Effect of Topographic Reliefs on Building Damage Distribution in Boumerdes City during the 2003 Algeria Earthquake

A. Meslem
University of Bath, UK

F. Yamazaki & Y. Maruyama
Chiba University, Japan

D. D'Ayala
University of Bath, UK

M. Naili
National Research Center of Earthquake Engineering (CGS), Algeria

D. Benouar
University of Bab-Ezzouar, Algeria

15 WCEE
LISBOA 2012

SUMMARY
This study highlights the effect of topographic reliefs on the observed damage distribution in the city of Boumerdes after the 2003 Algeria earthquake. Supported by field observations and using a 15-meter grid cell dimension ground digital elevation model (DEM), the topographical situation of the city is simplifically generalized to three possible terrain positions: small hill-tops, steep slopes, and plains. The results of analyses shows that the damaged buildings, mostly mid-rise RC moment frame systems, were located on steep slope and on a small hill-top along a river valley. The measured H/V ratios of free-field microtremor observations did not show clear results, expected to be influenced by the topographic reliefs. Whereas, the same structural characteristics of buildings located on plain situations did not suffer much damage, and clear H/V peaks were observed. The results show the importance of considering the amplification effects of topography when designing new buildings for earthquake resistance.

Keywords: Damage distribution, topographic reliefs, microtremor measurement, the 2003 Algeria earthquake

1. INTRODUCTION

Following the 21 May 2003, Mw 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 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 (Çelebi 1987, Kawase and Aki 1990, Hartzell et al. 1994, Bouchon and Barker 1996, Bouckovalas and Papadimitriou 2005).

In this study, 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 m2 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. In addition, 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. Furthermore, the resulting free-field microtremor measurements were also considered with respect to topographic features.

2. 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. Fig. 1 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 (Fig. 1).

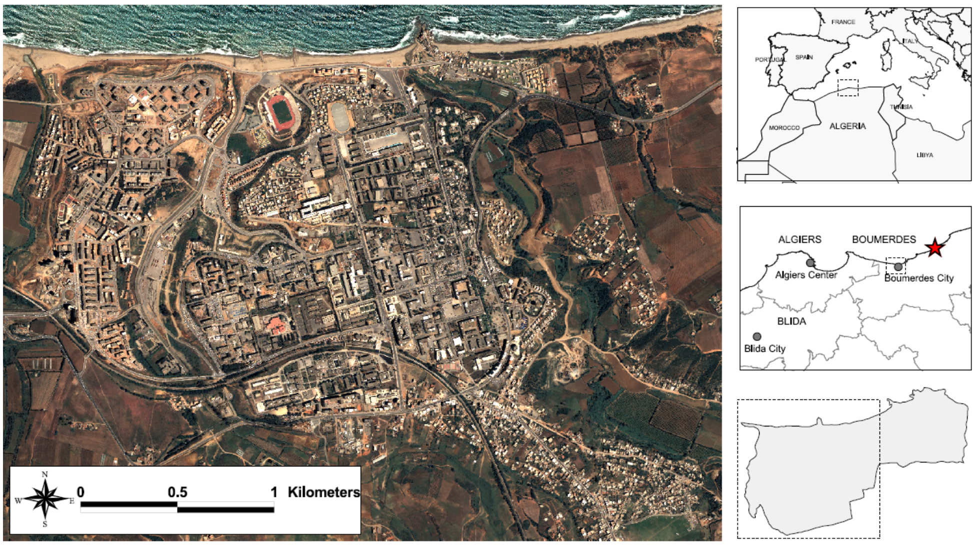


Figure 1. Location and QuickBird satellite image of Boumerdes city. The red star indicates the epicenter of the mainshock of the 2003 Algeria earthquake

2.1. Building Damage-Resistance Classification

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, hence, for this study only this category will be considered because the number of buildings in the study area constructed using other materials is almost negligible.

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%. All these RC buildings were built between 1969 and 2003; however, a comparison of the various seismic codes does not show any important differences regarding their damage-resistance characteristics.

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. It is worth to mention that most of these private houses were built without following any seismic code or using any quality control measures, and are therefore generally considered to be non-engineered buildings. 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.

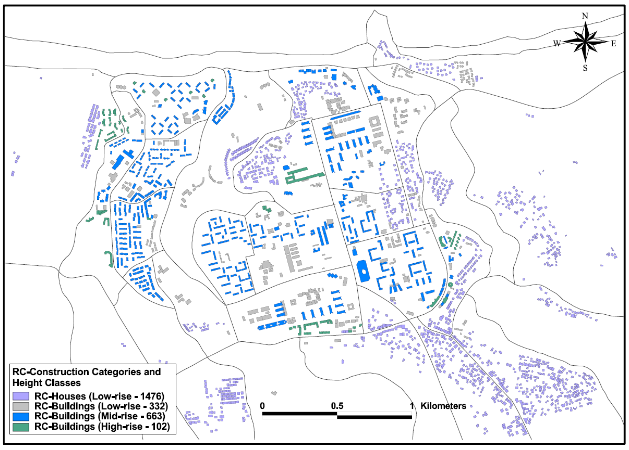


Figure 2. RC construction classification by categories and height classes in Boumerdes.

Based on this background information, 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. Fig. 2 shows the final classification of RC structures according to their categories and height classes.

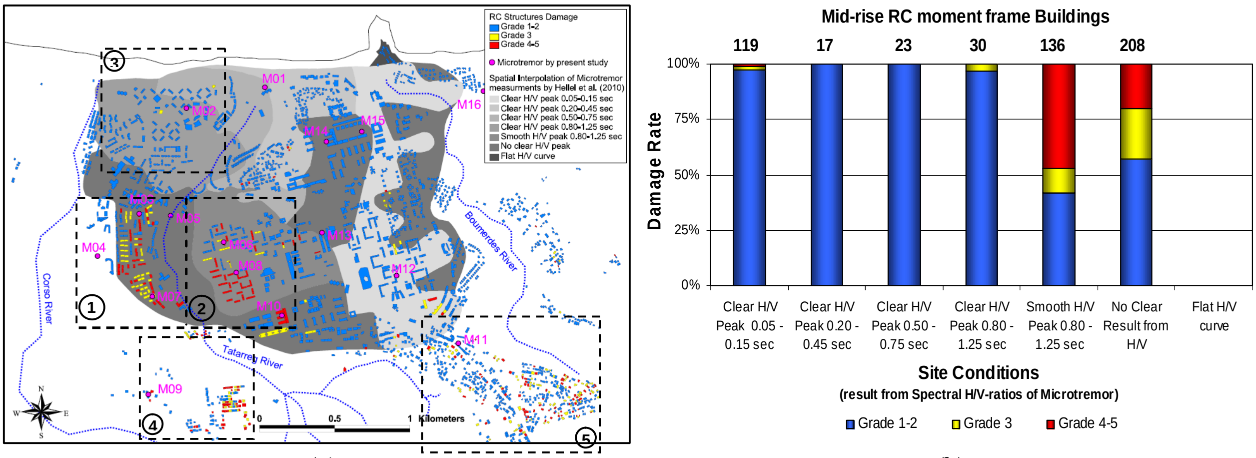
2.2. Topographical Features

As seen from the QuickBird image in Fig. 1 (see also Fig. 4), 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.

3. RESULTS

3.1. Damage Distribution

The damage distribution (Fig. 3a) shows that in the southwestern part of the city (Zones 1 and 2), where most of the buildings were of mid-rise height (Fig. 2), the damage was extensive. There were very few low-rise buildings and almost no high-rise buildings in this area. Furthermore, not far from Zones 1 and 2, in Zone 4, 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 5, in the southeastern part of the urbanized area, where almost all the existing buildings were single, nonengineered, one- to three-story houses (Fig. 2), 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.



(a) (b)

Figure 3. (a) GIS damage distribution map of RC structures in Boumerdes during 2003 Algeria earthquake, Spatial interpolation of a total 260 H/V peak ratios of microtremor measurements on ground surface (modified from Hellel et al. 2010), location of 16 microtremor measurements by present authors. (b) Damage rate for mid-storeyed RC moment frame buildings with respect to the site conditions in the city of Boumerdes

3.2. Site Effect from Local Subsoil Condition

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 (Fig. 3a). 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. The duration of a single microtremor observation was set at 5 min, and the record was divided into six segments, each lasting 50 s.
We calculated the H/V Fourier spectral ratio for six segments as the spectral ratio between the two horizontal components (*EW* and *NS*) and the vertical (*UD*) component, defined by:

$$R(f)=\frac{\sqrt{F_{NS}(f)\cdot F_{EW}(f)}}{F_{UD}(f)} \tag{3.1}$$

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, 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. Fig. 3a shows 2-D presentations of 260 H/V ratios from Hellel et al. (2010) incorporated with microtremor measurements by the present authors and the building damage distribution for the city of Boumerdès.

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. Fig. 3b 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.

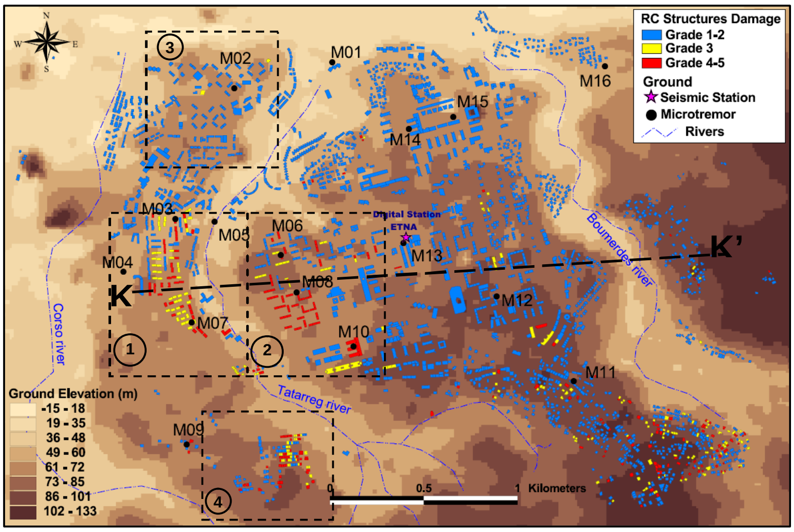


Figure 4. Ground elevation with 15-meter grid cell dimension, and building damage distribution for the city. K–K' is the area shown in the cross section in Fig. 7 illustrating a topographic relief of the damaged and undamaged zones in the city of Boumerdès

3.2. Site Effect from Topographic Features

In Fig. 4 we present the results DEM data for a grid of the Boumerdès area generated from ASTER images with cell dimensions of 15 m2. According to field observations, this ground elevation model matches quite well with the actual topography of the city.

Figure 5. Photograph showing the heaviness of damage occurrence for buildings located on hill-tops in Zone 1A along Tatarreg river valley (see Figure 15). Also we can see that the buildings located very close to scarp edge were totally collapsed, while those located with distance away from scarp edge were partially collapsed or suffered extensive damage to structural elements, columns, and beams

As mentioned above, according to the damage assessment after the 2003 earthquake, the zones with high damage—Zones 1, 2, and 4—were located on hilltops and steep slopes along the Tatarreg River valley (Fig. 4). The damage extended 160 to 200 m from the scarp edge of the slope. The damage extended 160 to 200 m from the scarp edge of the slope. Fig. 5 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 (Ms = 6.9) (Athanasopoulos 1998), the 1999 Parnitha (Athens) earthquake (Ms = 5.9) (Gazetas et al. 2002, Assimaki et al. 2005), the 2003 Bingöl, Turkey, earthquake (Ms = 6.4) (Aydan at al. 2003), and the 2003 San Simeon, California, earthquake (Mw = 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 (Mw = 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).

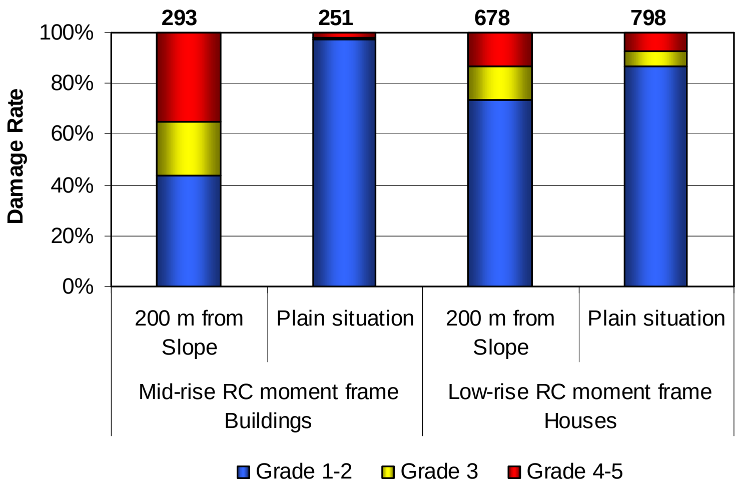


Figure 6. Damage rate for RC moment frame structures with respect to topographic position.

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 a large sample size. Fig. 6 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.

Fig. 7, shows a topographic relief of the cross section K-K' (see Fig. 4) in relation to the damage distribution and structural characteristics of 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 1 and 2 and three-story houses in Zone 4, 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.

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.

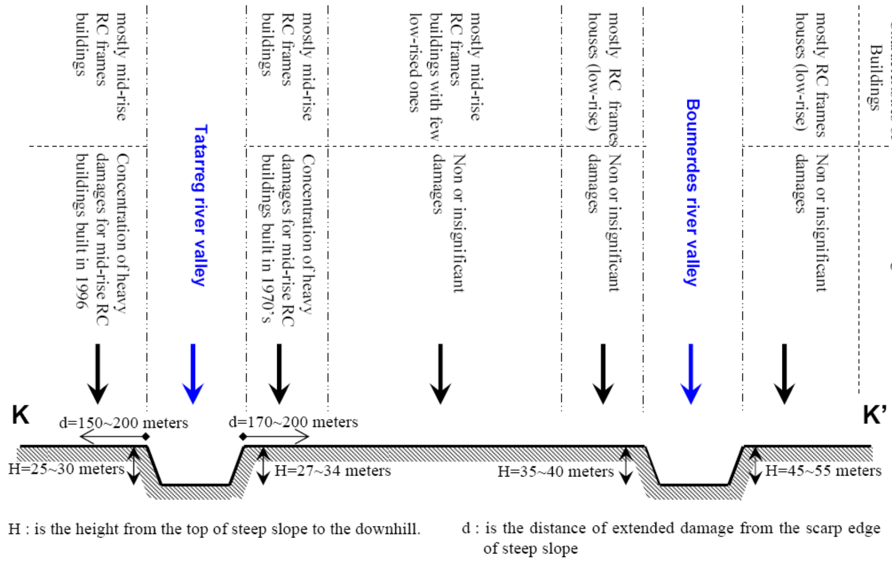


Figure 7. Illustration of topographic relief for the cross section K-K' (see Fig. 4) in relation to damage distribution and existing structural characteristics of buildings (see Fig. 2 and 3) in the city of Boumerdes.

4. 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 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.

Fig. 8 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 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 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 1 and 2 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 Fig. 5. 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 1 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 (Fig. 8). For Zone 2, 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 1. However, it can clearly be seen that there was a higher rate of damage in Zone 2 than in Zone 1, as shown in Fig. 8. Even though the local subsoil conditions (thickness of layers) in Zone 2 are probably different to those of Zone 1, the fact that the damaged buildings in Zone 2 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 1, most of the damaged buildings were four-story structures built in 1996 using the seismic code published in 1988.

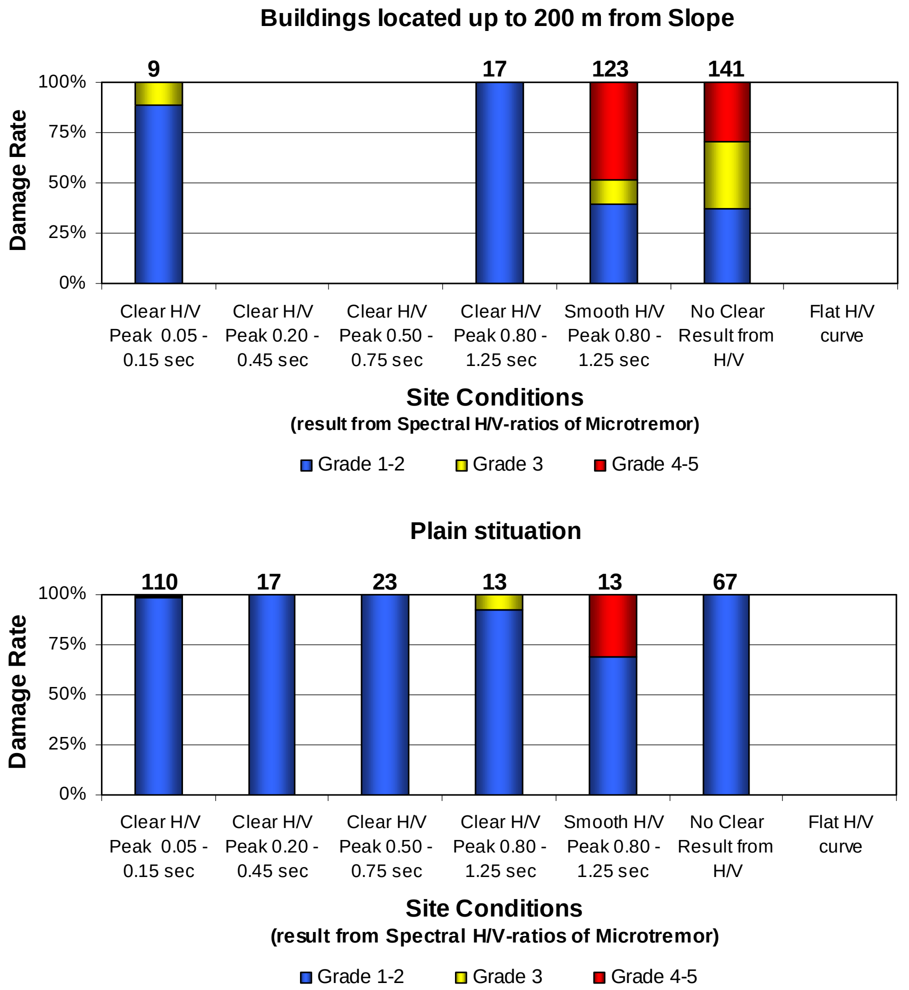


Figure 8. Damage rate for mid-rise RC moment frame buildings considering both topographic positions and site conditions resulted from microtremor measurements.

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 3, 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 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 3 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 (Fig. 8). 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 (Fig. 8). 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.

5. CONCLUSIONS

For many destructive earthquakes, topography reliefs were considered as main factors influencing the distribution of damage. Indeed, it has been reported that buildings located on hilltops and steep slopes suffer more damage than those located on flat ground.

The reconnaissance study, conducted to assess the damage distribution in Boumerdes following the 2003 Algeria earthquake, 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.

AKCNOWLEDGEMENT

The field survey ground dataset was provided by National Research Centre of Earthquake Engineering (CGS), Algeria.

REFERENCES

Ansary, M. A., Yamazaki, F., Kokusho, T. and Ueshima, T. (1995). Microtremor observation at Hualien LSST array site, Taiwan. *First International Conference on Earthquake Geotechnical Engineering.* **Vol I**: 357–362.

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. *Proceedings of the Eleventh European Conference on Earthquake Engineering*. 6–11.

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.

Çelebi, 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.
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.
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.
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
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.
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.
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.
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.
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.
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. *Proceedings of International Workshop on Annual Commemoration of Chi-Chi Earthquake.* **Vol II**: 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.