GROUND MOTION SIMULATION OF THE 2003 BOUMERDES EARTHQUAKE USING EMPIRICAL GREEN’S FUNCTION METHOD

Faouzi GHERBOUDJ¹, Hiroe MIYAKE², Toshiaki YOKOI³, Nasser LAOUAMI⁴

ABSTRACT

The 2003 Boumerdes earthquake is a major earthquake that occurred in Algeria and caused significant amounts of damage in the cities of Boumerdes and Algiers. Strong ground motions were recorded at several seismic stations by the national accelerometer network. The source model characteristics are established by comparing the observed ground motions to the simulated ground motions using the empirical Green’s function method. The source model is described first; two strong motion generation areas are used; this is nearly compatible with the asperities derived from the waveform inversion results. The results show good agreement between the observed and simulated ground motions in the frequency range of 0.25–10 Hz, which is of interest in nearly all engineering applications. In addition, the empirical Green’s function method is successfully used to define a source model for the Mw 5.7 aftershock, which was recorded by only two near stations, by comparing the simulated motions to the recorded motions at those stations. Source parameters of the Mw 6.8 mainshock and the Mw 5.7 aftershock, such as the asperities area and the rise time, are compared with scaling laws and show good agreement with previous published studies for crustal earthquakes. Therefore, the use of recipes for strong ground motion prediction is possible for seismic scenarios of crustal earthquakes corresponding to active faults in North Africa by constructing source models based on scaling laws.

Keywords: Boumerdes earthquake; strong motion; empirical Green’s function method

1. INTRODUCTION

Northern Algeria resides on the boundary of the African and Eurasian plates, and its active tectonics results from the collision between these two plates. Several destructive earthquakes have struck this region. The strongest earthquakes in the last century have been Orléansville on 9 September 1954 (M = 6.7) (Rothé, 1955), El Asnam on 10 October 1980 (M = 7.3) (Ouyed et al., 1980), Tipaza on 29 October 1989 (M = 6.0) (Meghraoui, 1991), Ain Temouchent on 22 December 1999 (M = 5.8) (Yelles et al., 2004), and Boumerdes-Zemmouri on 21 May 2003 (M = 6.8) (Ayadi et al., 2003). The latter was one of the most destructive earthquakes that has occurred and caused a large area of damage in the city of Boumerdes and the eastern part of Algiers with more than 2300 casualties and the destruction of more than 10,000 houses (Ayadi et al., 2003). Being nearly the largest ever recorded earthquake in North Africa, the strong ground motion of the 2003 Boumerdes earthquake is important to study in detail to understand how buildings performed during the earthquake and why they failed, particularly near the hypocenter area.

The empirical Green’s function method (EGFM) is a powerful method for strong ground motion prediction.
simulations that uses small earthquake records at the same site to simulate a large earthquake. This works because the site and the path effects are already contained in the small event waveforms recorded at the same site from the region of the hypocenter. Miyake et al. (2003) defined the strong ground motion generation area, which is a portion of the fault rupture surface with a large and uniform slip velocity area that is nearly equivalent to the asperity area (the large slip region). In this study, we attempted to define a source model and simulate the ground motion using the EGFM for two events: the Mw 6.8 mainshock and the Mw 5.7 event of the 2003 Boumerdes earthquake. In addition, we compared the source parameters obtained for the two events with scaling laws prepared in other regions of the world to use them for seismic hazard assessments of North Africa. This paper aims to apply the EGFM to reproduce the strong ground motion of this event at a different site.

2. STRONG GROUND MOTION SIMULATION OF THE MW 6.8 BOUMERDES EARTHQUAKE

2.1 Strong Motion Data

In this study, we used strong motion records obtained from the Algerian national accelerograph network monitored by the National Center of Applied Research in Earthquake Engineering (CGS; www.cgs.dz). Figure 1 shows the locations of those stations together with the epicenters of the mainshock and aftershocks used in this study. All stations are located on the hanging wall side extending from 30 km to 180 km from the epicenter. Therefore, we do not have much near-field strong motion data in the damaged area of Boumerdes and the eastern part of Algiers.

Of the many aftershock records available, only two or three aftershocks have an available focal mechanism solution and were recorded at nearly all stations; therefore, they were selected as the empirical Green’s functions. Table 1 shows the selected aftershocks for this study, their characteristics, and the stations at which they were recorded. The records of the Mw 4.3 aftershock at 17:42:24 on 2 February 2004 were selected for the empirical Green’s functions because the focal mechanism was close to that of the mainshock. This event was recorded by several stations, except for the TZO, MLA, and ADF stations, where we used Mw 4.7 on 1 October 2004 as the empirical Green’s function; this event has a focal mechanism that is different from that of the mainshock.

Figure 1. Map showing the Mw 6.8 mainshock, the two aftershocks used in this study, and the locations of the stations. The yellow stars indicate the epicenters of the earthquakes.
2.2 Source Modeling of Strong Motion Generation Areas

Several studies have determined slip distribution models of the 2003 Boumerdes earthquake using different types of data (e.g., geodetic, teleseismic, and strong motion). All of these published rupture models (Meghraoui et al., 2003; Delouis et al., 2004; Semmane et al., 2005; Belabbès et al., 2009; Santos et al., 2015) show the existence of at least two asperities: the first asperity is located northeast of the hypocenter where the maximal displacement reaches 3 m and the second asperity is located southwest of the hypocenter in a shallow region (Figure 2).

Asperities are regions that have large slip relative to the average slip in the rupture area (Somerville et al., 1999). In addition, it has been shown that strong ground motion is primarily produced by large slips occurring at asperities (Miyake et al., 2003). Therefore, synthetic ground motions can be calculated assuming that ground motions are only generated within the strong motion generation areas, which are redefined based on the asperity location and the area information (Kamae and Irikura, 1998; Miyake et al., 2003).

We fixed the following fault parameters: the epicenter is located at 36.846° N and 3.660° E, the strike, dip, and rake angles are 64°, 50°, and 97°, respectively, and the hypocenter depth is 8 km (Santos et al., 2015).

The initial source model for the ground motion simulation was established based on the slip distribution shown in Figure 2. Two strong motion generation areas (SMGAs) corresponding to the two asperities were constructed for this model. SMGA1 corresponds to the first asperity located southwest of the hypocenter, and SMGA2 corresponds to the second asperity located northeast of the hypocenter.

The parameters N and C, which are the number of subfaults at each asperity and the stress drop ratio, respectively, were obtained from the acceleration amplitude ratio of the small and large events. Figure 3 shows the amplitude ratio for the two stations EDB and TZO located west and east of the hypocenter, respectively. The ratio of the corner frequencies of the small and large events (fa and fo, respectively,) gives an estimate of N, while the ratio of the seismic moments (g) gives C × N³; then, we can estimate the values of C and N as an initial guess for the EGFM.

The final source parameters, such as N, C, the starting point rupture for each SMGA, and the rise time, were obtained by applying a trial-and-error forward modeling method that produced a good match between the observed and simulated ground motions. It has been shown that waveforms at the TZO station were primarily dominated by SMGA1, while waveforms at the CGS, EDB, and KTA stations located west of the hypocenter were dominated by SMGA2. Figure 4 shows the source model composed of two strong motion generation areas for the Mw 6.8 Boumerdes earthquake, and Table 2 shows all the parameters used for our simulation. After trial and error, we selected a rupture velocity of 2.8 km/s corresponding to 90% of the shear wave velocity (3.1 km/s).

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Depth (km)</th>
<th>Magnitude</th>
<th>Strike/dip/rake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main shock</td>
<td>05/21/2003</td>
<td>18:44:11</td>
<td>36.83</td>
<td>3.65</td>
<td>Mw 6.8</td>
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<td></td>
<td>54/50/88</td>
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<tr>
<td>After shock 1</td>
<td>01/10/2004</td>
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<td>36.85</td>
<td>3.42</td>
<td>Mw 4.7</td>
<td>24/67/-5</td>
</tr>
<tr>
<td>After shock 2</td>
<td>02/02/2004</td>
<td>17:42:24</td>
<td>36.85</td>
<td>3.45</td>
<td>Mw 4.3</td>
<td>18/48/45</td>
</tr>
<tr>
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<td></td>
<td>255/58/128</td>
</tr>
</tbody>
</table>

Table 1. Characteristics of the Mw 6.8 mainshock and the two aftershocks used in this study.

The hypocenter locations are from the International Seismological Center Bulletin.
Figure 2. Slip model of the Mw 6.8 mainshock (Santos et al., 2015).

Figure 3. Fourier spectral ratios of the Mw 4.3 and Mw4.5 aftershocks to the mainshock for the EDB and TZO stations.
Figure 4. Source model composed of two strong motion generation areas for the Mw 6.8 Boumerdes earthquake.

| Table 2. Source parameters of the two strong motion generation areas for the Mw 6.8 Boumerdes earthquake. |
|---|---|---|---|---|
| SMGA1 | SMGA2 |
| N  C  Rise time (s) Starting point (along strike, along dip) | N  C  Rise time (s) Starting point (along strike, along dip) |
| 4  3.12  0.12 (3, 2) | 7  1.0  0.12 (7, 4) |

2.3 Results and Discussion

Figure 5 shows a comparison between the simulated and observed waveforms of the mainshock in terms of acceleration, velocity, and displacement in the frequency range of 0.25–10 Hz. The Fourier amplitudes and the response spectra comparison between the recorded and simulated ground motions are shown in Figure 6.

The best source model was obtained by fitting the synthetic accelerations, velocities, and displacement waveforms to the observed ones. Seismic wave propagation and site amplification effects on the strong ground motion were explicitly taken into account by considering the aftershocks recorded at the same stations as the empirical Green’s functions.

The EGFM was applied using the Mw 4.3 aftershock for all stations, except TZO, where we used an Mw 4.5 aftershock event as the Green’s function. The quality of the fit between the simulated and observed waveforms was quantified via a visual inspection, and an acceptable visual match was obtained for all stations, except CGS and KTA, which are located 60 km from the hypocenter and where we can show that the accelerations obtained are underestimated compared to the observed ones. This could be due to the inadequacy of the Green’s function used (the location and focal mechanism), or it may be due to problems with the localization of the fault plane.

Large displacements at later phases for the EDB, CGS, and KTA stations could be due to the surface waves generated along the path due to the presence of the quaternary Metija Basin (Laouami and Slimani, 2013). These displacements were roughly reproduced by the EGFM.
The TZO station is 40 km from the hypocenter in the eastern region, and there is only one Mw 4.5 aftershock that has a record available for use as an empirical Green's function. We found that the strong ground motion was produced primarily by SMGA1. The rupture starting point was assumed to be close to the hypocenter. Conversely, the EDB, CGS, and KTA stations were primarily influenced by SMGA2, which is located northeast of the hypocenter.

Waveforms at the EDB station located 40 km from the hypocenter show large values of peak ground velocity (PGV) for the two components and reach a value of PGV = 41 cm/s for the north/south component with a pulse-like shape with a period of approximately 3–4 s. This effect was moderately
reproduced by the EGFM and is related to rupture propagation at the second asperity (SMGA2) located less than 25 km from this station (a directivity effect). A peak ground acceleration of 0.5 g was recorded at this station in both directions. This value was obtained by our EGFM simulation in both directions, which reveals important site effect amplifications. As for the waveform comparisons at the CGS and KTA stations, there is a possibility of the source model and asperity locations based on the slip inversion result are sensitive, and there are still room to be improved.

![Waveform comparisons for different stations](image)

Figure 6. Comparison of observed (blue) and simulated (red) Fourier amplitudes and 5%-damped acceleration response spectra at different stations for the Mw 6.8 mainshock.

Other source parameters, such as N, C, and the rise time, were estimated using the EGFM. Broadband ground motion simulations were performed for stations located primarily west of the hypocenter, except for TZO, which is located to the east. The results show good agreement between the simulated
3. STRONG MOTION SIMULATION OF THE MW 5.7 BOUMERDES AFTERSHOCK EARTHQUAKE

We applied the EGFM to simulate the Mw 5.7 event that occurred on 27 May 2013, which was one of the largest aftershocks of the mainshock. This event was recorded by two stations: CRD (Boumerdes) and ST1 (Keddara). We set the fault plane solution of this aftershock using the CMT solution. The actual fault plane considered in this study has strike, dip, and rake angles equal to 68°, 24°, and 92°, respectively.

Table 3 shows the characteristics of the aftershocks used as the empirical Green’s functions. The location of the Mw 4.3 aftershock is very close to the CRD station (less than 5 km), therefore we decided to use, as the empirical Green’s function, the Mw 4.7 earthquake event, which has a similar focal mechanism and is located at the same distance as the Mw 5.7 event from the station (Figure 7). We used the same rupture velocity and shear wave velocity for the simulation of the Mw 5.7 event.

The source spectral ratio fitting method was used to estimate the parameters N and C that correspond to the two aftershocks used for the CRD and ST1 stations (Table 3). The parameters of the strong motion generation area were estimated using forward modeling by fitting the simulated waveforms to the observed waveforms. Table 4 shows all the parameters used for our simulation. The size of each subfault is 1.4 km × 1.2 km; therefore, the strong motion generation area is estimated to be 5.6 km long × 4.8 km wide (Figure 8). The starting point is assumed to be the hypocenter location. There are a lot of uncertainties about the SMGA locations, N and C parameters, starting point, rise time. This is why we do not obtain the exact same values for source parameters to simulate acceleration, velocity, and displacement. Currently, the waveform comparisons were done visually and the results show good agreement for some stations. For other stations, there are still some works to check the source model as well as Green’s functions to obtain a better source model for strong ground motion simulation of the 2003 Boumerdes earthquake sequence. Figure 9 shows the waveform fittings for the two stations in terms of acceleration, velocity, and displacement in the frequency range of 0.25–10 Hz. The overall fit is very good for the two stations.
Figure 7. Map showing the Mw 5.7 event, the two aftershocks used in this study, and the locations of the stations. The yellow stars indicate the epicenters of the earthquakes.

Table 3. Characteristics of the Mw 5.7 event and the two aftershocks used in this study.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Depth (km)</th>
<th>Magnitude</th>
<th>Strike/dip/rake</th>
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<td>05/27/2003</td>
<td>17:11:28</td>
<td>36.94</td>
<td>3.58</td>
<td>Mw 5.7</td>
<td>68/24/92</td>
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<td>246/66/89</td>
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<tr>
<td>After</td>
<td>12/01/2004</td>
<td>17:42:24</td>
<td>36.85</td>
<td>3.45</td>
<td>Mw 4.3</td>
<td>18/48/45</td>
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<td>shock 1</td>
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<td>255/58/128</td>
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<tr>
<td>After</td>
<td>28/05/2003</td>
<td>06:58:37</td>
<td>36.88</td>
<td>3.27</td>
<td>Mw 4.7</td>
<td>88/28/107</td>
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<td>shock 2</td>
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<td>248/63/81</td>
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</table>

Table 4. Source parameters of the strong motion generation area for the Mw 5.7 event.

<table>
<thead>
<tr>
<th>N</th>
<th>C</th>
<th>Rise time (s)</th>
<th>Starting point (along strike, along dip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mw 4.7 (CRD station)</td>
<td>4</td>
<td>0.7</td>
<td>(4 , 2)</td>
</tr>
<tr>
<td>Mw 4.3 (ST1 station)</td>
<td>4</td>
<td>1.0</td>
<td>(4 , 2)</td>
</tr>
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</table>
Source scaling

Based on the results of the empirical Green’s function simulations, we investigated the source scaling properties of the Mw 6.8 mainshock and the Mw 5.7 event for the 2003 Boumerdes earthquake by comparing the estimated source parameters with the empirical source scaling relationship for crustal earthquakes proposed by Somerville et al. (1999) and Miyake et al. (2003). The scaling relationship of Somerville et al. (1999) was derived using the results of waveform inversions at frequencies less than 1 Hz, and that of Miyake et al. (2003) was derived using empirical Green’s function simulations in the frequency band between 0.2 Hz and 10 Hz.

A comparison was made in terms of the size of the strong motion generation area versus the seismic moment and in terms of the rise time for the strong motion generation area versus the seismic moment.
For the Mw 6.8 mainshock, the total area of the two SMGAs used and the rise time were \( Sa = 130 \text{ km}^2 \) and \( T = 1.0 \text{ s} \) respectively. For the Mw 5.7 aftershock, we obtained \( Sa = 30 \text{ km}^2 \) and \( T = 0.4 \text{ s} \). The results of the source scaling characteristic analysis are presented in Figure 10. We can clearly conclude that the source parameters obtained in this study in terms of the strong motion generation area and the rise time are in good agreement with the published scaling laws of Somerville et al. (1999) and Miyake et al. (2003) for crustal earthquakes.

Figure 10. (a) Source scaling of the combined areas of the asperities and the strong motion generation areas to the seismic moment. (b) Source scaling of the rise time to the seismic moment. In both panels, based on Somerville et al. (1999) and Miyake et al. (2003) for crustal earthquakes, the red and blue triangles mark the Mw 6.8 and Mw 5.7 source parameters, respectively.

5. CONCLUSIONS

The strong ground motion of the 2003 Boumerdes earthquake was simulated using the EGFM. The source model of the Mw 6.8 mainshock included two SMGAs that are nearly compatible with the asperities derived from the waveform inversions. Other source parameters, such as N, C, and the rise time, were estimated using the EGFM.

Broadband ground motion simulations were performed for stations located primarily west of the hypocenter, except for the TZO station, which is located east of the hypocenter. Waveforms recorded at a station located in Dar el Beida, 40 km from the hypocenter, show a clear forward directivity pulse with a dominant period of 3–4 s corresponding to the second asperity located in the southeastern part of the surface rupture.

In addition, the EGFM was used to simulate the strong ground motion of the Mw 5.7 aftershock recorded by two stations in the near field. The source model allowed for the simulation of ground motion waveforms that showed good agreement with the observed waveforms.

The source parameters, in terms of the strong motion generation area and rise time, obtained for the two events simulated in this study were compared to the scaling laws established for inland earthquakes by Miyake et al. (2003); we found that the obtained results conform to the scaling laws. Therefore, the use of a recipe (Irikura and Miyake, 2011) is possible for seismic scenarios with crustal earthquakes corresponding to active faults in North Africa by constructing source models based on scaling laws.
6. ACKNOWLEDGMENTS

Several figures are drawn by using the Generic Mapping Tools (Wessel and Smith, 1998) and ViewWave (Kashima, 2014).

7. REFERENCES


