several authors have shown the dependent relationship between building damage and the correspondence between the natural period of buildings and the predominant period of the soil layers (Cranswick et al. 2000, Navarro et al. 2000 and 2008, Bakir et al. 2002, Oliveira et al. 2006, Motamed et al. 2007).

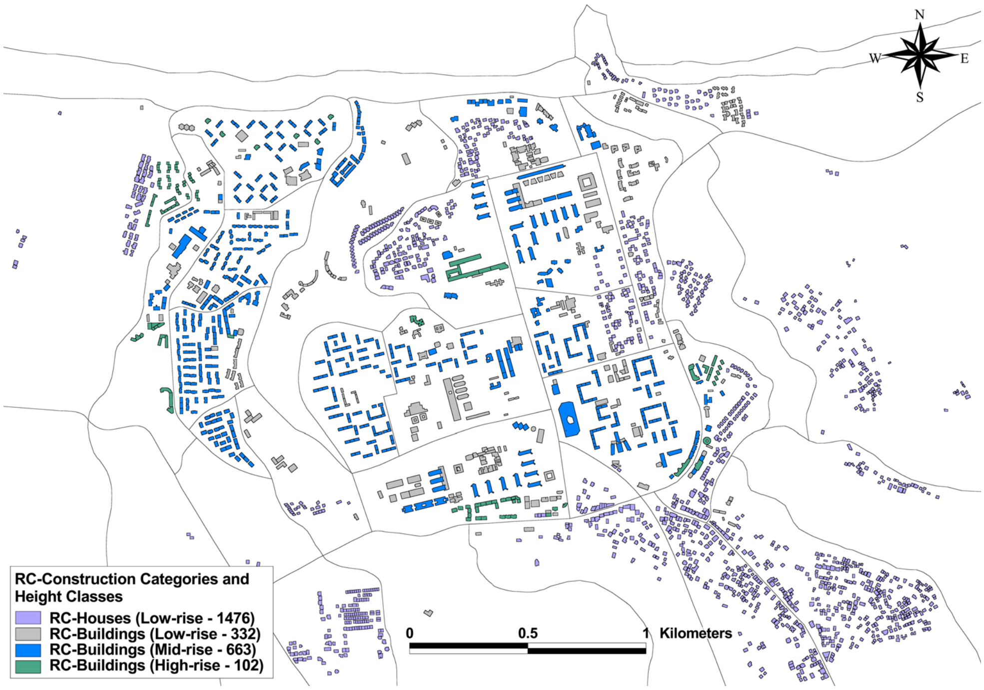


Figure 5. RC construction classification by categories and height classes in Boumerdès.

As mentioned earlier, for our area of study the main shock was not recorded; however, many strong aftershocks were recorded. The city of Boumerdès is located just above the source plane, thus the ground motion was very intense.

We calculated the H/V Fourier spectral ratio for six seismic records, selected from Table 2, as the spectral ratio between the two horizontal components (*EW* and *NS*) and the vertical (*UD*) component, defined by:

$$R(f) = \frac{\sqrt{F_{NS}(f) \cdot F_{EW}(f)}}{F_{UD}(f)} \qquad (1)$$

where $F_{NS}(f)$, $F_{EW}(f)$, and $F_{UD}(f)$ are the smoothed Fourier amplitude spectra for the two horizontal components and the and vertical component, respectively. These Fourier spectra were smoothed by a Parzen window with a bandwidth of 0.4 Hz (Ansary et al. 1995, Tuladhar et al. 2004, Shimizu et al. 2009).

In addition, and to better correlate the observed damage distribution with structural characteristics by taking the actual site conditions into account, the authors conducted 16 free-field microtremor measurements at several locations in Boumerdès (Figure 6). The locations of measurements were chosen by taking into account the characteristics of the targeted group of structures, the observed damage, and the topography of the location. One measurement was taken in almost each district. Geophysical data acquisition system

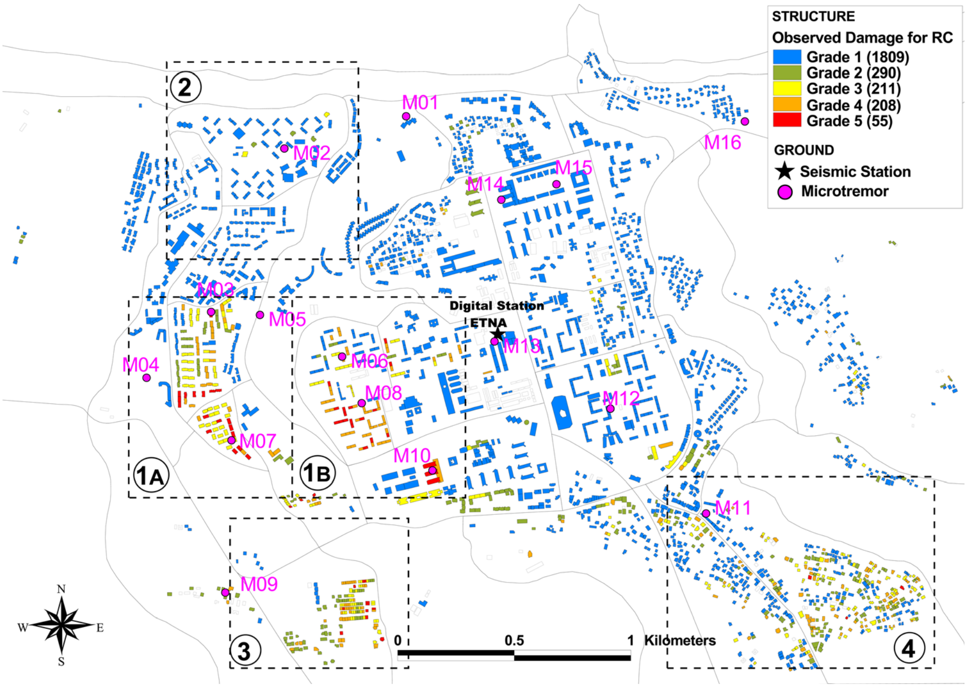


Figure 6. GIS damage distribution map of RC structures in Boumerdès after the 2003 Algeria earthquake, including the locations of microtremor measurements on the ground surface. The star indicates the location of the seismic station (digital station ETNA). B1 and B2 are two three-story RC buildings that have the same structural configuration and are located within 1 km of each other (see Figure 11).

(GEODAS) portable microtremor equipment, made by Butan Service Co. (Japan), was used for data acquisition (Figure 7). The sensor used for the measurements produces an output voltage proportional to velocity and can measure three components of vibration: two horizontal and one vertical. The sensor has a natural period of 2 s, and its frequency response range is between 0.5 and 20 Hz. The sampling frequency set for all measurements was 100 Hz, and 50 Hz was set as the low-pass filter. The duration of a single microtremor observation was set at 5 min, and the record was divided into six segments, each lasting 50 s, to calculate an average H/V spectral ratio using a smoothing method similar to that described earlier (Lu et al. 1992, Ansary et al. 1995, Arai et al. 2000, Tuladhar et al. 2004, Shimizu et al. 2009).

TOPOGRAPHICAL FEATURES

It is well-known that topographical features can be a source of site effects that have a considerable influence on the frequency and amplitude characteristics of earthquake ground motions, and thus on the extent of local structural earthquake damage. However, in engineering practice this factor received only minor attention for a long time.

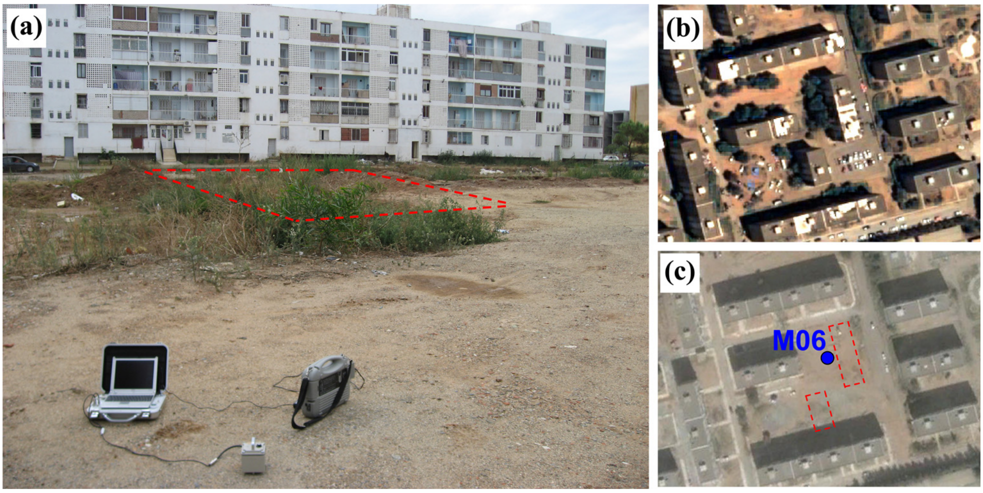


Figure 7. Example of microtremor measurement at locations of heavily damaged buildings in the city of Boumerdès: (a) photograph showing location of removed building (red dashed line) and location of portable microtremor equipment (GEODAS and sensor) used for data acquisition at M06, (b) QuickBird image (23 May 2003) showing damaged buildings, and (c) image from Google (20 March 2006) showing removed buildings (red dashed line) and location of microtremor measurements (M06).

For the case of the 2003 earthquake in Boumerdès, this study considered the topography of different locations in the city to examine possible links between damage rates and topographical effects. As seen from the QuickBird image in Figure 2 (see also Figure 15), the city of Boumerdès is crossed by three rivers—the Boumerdès River, the Tatarreg River, and the Corso River—which flow toward the Mediterranean Sea in a mainly south–north direction. This leads to rugged topography that has left its mark on the urbanization of the city. According to field observations, the topographic features of the city include three possible terrain situations: small hilltops, steep slopes, and flat ground. In general, the small hilltops and steep slopes are observed along the rivers. Along the Tatarreg River, the existing buildings on hilltops and steep slopes were mostly mid-rise RC buildings. Along the Boumerdès River, the existing structures were mostly low-rise RC houses. The buildings were more varied at the locations on the flat ground between the Tatarreg and Boumerdès rivers. Some areas on the flat locations were characterized by small inclines to the north.

RESULTS

EFFECTS OF STRUCTURAL CHARACTERISTICS

Figure 8 shows the extent of damage in terms of both RC structure classification and year of construction. Of the total number of RC buildings, most of which (107 units) were buildings of mid-rise height (four to five stories), 10.21% (112 units) suffered Grade 4 or 5 damage (collapsed, very heavily damaged, or building rendered unusable). Only a few RC buildings (five units) of low-rise height (one to three stories) suffered damage at the Grade

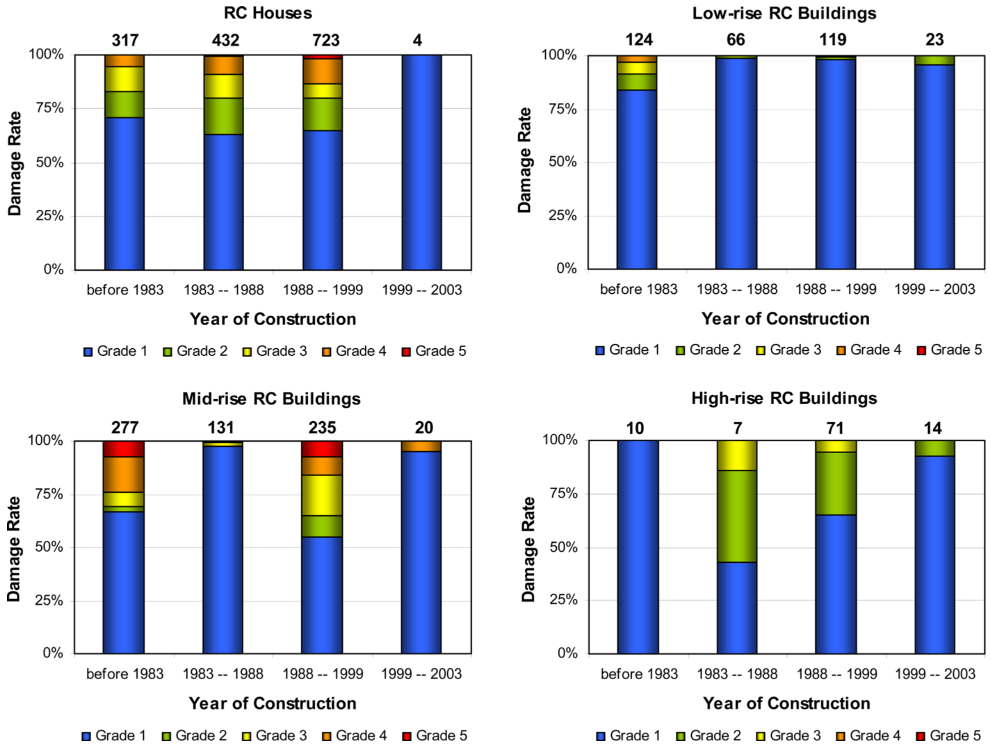


Figure 8. Damage rate in relation to year of construction for different types of RC structures at the time of the earthquake.

4 level, while no heavy damage was observed for high-rise RC buildings. Of the total number of RC houses, most of which were three stories high, 10.23% (151 units) suffered Grade 4 or 5 damage. Furthermore, it can be observed from Figure 8 that the correlation between the damage rate and the year of construction (which reflects the version of the seismic code that was applicable at that time) suggests that the damage distribution was not strongly influenced by the version of the seismic code in use at the time of construction. For the type of structure which suffered the most extensive damage, RC buildings of mid-rise height, there is almost no correlation between the damage rate and the year of construction. The same can be said of the RC houses in the study area.

The damage distribution (Figure 6) shows that in the southwestern part of the city (Zones 1A and 1B), where most of the buildings were of mid-rise height (Figure 5), the damage was extensive. There were very few low-rise buildings and almost no high-rise buildings in this area. From Figure 8 it can be clearly seen that there was a higher rate of damage for mid-rise buildings as compared to low-rise and high-rise buildings. Furthermore, not far from Zone 1, in Zone 3, in the southwestern part of the city, where the majority of the buildings were newly built three-story houses, the damage was also extensive. In contrast, in Zone 4, in the southeastern part of the urbanized area, where almost all the existing buildings were single, nonengineered, one- to three-story houses (Figure 5), only some houses were damaged, and the damage was not spread evenly throughout the entire zone. Analysis of the damaged houses in this zone shows that the damage was a result of poor design in terms of seismic resistance, and the poor quality of construction and structural materials used. More specifically, the concrete used was of a very low strength (an average of 14 to 17 MPa, as opposed to 25 MPa, which is the strength required by the current standards), and the concrete in the columns was inadequately poured.

EFFECTS OF SITE CONDITIONS FROM LOCAL SUBSOIL

Figure 9 shows the H/V spectral ratios for the six selected seismic records and the computed average. The resulting H/V spectral ratios for different PGA levels have similar shapes; they have large amplitude ratios at the periods between 0.1 and 0.2 s, but the peaks are not so clear. There is the presence of noise, including fluctuation around these unclear peaks. The measured H/V ratio curves of the microtremor measurements from several locations across the city (Figure 6) exhibit certain differences that could reflect variations in local site conditions (Figure 10). The shape of the H/V ratio curves are unclear or smoothed at some sites, while at other sites the resulting H/V ratio curves have clear, medium-to-small peaks. At position M13, which is the site of the seismic station, the shape of the H/V ratio curve is different to the shape computed from the seismic records; however, both computations show unclear-to-smoothed peaks. As mentioned earlier, the presence of firm deposits in the soil layers under the Boumerdès seismic station is assumed since the resulting H/V spectral ratio curves from the seismic-motion dataset of the 2003 Algeria earthquake showed insignificant shifts in amplitude for different levels of excitation (Meslem et al. 2010). Only 600 m from the seismic station (Figure 6), the damage was very extensive; several RC buildings collapsed and others were heavily damaged.

As a case study, we selected two three-story RC buildings, B1 and B2 (Figure 11), that have the same structural configurations but are located on two different campuses of the University of Boumerdès within around 1 km of each other (Figure 6). Building B1, located

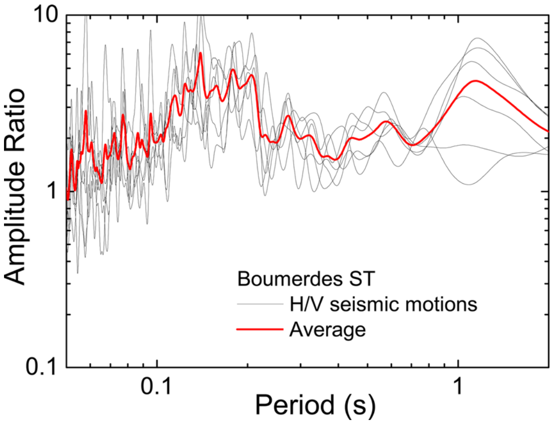
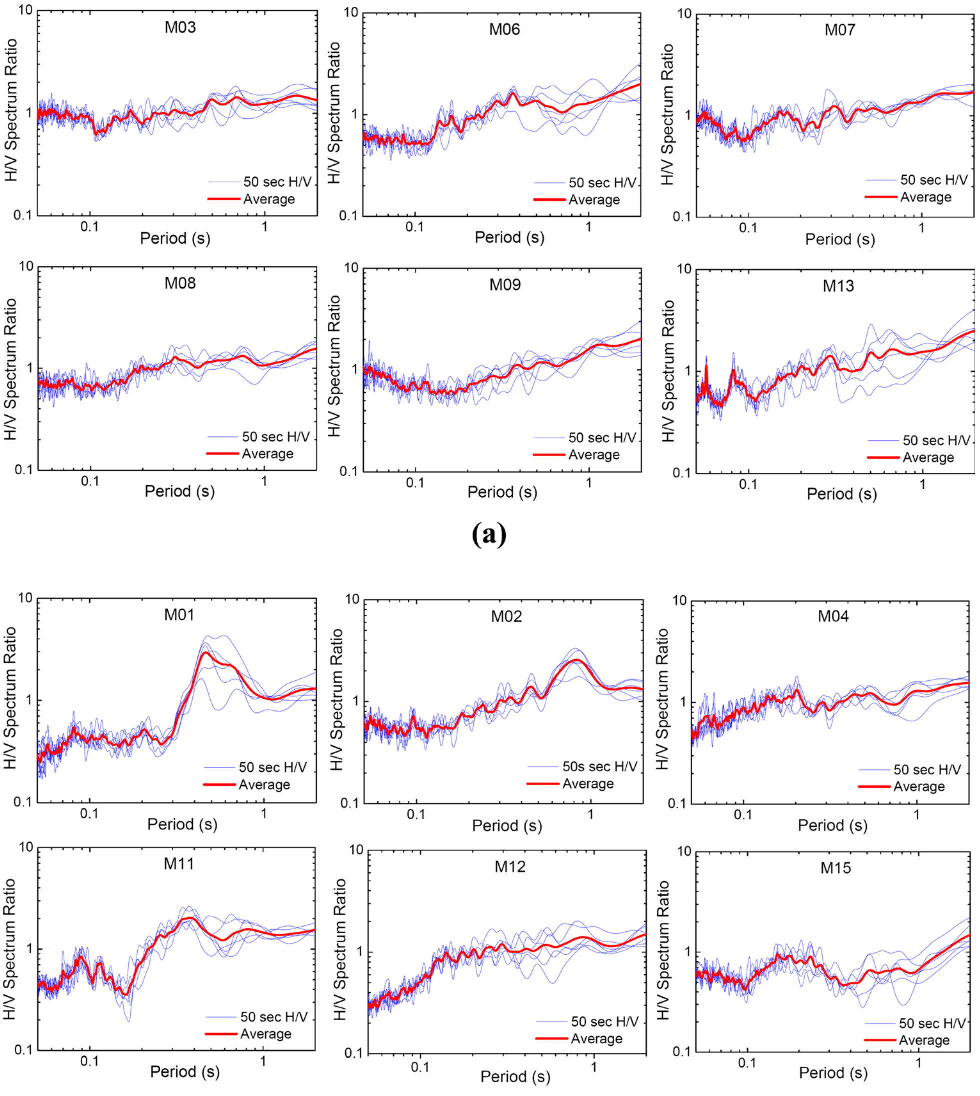


Figure 9. Average of six selected H/V spectral ratios for aftershock motion (thick red line) recorded by Boumerdès seismic station.



(a)

(b)

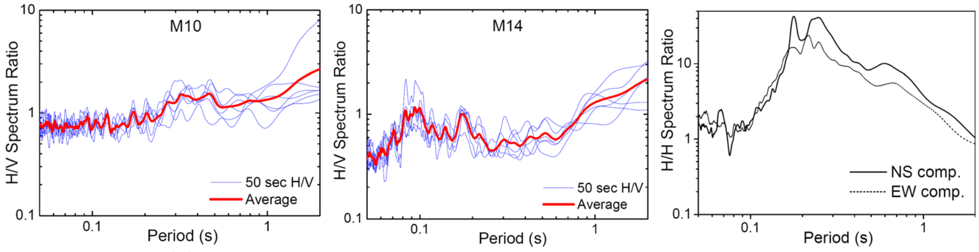
Figure 10. Averaged H/V Fourier spectral ratios of microtremors computed from six 50-s segments recorded at each location: (a) H/V spectral characteristics at several sites of heavy damage in Boumerdès, and (b) H/V spectral characteristics at several sites with no damage or only slight damage in Boumerdès.

on the south campus within Zone 1B, collapsed completely during the earthquake. Building B2, located on the north campus, did not suffer any damage. A comparison of the H/V ratios of microtremor measurements close to Building B1, the one that collapsed, at position M10 (Figure 12a), with those measured close to Building B2, the undamaged building, at position M14 (Figure 12b), shows no clear difference with regard to the effects of

Figure 11. Example of two three-story RC buildings with the same structural characteristics located in two different zones in Boumerdès within approximately 1 km of each other (see Figure 6). B1 is located on the south campus of Boumerdès University, whereas B2 is located on the north campus.

amplification and no clear peaks in the H/V curves. In fact, microtremor measurements between Building B2 and the soil of position M14 were conducted simultaneously to ensure the consistency of the measurements and to identify the natural period of the building and the predominant period of the soil layers. The computed H/H Fourier spectral ratio between Building B2 and the ground surface of M14 (Figure 12c) shows an expected predominant period of around 0.2 s, which is the fundamental period for a three-story building.

Recently, complementary results from extensive microtremor measurements have been presented in a study by Hellel et al. (2010) that was conducted in the same area as the present study. However, this extensive field survey did not cover those locations where almost all the existing structures were single houses, for example Zones 3 and 4. Figure 13 shows 2-D presentations of 260 H/V ratios from Hellel et al. (2010) incorporated with microtremor



(a) **(b)** **(c)**

Figure 12. Analysis of possible amplification effect for three-story RC buildings: (a) measured H/V ratio on the ground surface where B1 collapsed, (b) measured H/V ratio on the ground surface close to B2, and (c) H/H Fourier spectral ratio between building B2 and ground surface M14.

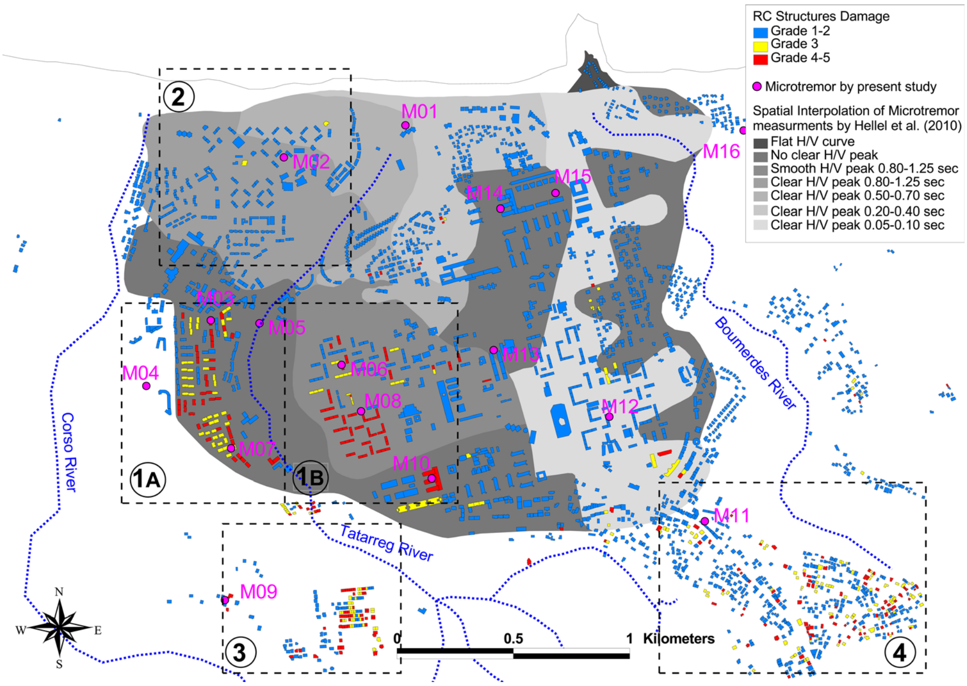


Figure 13. Spatial interpolation of 260 H/V peak ratios from microtremor measurements (modified from Hellel et al. 2010), location of 16 microtremor measurements by the authors, and building damage distribution in the city of Boumerdès.

measurements by the present authors and the building damage distribution for the city of Boumerdès. The microtremor measurements by the present authors match quite well with the detailed H/V ratio-based site mapping provided by Hellel et al. (2010). As shown in Figures 10 and 13, both studies come to the same conclusion: All the H/V ratios measured for sites that sustained heavy damage were characterized by unclear results; however, the H/V ratio curves showed more variation in shape at the sites that sustained no damage or only slight damage.

Considering the damage rate with respect to site conditions, mid-rise RC moment-frame buildings comprise almost the only group with a large sample size (see Figures 4, 5 and 13). The damage rate for RC houses (moment-frame systems) was also remarkably high, but extensive microtremor measurements were not available for the areas where they were most strongly affected, i.e., Zones 3 and 4 (Figure 13). Figure 14 shows the damage rate with respect to site conditions from microtremors for mid-rise RC moment-frame buildings. For this type of building, which has a natural period ranging between 0.28 and 0.35 s, there is a pronounced increase in the damage rate for locations with site conditions showing no clear results or smoothed H/V ratios; however, the damage rate was slight or almost insignificant for sites showing clear H/V ratio peaks ranging from 0.05 to 1.25 s.

In fact, for Zone 1A in the southwestern part of the city, the H/V ratios showed no clear results (Figures 10a and 13); however, this zone suffered very extensive damage, with

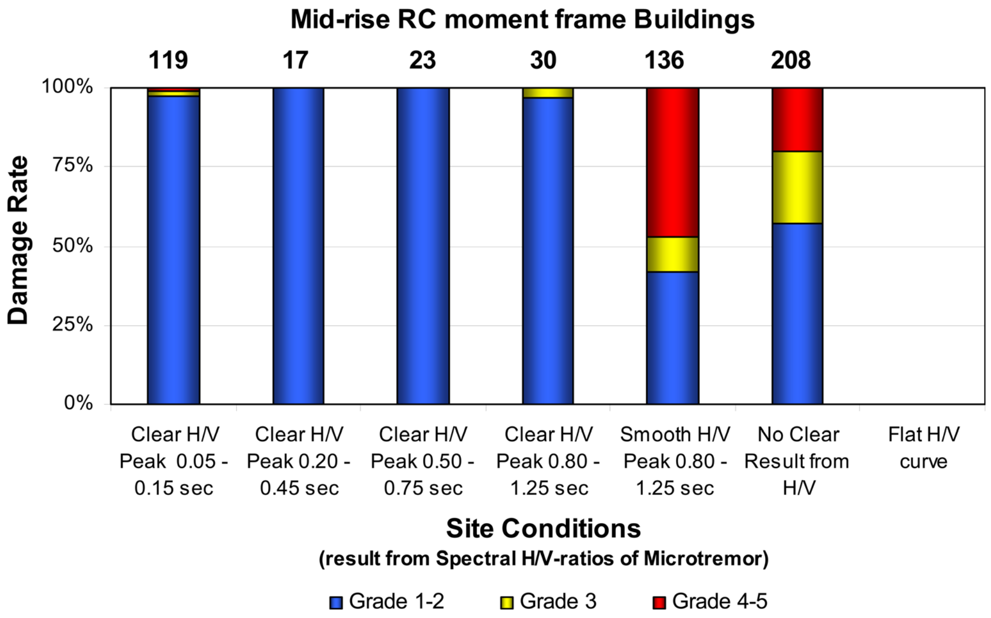


Figure 14. Damage rate for mid-rise RC moment-frame buildings with respect to the site conditions in the city. Large numbers of this building type were located at sites that presented smoothed-to-unclear results of spectral H/V ratios of ambient noise. The buildings located at sites with smoothed H/V ratios were five stories and were built in 1970 (Figure 4b), and those located at sites with unclear H/V ratios were four stories and were built in 1996 (Figure 4a).

several mid-rise (four-story) RC moment-frame buildings (Figure 4a shows details of the plan view for this category of buildings in Zones 1A) suffering heavy damage or collapsing. In Zone 1B, the H/V ratios showed smoothed peaks estimated to be in the range of 0.8 to 1.25 s. In this zone, a significant number of mid-rise (five-story) RC moment-frame buildings collapsed and others were heavily damaged (Figure 4b shows details of the plan view for this category of buildings in Zones 1B). The natural period measured for several buildings in this class showed values ranging between 0.28 and 0.35 s (Dunand et al. 2004); these values are quite different to the estimated soil period range. The existing soil conditions report, dated from 1970 (Scandinavian Engineering Corporation 1970), states that in this part of city, which includes Zones 1A and 1B, the geological layers are composed of granulitic mica schist formations (hard soil) as the base, which can be seen on the surface in some locations in Zone 1A. These formations are overlain by preconsolidated lower Pliocene marl (hard-to-stiff soil).

Not far from Zone 1A, in Zone 3, where damage was also extensive and several three-story houses (RC frame systems) collapsed, the H/V ratios measured for the site at M09 showed unclear results, similar to those seen in Zone 1A.

At the sites that sustained no damage or only slight damage, which correspond to the northern and southeastern parts of the city, Zone 2 and Zone 4, respectively, the H/V ratios showed more variation in shape, as can be seen in Figures 10b and 13. In Zone 2, in the northern part of the city, the preconsolidated lower Pliocene marl is likely overlain by red sands, recent clays, beach sands, and Quaternary dune sands (soft deposits); the H/V ratios showed clear peaks in the range between 0.5 and 1.25 s, with the latter having a lower amplitude. In this location, RC shear-wall systems constituted the majority of the existing buildings. The five-story RC shear-wall buildings (Figure 4c shows details of the plan view for this category of buildings), which have natural periods ranging between 0.23 and 0.25 s (Dunand et al. 2004)—values which are quite far from the estimated soil period range—did not suffer any damage. At the same location, only a few ten-story RC shear-wall buildings suffered Grade 2 or Grade 3 damage. The natural period measured for several buildings in this category showed values ranging between 0.4 and 0.5 s (Dunand et al. 2004), which is close to the estimated soil period range. For the clear peak observed at location M11 (period = 0.4 s) in the southeastern part of the city in Zone 4, where almost all the buildings are low-rise RC frame houses, only a few of the houses suffered damage and those were in very poor condition.

SITE EFFECTS FROM TOPOGRAPHIC FEATURES

In Figure 15 we present the results DEM data for a grid of the Boumerdès area generated from ASTER images with cell dimensions of 15 m^2. According to field observations, this ground elevation model matches quite well with the actual topography of the city.

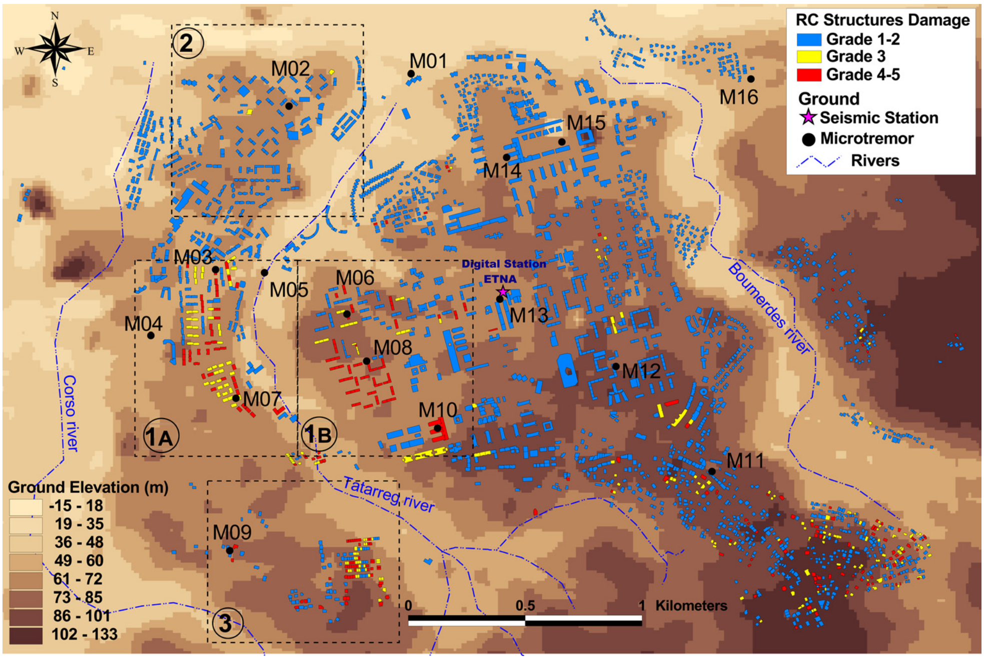


Figure 15. Ground elevation model with cells measuring 15 m^2, and building damage distribution for the city of Boumerdès. K–K' is the area shown in the cross section in Figure 18 illustrating a topographic relief of the damaged and undamaged zones in the city of Boumerdès.

As mentioned above, according to the damage assessment after the 2003 earthquake, the zones with high damage—Zones 1A, 1B, and 3—were located on hilltops and steep slopes along the Tatarreg River valley (Figure 15). The damage extended 160 to 200 m from the scarp edge of the slope. Figure 16 shows some of the collapsed buildings located on hilltops in Zone 1A along the Tatarreg River valley. Several past earthquakes around the world have caused similar damage concentrations along the tops of steep slopes and on hilltops, for instance, the 1980 Irpinia earthquake ($M_s = 6.9$) (Athanasopoulos 1998), the 1999 Parnitha (Athens) earthquake ($M_s = 5.9$) (Gazetas et al. 2002, Assimaki et al. 2005), the 2003 Bingöl, Turkey, earthquake ($M_s = 6.4$) (Aydan at al. 2003), and the 2003 San Simeon, California, earthquake ($M_w = 6.5$) (McCrink et al. 2010).

It has been mentioned that the amplification of ground motion on hilltops and steep slopes is caused by the interaction between the incoming seismic waves and these geomorphic features. This amplification increases in areas of extreme topography. For instance, in the case of Pacoima Canyon, in southern California, a PGA of 1.58 g was recorded on the ridge that forms the Pacoima Dam abutment during the 1994 Northridge earthquake ($M_w = 6.7$), however in surrounding areas and at the bottom of the canyon the PGA was less than 0.50 g (Harp and Jibson 2002).

Considering the damage rates with respect to topography, mid-rise RC moment-frame buildings and RC moment-frame houses (low-rise) constituted the only groups with large sample sizes. Figure 17 shows that for mid-rise RC moment-frame buildings located up to 200 m from slopes, the damage rate increased considerably, mostly for four- and five-story buildings, and became insignificant for those buildings located on flat ground. The damaged RC moment-frame houses mostly had three stories, which suggests, as mentioned earlier, that these building had fundamental period values close to those of the damaged four- and five-story buildings. Figure 18, shows a topographic relief of the cross section K-K' (see Figure 15) in relation to the damage distribution and structural characteristics of buildings

Figure 16. Photograph showing the damage to buildings located on hilltops in Zone 1A along Tatarreg River valley (see Figure 15). It can also be seen that the buildings located very close to the scarp edge collapsed totally, while those located some distance away from the scarp edge were only partially collapsed or suffered extensive damage to their structural elements, columns, and beams.

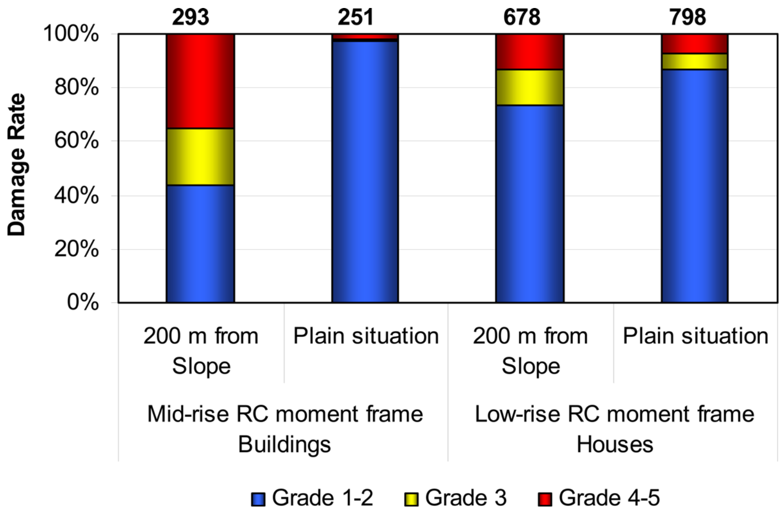


Figure 17. Damage rate for RC moment-frame structures with respect to topographic position. The damage rate increases for mid-rise RC moment-frame buildings with four and five stories located up to 200 m from slopes and becomes insignificant for buildings located on flat ground. The damaged RC moment-frame houses mostly had three stories, which suggests that they had fundamental period values close to those of the damaged four- and five-story buildings.

in Boumerdès. In the western part of the city, almost all the buildings that suffered heavy damage were mid-rise RC moment-frame structures, mostly four- to five-story buildings in Zones 1A and 1B and three-story houses in Zone 3, which suggests that these building types had fundamental period values close to each other, and also close to the period of amplification created under the effects of hilltops and steep slopes along the Tatarreg River valley. Figure 4a shows a typical four-story RC moment-frame building in Zone 1A that was built in 1996. Figure 4b shows a typical five-story RC moment-frame building in Zone 1B, which was built by the same contractor in the 1970s.

In contrast to the Tatarreg River valley, only insignificant damage was observed along the Boumedes River valley, in the eastern part of the city. This can be explained by the fact that almost all the buildings on hilltops and close to steep slopes were low-rise RC moment-frame structures and one- to two-story houses with fundamental periods that were likely different to the period of amplification created by the topography. Only slight damage was observed for the five-story mid-rise RC moment-frame structures in the central part of the city. Due to the flat terrain in this location, topographical effects leading to remarkable ground motion amplifications can be excluded; however, at some locations in the city center the terrain shows significant inclines in the northern direction.

DISCUSSION

If we consider the discrepancies in damage distribution across the entire city, with respect to the structural characteristics of constructions, the results lead to the assumption that the ground motion amplification was not uniformly distributed throughout the city. A

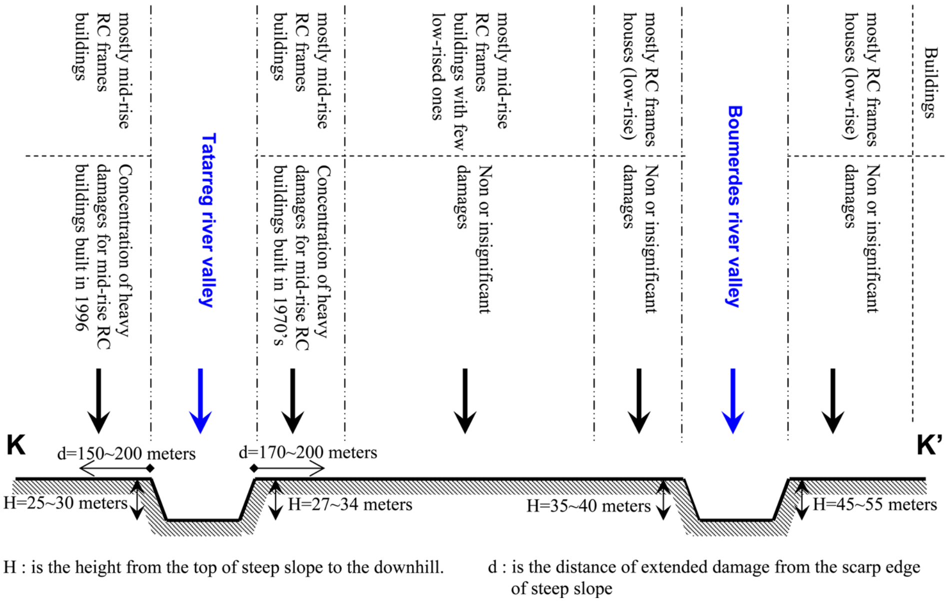


Figure 18. Topographic relief of the cross section K–K' (as shown in Figure 15) in relation to the damage distribution and existing structural characteristics of buildings (see Figures 5 and 6) in the city of Boumerdès.

very serious concentration of damage was observed in zones with strong topographic relief. On the other hand, one can clearly see from the free-field microtremor recordings presented in this study that at the most locations where spectral H/V-ratios displayed no clear results are corresponding to these topographic features, such as hill-top and steep slope situations. As pointed out by Lang (2004), the applicability of the spectral H/V-method or stability of results could depend on topographical site conditions, which may unfavorably alter the spectral H/V ratios. Indeed, the same observations noted here were also noted by Lang (2004) when conducting free-field microtremor recordings in the city of Bingöl, Turkey. The H/V ratios observed on the steep slopes displayed no clear results. In addition, the results of investigations conducted by Lermo and Chávez-García (1993) showed that an unusual generation of distinct peaks and troughs can occur with respect to the shape of spectral H/V ratios of microtremors recorded on hilltops or steep slopes.

Figure 19 shows the damage rate with respect to both topographic position and the resulting H/V ratios of ambient noise for mid-rise RC moment-fame buildings, which constitute the only group with a large sample size. This figure shows a clear relationship between the observed damage patterns, the site conditions obtained from the H/V ratios, and the topographic conditions of the building site. It can be concluded that the hilltops and steep slopes in Boumerdès along the Tatarreg and Boumerdès river valleys had a strong effect on the damage concentrations during the 2003 earthquake. The amplification of ground motion created by this topography had a significant effect on mid-rise RC moment-frame systems with four to five stories. Along the Boumerdès River valley, only insignificant damage was observed, since almost all the buildings were low-rise RC moment-frame

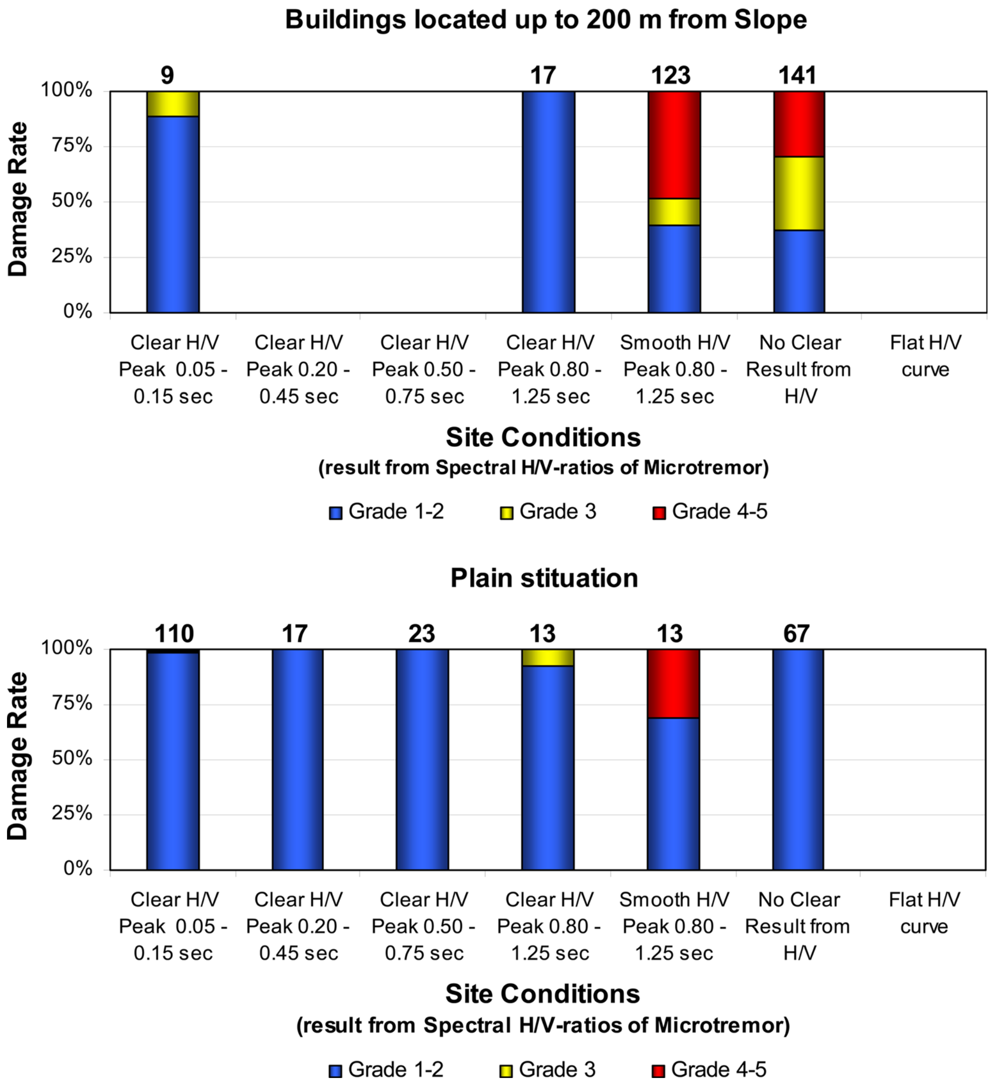


Figure 19. Damage rate for mid-rise RC moment-frame buildings considering both topographic positions and site conditions from microtremor measurements. For buildings located up to 200 m from slopes, the damage rate increases and almost all the microtremor measurements show unclear results or smoothed H/V ratios of ambient noise. The clear peaks observed at some locations are due to the fact that the angle of the slope is small, which suggests that the topographic effects were insignificant. For flat locations, almost all of the microtremor measurements show H/V ratios with clear peaks, and there were insignificant damage rates at these locations.

systems. In addition, this study shows that topographic features may also significantly affect the free-field H/V ratios of microtremors. As shown in Figure 19, it is expected that when there are no clear results from H/V ratios, it indicates the presence of topographic effects due to hilltops and steep slopes.

The damage rate increased for mid-rise RC moment-frame buildings located up to 200 m from slopes. In fact, in Zones 1A and 1B along the Tatarreg River valley, the buildings located very close to the scarp edge of the slope totally collapsed, while those located some distance away from the scarp edge either partially collapsed or suffered extensive damage to their structural elements, columns, and beams, as shown in Figure 16. As mentioned by Géli et al. (1988), topographic effects generally result in larger amplitudes of ground motion toward ridge crests, which can increase damage to the buildings in these locations. In addition, the microtremor measurements in Zone 1A showed no clear results for H/V ratios, suggesting that the ambient noise records were strongly influenced by the topography, which concurs with the possibility that the amplitude of the ground motion was strongly affected, leading to extensive damage (Figure 19). For Zone 1B, microtremor measurements showed H/V ratios with smoothed peaks, suggesting that the ambient noise records in this zone were not as strongly influenced by topographic effects as in Zone 1A. However, it can clearly be seen that there was a higher rate of damage in Zone 1B than in Zone 1A, as shown in Figure 19. Even though the local subsoil conditions (thickness of layers) in Zone 1B are probably different to those of Zone 1A, the fact that the damaged buildings in Zone 1B were five-story structures built in 1970 (before the publication of seismic design codes in Algeria) may explain the difference in the damage rate between these two zones. In Zone 1A, most of the damaged buildings were four-story structures built in 1996 using the seismic code published in 1988.

The clear peaks and low damage rates observed at some locations with hilltops and slopes can be explained by the small angle of these slopes, which suggests that the topographic effects were insignificant. This was the case in Zone 2, where the buildings are situated on terrain with relatively small topographic features. In addition, the H/V ratios showed clear peaks in the range 0.5 to 1.25 s, which suggests that of the topography had no effect

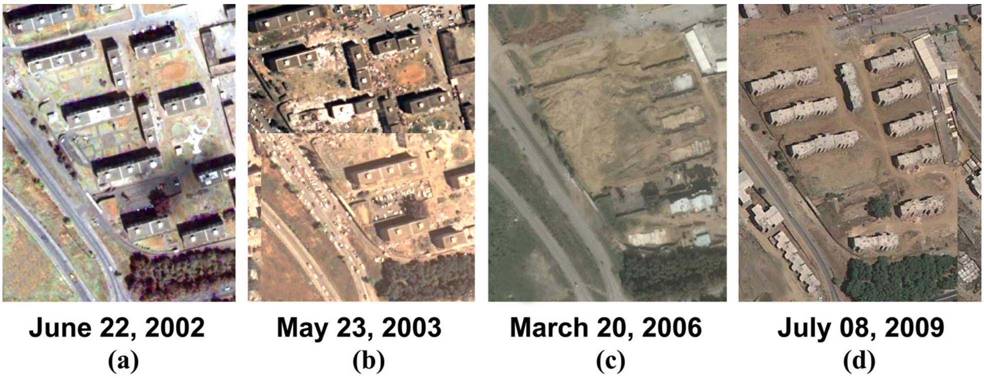


Figure 20. New mid-rise RC shear-wall buildings were recently built on the same site as old mid-rise RC moment-frame buildings that collapsed in the earthquake. They are located in Zone 1B on hilltops along Tatarreg River valley (see Figure 15): (a) QuickBird image of the mid-rise RC moment-frame buildings before the earthquake, (b) QuickBird image of the collapsed mid-rise RC moment-frame buildings after the earthquake, (c) Google image of the site of the collapsed mid-rise RC moment-frame buildings after they were removed, and (d) Google image of the new mid-rise RC shear-wall buildings built at the same location.

on ambient noise at this location. Since the amplification of incoming seismic waves is directly related to the sharpness of the topography (Bard and Tucker 1985), and considering the results from the microtremor measurements, the slight damage observed in Zone 2 can be ascribed to subsoil effects.

For flat locations, most of the H/V curves from the microtremor measurements exhibited clear peaks, in contrast to the locations with hilltops and steep slopes (Figure 19). In fact, it is well-known that when the terrain of a site is flat, damage rates decrease and the peaks of H/V ratios from microtremor measurements are clearer. This observation suggests that in flat locations, the topography does not amplify ground motions. However, for some of these locations, the H/V ratios of microtremor measurements showed either no clear results or smoothed peaks, whereas the damage rate was insignificant (Figure 19). Based on the field survey, the terrain at these locations, situated in the center of the city, is characterized by a significant incline to the north, toward the sea. Accordingly, the microtremor measurements seem to be influenced by the incline.

CONCLUSIONS

To assess the damage distribution observed in Boumerdès following the 2003 Algeria earthquake, a correlation analysis was conducted considering not only the structural characteristics of the buildings in the area and subsoil factors, but also the additional vulnerability related to topographic conditions. Topography is one of the main factors influencing the distribution of damage caused by earthquakes. Indeed, for many destructive earthquakes it has been reported that buildings located on hilltops and steep slopes suffer more damage than those located on flat ground.

In this study the buildings in Boumerdès at the time of the earthquake were classified by their structural characteristics in order to evaluate their damage-resistance. Due to a lack of geological and stratum layer data, subsoil consistency was estimated using data from free-field microtremor measurements conducted at several locations in the city. The topography of the city has been categorized into three generalized positions: hilltops, steep slopes, and flat ground.

It has been observed that the version of the seismic code used was not the main factor affecting the damage distribution. In fact, before the 2003 earthquake, the seismic damage-resistance capacities mandated by different versions of the seismic code did not differ greatly. The relationship between the damage-resistance capacities of the buildings and the actual damage distribution showed some variation for the same type of building at different locations. Mid-rise (four- and five-story) RC moment-frame systems were more vulnerable, as were three-story RC houses, which suggests that these two types of structures have fundamental period values close to each other.

The reconnaissance study showed a concentration of damage in zones with hilltops and steep slopes. Specifically, there was an increase in the damage rate for mid-rise RC moment-frame structures on hilltops and steep slopes along the Tatarreg River valley, which extends toward a plateau. For these locations, the spectral H/V ratios from the free-field microtremor measurements displayed no clear results. The importance of taking topographic features into account has been noted in terms of interpreting results generated using the H/V ratio method. Microtremor recording sites close to strong topographic formations such as hilltops and steep slopes should be avoided since these formations may influence ambient noise and unfavorably alter the shape of the H/V ratios, resulting in the generation of distinct peaks not suitable for subsoil classification (Lermo and Chávez-García 1993, Lang 2004).

This study revealed the importance of carefully considering site conditions such as topography, a factor that has received only minor attention in engineering practice in Algeria, in order to obtain a more accurate measure of safety in the structural design of buildings. Recently, new structures have been built in Boumerdès in exactly the same locations as buildings that collapsed during the 2003 earthquake, as shown in Figure 20. In fact, the location in this figure is in Zone 1B, close to a steep slope along the Tatarreg River valley. The collapsed buildings were mid-rise RC moment-fame systems, as mentioned earlier, and the newly built ones are mid-rise RC shear-wall systems. Although it is true that the mid-rise RC shear-wall buildings in Zone 2, which were also located along the Tatarreg River valley, did not suffer as much damage from the earthquake as the RC moment-frame systems, the H/V ratios from microtremor measurements in Zone 2 suggest that topography was not a major factor in the damage distribution in this zone, whereas it was in Zone 1B. In addition, these new RC shear-wall buildings were designed according to the newly revised Algerian seismic code, RPA99'03, which does not incorporate the amplification effects of earthquake ground motion at topographic features.

ACKNOWLEDGMENTS

Financial support for this research was provided by Chiba University, Chiba, Japan. The QuickBird images used were licensed and provided by the Earthquake Engineering Research Institute (EERI), Oakland, California. The field survey ground dataset was provided by National Research Centre of Earthquake Engineering (CGS), Algeria. The authors gratefully acknowledge the valuable comments provided by several anonymous reviewers.

REFERENCES

Ansary, M. A., Yamazaki, F., Kokusho, T., and Ueshima, T., 1995. Microtremor observation at Hualien LSST array site, Taiwan, in *First International Conference on Earthquake Geotechnical Engineering*, Vol. 1, Ishihara, Balkema, Rotterdam, Netherlands, 357–362.

Arai, H., Hibino, H., Okuma, Y., Matsuoka, M., Kubo, T., and Yamazaki., F., 2000. Estimation of ground motion characteristics and damage distribution in Golcuk, Turkey, based on microtremor measurements, *6th International Conference on Seismic Zonation*, 12–15 November 2000, Palm Springs, CA.

Ashford, S. A., Sitar, N., Lysmer, J., and Deng, N., 1997. Topographic effects on the seismic response of steep slopes, *Bulletin of the Seismological Society of America* **87**, 701–709.

Assimaki, D., Kausel, E., and Gazetas, G., 2005. Soil-dependent topographic effects: A case study from the 1999 Athens earthquake, *Earthquake Spectra* **21**, 929–966.

Athanasopoulos, G. A., Pelekis, P. C., and Leonidou, E. A., 1998. Effects of surface topography and soil conditions on the seismic ground response - including liquefaction - in the Aegion (Greece) 15/6/1995 earthquake, *Eleventh European Conference on Earthquake Engineering*, 6–11 September 1998, Paris, France.

Aydan, Ö., Ulusay, R., and Miyajima, M., 2003. *The Bingöl Earthquake of May 1, 2003, Reconnaissance Report*, Japan Society of Civil Engineers, Tokyo.

Bakir, B. S., Sucuoglu, H., and Yilmaz, T., 2002. An overview of local site effects and the associated building damage in Adaparzari during the 17 August 1999 Izmit earthquake, *Bulletin of the Seismological Society of America* **92**, 509–526.

Bard, P-Y., and Tucker, B. E., 1985. Underground and ridge site effects: A comparison of observation and theory, *Bulletin of the Seismological Society of America* **75**, 905–922.

Belazougui, M., 2008a. Overview of last 30 years Algerian experience in the field of seismic risk reduction, *History of Earthquake Engineering Lessons Learned and Outcomes in Today Practice – Perspectives from Different Countries*, Association Française du Génie Parasismique (AFPS), 13 June 2008, Nice, France.

Belazougui, M., 2008b. Boumerdes Algeria earthquake of May 21, 2003: Damage analysis and behavior of beam-column reinforced concrete structures, *14th World Conference on Earthquake Engineering*, 12–17 October 2008, Beijing, China.

Benouar, D., and Meslem, A., 2007. Seismic risk in existing school buildings in Algeria, *Regional Development Dialogue* **28**, 50–63.

Boore, D. M., 1972. A note on the effect of simply topography on seismic SH waves, *Bulletin of the Seismological Society of America* **62**, 275–284.

Bouchon, M., and Barker, S., 1996. Seismic response of a hill: The example of Tarzana, California, *Bulletin of the Seismological Society of America* **86**, 66–72.

Bouckovalas, G. D., and Papadimitriou, A. G., 2005. Numerical evaluation of slope topography effects on seismic ground motion, *Soil Dynamics and Earthquake Engineering* **25**, 547–558.

Bounif, A., Dorbath, C., Ayadi, A., Meghraoui, M., Beldjoudi, H., Laouami, N., Frogneux, M., Slimani, A., Kharroubi, A., Ousadou, F., Chikh, M., Harbi, A., Larbes, S., and Maouche, S., 2004. The 21 May 2003 Zemmouri (Algeria) earthquake M_w 6.8: relocation and aftershock sequence analysis, *Geophysical Research Letters* **31**, L19606, DOI:10.1029/2004GL020586.

Bour, M., Fouissac, D., Dominique, P. D., and Martin, C., 1998. On the use of microtremor recording in seismic microzonation, *Soil Dynamics and Earthquake Engineering* **17**, 465–474.

Čelebi, M., 1987. Topographical and geological amplifications determined from strong-motion and aftershock records of the 3 March 1985 Chile earthquake, *Bulletin of the Seismological Society of America* **77**, 1147–1167.

Construction Technology Control (CTC), 1981. *Règles parasismiques Algériennes, RPA81*, Algiers, Algeria.

Construction Technology Control (CTC), 1983. *Règles parasismiques Algériennes, RPA83*, Algiers, Algeria.

Chatelain, J-L., Guillier, B., and Parvez, I., 2008. False site effects: The Anjar case, following the 2001 Bhuj (India) earthquake, *Seismological Research Letters* **79**, 816–819.

Chávez-García, F. J., and Cuenca, J., 1998. Site effects and microzonation in Acapulco, *Earthquake Spectra* **14**, 75–93.

Chávez-García, F. J., Rodríguez, M., Field, E. H., and Hatzfeld, D., 1997. Topographic site effects: A comparison of two nonreference methods, *Bulletin of the Seismological Society of America* **87**, 1667–1673.

Cranswick, E., Özel, O., Meremont, M., Erdik, M., Safak, E., Mueller, C., Overturr, D., and Frankel, A., 2000. Earthquake damage, site response and building response in Avcilar, west of Istanbul, Turkey, *International Journal for Housing Science and Its Applications* **24**, 85–96.

Delouis, B., Vallee, M. Meghraoui, M., Calais, E., Maouche, S., Lammali, K., Mahras, A., Briole, P., Benhamouda, F., and Yelles, K., 2004. Slip distribution of the 2003 Boumerdes-Zemmouri earthquake, Algeria, from teleseismic, GPS, and coastal uplift data, *Geophysical Research Letters* **31**, L18607, DOI:10.1029/2004GL020687.

Direction du Logement, des Equipements Publics (DLEP), 2004. Conséquence du séisme sur le parc logement et les équipements publics, Wilaya de Boumerdès.

Dunand, F., Ait-Meziane, Y., Gueguen, P., Chatelain, J-L, Guillier, B., Ben Salem, R., Hadid, M., Hellel, M., Kiboua, A., Laouami, N., Machane, D., Mezouer, N., Nour, A., Oubaiche, E., and Remas, A., 2004. Utilisation du bruit de fond pour l'analyse des dommages des bâtiments de Boumerdes suite au séisme du 21 Mai 2003, *Mémoire du Service Géologique de l'Algérie* **12**, 177–191.

Earthquake Engineering Research Institute (EERI), 2003. The Boumerdes, Algeria earthquake of May 21, 2003, Reconnaissance Report, Learning from Earthquakes Program, Oakland, CA.

European Seismological Commission (ESC), 1998. European Macroseismic Scale 1998, EMS-98, Luxembourg.

Fallahi, A., Alaghebandian, R., and Miyajima, M., 2003. Microtremor measurements and building damage during the Changureh-Avaj, Iran earthquake of June 2002, *Journal of Natural Disaster Science* **25**, 37–46.

Gazetas, G., Kallou, P. V., and Psarropoulos, P. N., 2002. Topography and soil effects in the Ms 5.9 Parnitha (Athens) earthquake: The case of Adámes, *Natural Hazards* **27**, 133–169.

Géli, L., Bard, P-Y., and Jullien, B., 1988. The effect of topography on earthquake ground motion: A review and new results, *Bulletin of the Seismological Society of America* **78**, 42–63.

Gosar, A., 2007. Microtremor HVSR study for assessing site effects in the Bovec Basin (NW Slovenia) related to 1998 Mw 5.6 and 2004 Mw 5.2 earthquakes, *Engineering Geology* **91**, 178–193.

Harbi, A., Maouche, S., Ousadou, F., Rouchiche, Y., Yelles-Chaouche, A., Merahi, M., Heddar, A., Nouar, O., Kherroubi, A., Beldjoudi, H., Ayadi, A., and Benouar, D., 2007. Macroseismic study of the Zemmouri earthquake of 21 May 2003 (Mw 6.8, Alegeria), *Earthquake Spectra* **23**, 315–332.

Harp, E. L., and Jibson, R. W., 2002. Anomalous concentrations of seismically triggered rock falls in Pacoima Canyon: Are they caused by highly susceptible slopes or local amplification of seismic shaking? *Bulletin of the Seismological Society of America* **92**, 3180–3189.

Hartzell, S. H., Carver, D. L., and King, K. W., 1994. Initial investigation of site and topographic effects at Robinwood Ridge, California, *Bulletin of the Seismological Society of America* **84**, 1336–1349.

Havenith, H-B., Vanini, M., Jongmans, D., and Faccioli, E., 2003. Initiation of earthquake-induced slope failure: Influence of topographical and other site specific amplification effects, *Journal of Seismology* **7**, 397–412.

Hellel, M., Chatelain, J-L., Guillier, B., Machane, D., Ben Salem, R., Oubaiche, E. H., and Haddoum, H., 2010. Heavier damages without site effects and lighter damages with lighter damages in Boumerdes City (Algeria) after the May 2003 earthquake, *Seismological Research Letters* **81**, 37–43.

Kawase, H., and Aki, K., 1990. Topography effect at the critical SV-wave incidence: Possible explanation of damage pattern by the Whittier Narrows, California, earthquake of 1 October 1987, *Bulletin of the Seismological Society of America* **80**, 1–22.

Lang, D. H., 2004. Damage Potential of Seismic Ground Motion Considering Local Site Effects, Ph.D. Thesis, Bauhaus-Universität Weimar, Germany, http://e-pub.uni-weimar.de/volltexte/2004/91.

Laouami, N., Slimani, N., Bouhadad, Y., Chatelain, J-L., and Nour, A., 2006. Evidence for fault-related directionality and localized site effects from strong motion recordings of the 2003 Boumerdes (Algeria) earthquake: Consequences on damage distribution and the Algerian Seismic Code, *Soil Dynamics and Earthquake Engineering* **26**, 991–1003.

Lermo, J., and Chávez-García, F. J., 1993. Site effect evaluation using spectral ratios with only one station, *Bulletin of the Seismological Society of America* **83**, 1574–1594.

Lu, L., Yamazaki, F., and Katayama, T., 1992. Soil amplification based on seismometer array and microtremor observations in Chiba, Japan, *Earthquake Engineering and Structural Dynamics* **21**, 95–108.

McCrink, T. P., Wills, C. J., Real, C. R., and Manson, M. W., 2010. Effects of topographic position and geology on shaking damage to residential wood-framed structures during the 2003 San Simeon earthquake, western San Luis Obispo County, California, *Earthquake Spectra* **26**, 779–802.

Meghraoui, M., Maouche, S., Chemaa, B., Cakir, Z., Aoudia, A., Harbi, A., Alasset, P. J, Ayadi, A., Bouhadad, Y., and Benhamouda, F., 2004. Coastal uplift and thrust faulting associated with the Mw = 6.8 Zemmouri (Algeria) earthquake of 21 May 2003, *Geophysical Research Letters* **31**, L19605, DOI:10.1029/2004GL020466.

Meslem, A., Yamazaki, F., Maruyama, Y., Benouar, D., Laouami, N., and Benkaci, N., 2010. Site-response characteristics evaluated from strong motion records of the 2003 Boumerdes, Algeria, earthquake, *Earthquake Spectra* **26**, 803–823.

Motamed, R., Ghalandarzadeh, A., Tawhata, I., and Tabatabaei, S. H., 2007. Seismic microzonation and damage assessment of Bam city, *Journal of Earthquake Engineering* **11**, 110–132.

Nakamura, Y., 1989. A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface, in *Quarterly Report of the Railway Technical Research Institute (RTRI)*, Vol. 30, 25–33.

National Research Centre of Earthquake Engineering (CGS), 1988. *Règles parasismiques Algériennes, RPA88*, Algiers, Algeria.

National Research Centre of Earthquake Engineering (CGS), 1999. *Règles parasismiques Algériennes, RPA99*, Algiers, Algeria.

National Research Centre of Earthquake Engineering (CGS), 2003. *Règles parasismiques Algériennes, RPA99'03*, Algiers, Algeria.

Navarro, M., Enomoto, T., Yamamoto, T., García-Jerez, A., Vidal, F., and Bretón, M., 2008. Analysis of site effects and their correlation with damage distribution observed during the colima (Mexico) earthquake of January 21, 2003, *14th World Conference on Earthquake Engineering*, 12–17 October 2008, Beijing, China.

Navarro, M., Sánchez, F. J., Enomoto, T., Vidal, F., and Rubio, S., 2000. Relation between the predominant period of soil ant the damage distribution after the Mula 1999 earthquake, *Sixth International Conference on Seismic Zonation*, 12–15 November 2000, Palm Spring, CA.

Oliveira, C. S., Roca, A., and Goula, X., 2006. Geo-scientific and engineering knowledge for earthquake risk mitigation: Developments, tools, techniques, in *Assessing and Managing Earthquake Risk*, Springer, Netherlands, 561 pp.

Ousalem, H., and Bechtoula, H., 2005. Inventory survey of the 2003 Zemmouri (Algeria) earthquake: Case study of Dergana City, *Journal of Advanced Concrete Technology* **3**, 175–183.

Rodriguez, V. H. S., and Midorikawa, S., 2003. Comparison of spectra ratio techniques for estimation of site effects using microtremor data and earthquake motions recorded at the surface and in boreholes, *Earthquake Engineering and Structural Dynamics* **32**, 1691–1714.

Scandinavian Engineering Corporation, 1970. Boumerdès Plan d'Urbanisme, Internal Report, Société Nationale pour la Recherche, la Production, le Transport, la Transformation, et la Commercialisation des Hydrocarbures (Sonatrach), Algiers, Algeria, 128 pp.

Shimizu, Y., Koganemaru, K., Suetomi, I., Yamazaki, F., and Tamura, I., 2009. Seismic motion observed by new SI sensors and microtremor measurement in Taipei Basin, in *Proceedings of International Workshop on Annual Commemoration of Chi-Chi Earthquake*, Vol. 2, 248–259.

Tuladhar, R., Yamazaki, F., Warnitchai, P., and Saita, J., 2004. Seismic microzonation of the greater Bangkok area using microtremor observations, *Earthquake Engineering and Structural Dynamics* **33**, 211–225.

Yamazaki, F., and Ansary, M. A., 1997. Horizontal-to-vertical spectrum ratio of earthquake ground motion for site characterization, *Earthquake Engineering and Structural Dynamics* **26**, 671–689.

(Received 3 June 2010; accepted 24 December 2010)