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PRELIMINARY OBSERVATIONS OF GEOTECHNICAL FAILURES DURING THE 21 MAY 2003 M 6.8 BOUMERDES, EARTHQUAKE, ALGERIA[*]

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ABSTRACT

At 18:44 UTC (19:44 local time) on May 21, 2003, a strong, shallow earthquake of Moment Magnitude (M) 6.8 shook northern Algeria and caused damage in five provinces in the north-central section of the country. Damage was reported over an area about 100 km long and 35 km wide, centered on the city of Boumerdes. The hardest hit areas were in the coastal province of Boumerdes, mainly in the cities of Boumerdes, Zemmouri and Thenia. The earthquake appears to have been generated by an offshore south-dipping thrust fault oriented N54°E extending for about 35 km from Dellys to Corso. The fault rupture was bilateral, with a greater asymmetry to the southwest. The ground motions recorded from the mainshock were significantly higher than median values predicted by standard attenuation relationships. Liquefaction and lateral spreading occurred near the Isser River and areas with extensive beach sand deposits. In the port of Algiers, nine piers suffered damage where liquefaction, loss of ground support, and lateral displacement (seaward movements) of the bulkheads were pervasive. Cracks developed on the Keddara and Beni Amrane Dams and the water line running from the Keddara Dam to the Boudouaou water treatment plant suffered damage at two locations.

INTRODUCTION

At 18:44 UTC (19:44 local time) on May 21, 2003, a strong, shallow earthquake of Moment Magnitude (**M**) 6.8 shook northern Algeria and caused damage in five provinces in the north-central section of the country. The epicenter was located offshore at 36.91°N 3.58°E (Center of Research in Astrophysics, Astronomy and Geophysics [CRAAG]), 7 km north of Zemmouri in the province of Boumerdes, and about 50 km east of the capital city of Algiers (Fig. 1).

Damage was reported over an area about 100 km long and 35 km wide, centered on the city of Boumerdes. The hardest hit areas were in the coastal province of Boumerdes, mainly in the cities of Boumerdes, Zemmouri and Thenia (Fig. 1), as well as the eastern districts of Algiers. Most of the construction in the damaged areas was built in the last 30 years; however, several large buildings dating from the colonial era (early 20th century) were heavily damaged in the districts of Belcourt, Bab-El-Oued and El-Casbah in Algiers.

The affected area is heavily developed and urban. The total estimated death toll was over 5,000 and about 11,000 people were injured. Damage was estimated at US$5 billion. About 182,000 apartments and private houses were damaged, of which 19,000 suffered complete collapse.

The earthquake also generated a tsunami observed as far away as the Balearic Islands and the southern coast of Spain. However, there was little or no tsunami damage along the Algerian coast.

In this paper, we document some preliminary observations concerning the source of the earthquake, the earthquake ground motions recorded in northern Algeria, and geotechnical ground failures resulting from strong ground shaking.

SEISMOTECTONIC SETTING

Northern Algeria is located along the convergent plate boundary between Eurasia and Africa (Fig. 2). This is one of the most seismically-active regions in the western Mediterranean, having experienced several large, damaging earthquakes during historic time, including the 1716 Algiers (Epicentral Intensity, I_o IX), 1790 Oran (I_o XI), 1889 Mascara (I_o IX) earthquakes, and more recently the 1980 surface wave magnitude (M_s) 7.3 El Asnam, 1985 M_s 6.0 Constantine, 1989 M_s 6.0 Tipasa, 1994 M_s 6.0 Mascara, 1996 M_s 5.7 Algiers, and 1999 Ain Temouchent M_s 5.8 earthquakes.

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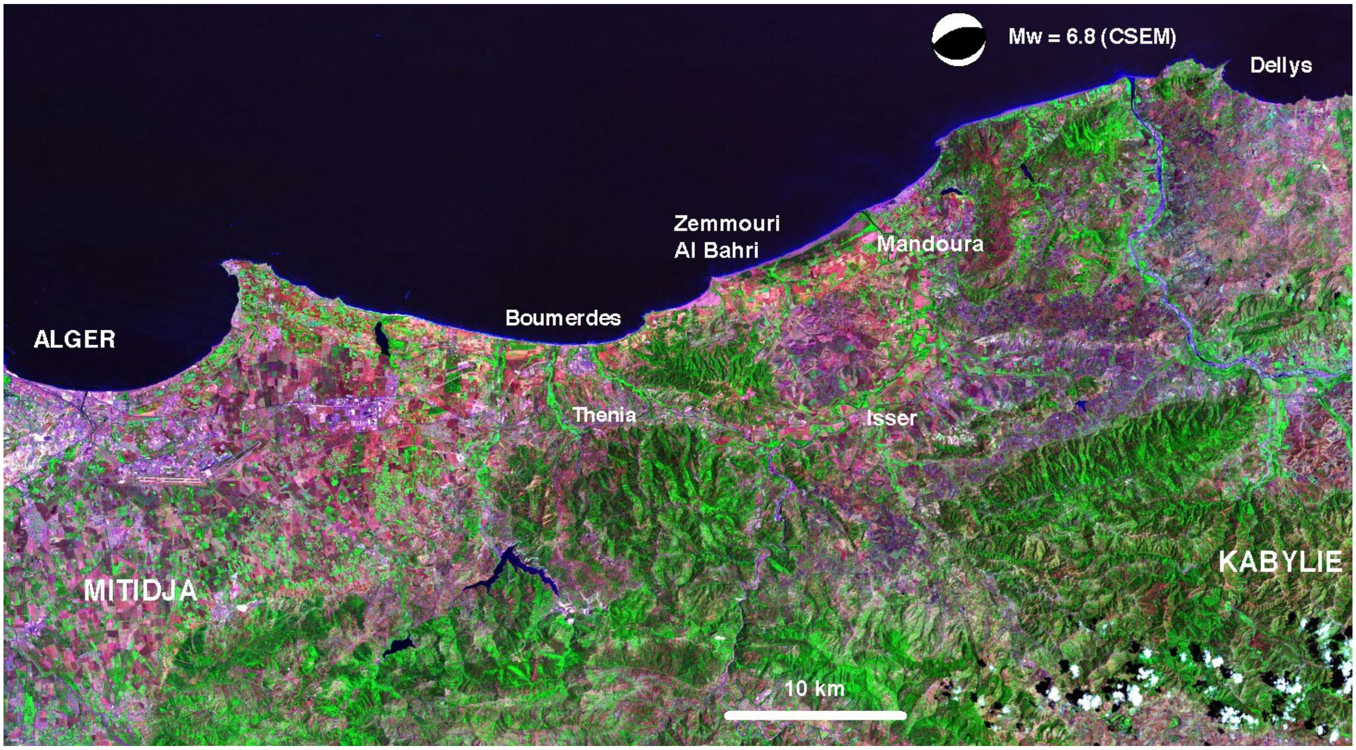


*Fig. 1. Location of the May 21 2003, **M** 6.8 Boumerdes, Algeria Earthquake*

All these events have been located in the Tellian Atlas (Fig. 2), a broad region of active east-northeast-oriented folds and thrust faults along the northern margin of a broad zone of crustal deformation that is at least 200 km wide and 1200 km long (Hamdache, 1998). Present day plate convergence, calculated from the NUVEL-1A global plate model of DeMets *et al.* (1990; 1994), is occurring at a rate of 6.2 ± 0.5 mmyr^{-1} in a N17°W ± 9° direction. Although this large-scale plate motion is relatively well constrained, the kinematics of the deformation within the Africa/Eurasia plate boundary zone is still poorly understood, primarily because of the lack of high quality geodetic measurements from the North African side of the plate boundary.

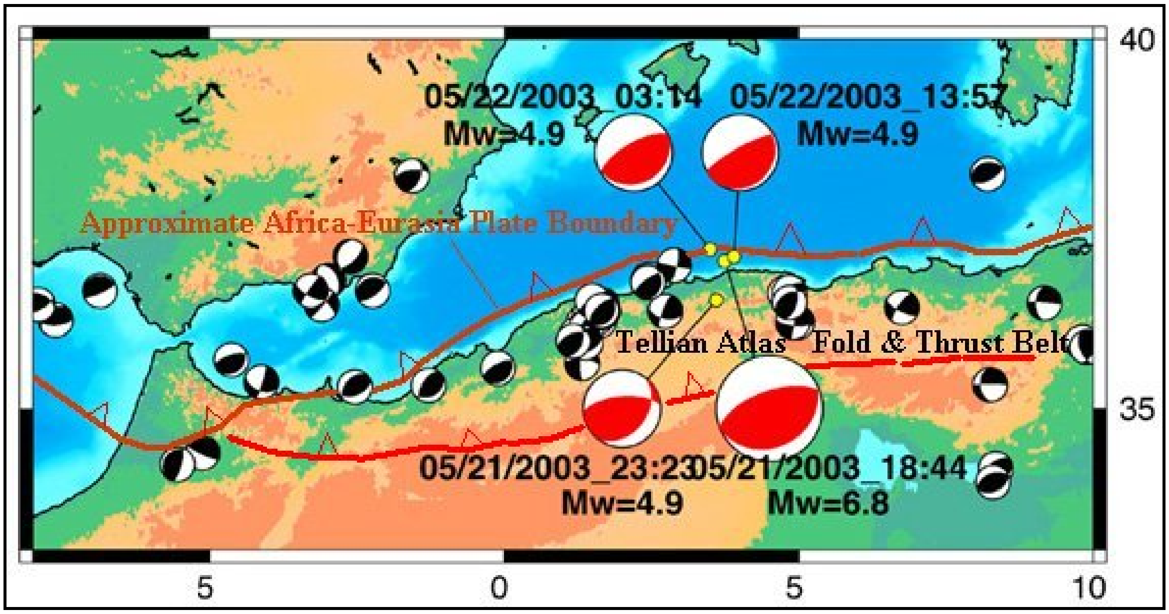


Fig. 2. Plate tectonic setting of Northern Algeria

The folds and thrust nappes of the Tellian Atlas are separated by intervening basins (*e.g.*, Cheliff and Mitidja basins). These basins formed during the Miocene as a result of N-S extension (Philip, 1987). However, since the Pliocene, this region has been undergoing N- to NNW-oriented compression as Africa moved northwards with respect to Eurasia. This compression is still active as demonstrated by the contemporary seismic activity in the region. These earthquakes occur predominantly around the Cheliff and Mitidja basins, which are bounded by active faults (Boudiaf *et al.*, 1998). The Mitidja basin is bordered to the north by the Sahel anticline (Fig. 3). This structure deforms Plio-Pleistocene deposits and is considered the surface manifestation of a blind thrust (Meghraoui, 1990). Northwest-striking right-lateral strike-slip faults segment the anticline. Near Thenia, the eastern continuation of the Mitidja basin is displaced in a right-lateral manner by the west-northwest-striking Thenia fault which extends offshore of Algiers. Northwest of Boumerdes, the fault is marked by a N70°W-trending scarp in Plio-Pleistocene deposits, also indicating a component of up-to-the-south reverse movement (Boudiaf *et al.*, 1998).

The 2003 Boumerdes earthquake was located along the northern margin of the Tellian Atlas, along the offshore part of the eastern continuation of the Mitidja basin (Fig. 3). This is an area characterized by a crystalline basement complex of gneiss, basalt, schist, and some granite, and un-metamorphosed to slightly metamorphosed Paleozoic sandstone, shale and limestone with basin-fill cover rocks of Mesozoic and Cenozoic flysch and carbonates. This structure of this area is dominated by inverted basin-bounding faults that now form a series of south-vergent nappes. Like the remainder of the Tellian Atlas region, this area is characterized by N-S to NNW-SSE compression, which peaked during the Upper Pliocene. This compression continues today. The previously unidentified Zemmouri fault, a south-dipping, blind back thrust, located offshore, is considered the source of the 2003 earthquake (Fig. 3). This fault was unknown previously because no fault mapping has ever been done offshore the coastline of Algeria.

The Boumerdes region has been affected by numerous low to moderate magnitude earthquakes (M_L 3.5 to 5.0) (Fig. 4). Some of these earthquakes, for example, the earthquake of January 28, 1961, occurred along the coastline. The historical seismicity catalog reveals several large earthquakes in the Algiers region, including that of January 28, 1716 (I_o X) earthquake, which destroyed Algiers and caused more than 20,000 deaths. It is possible that some of the historic earthquakes identified by CRAAG in the vicinity of the Thenia fault may actually have occurred on the Zemmouri fault. The orientation of the Thenia fault with respect to the neotectonic stress field indicates that it is possibly a tear fault, accommodating differential contraction across the Sahal anticline – Mitidja basin region. This suggests that the Thenia fault is currently not a major independent seismic source capable of generating large, damaging earthquakes. Instead, the Zemmouri fault and other blind thrusts in the region are the dominant seismic sources with the Thenia fault accommodating along-strike slip heterogeneity. Repeated movement on the Zemmouri fault during recent geologic time is indicated by the series of uplifted and warped marine terraces along the coast near Zemmouri Al Bahari (Boudiaf *et al.*, 1998).

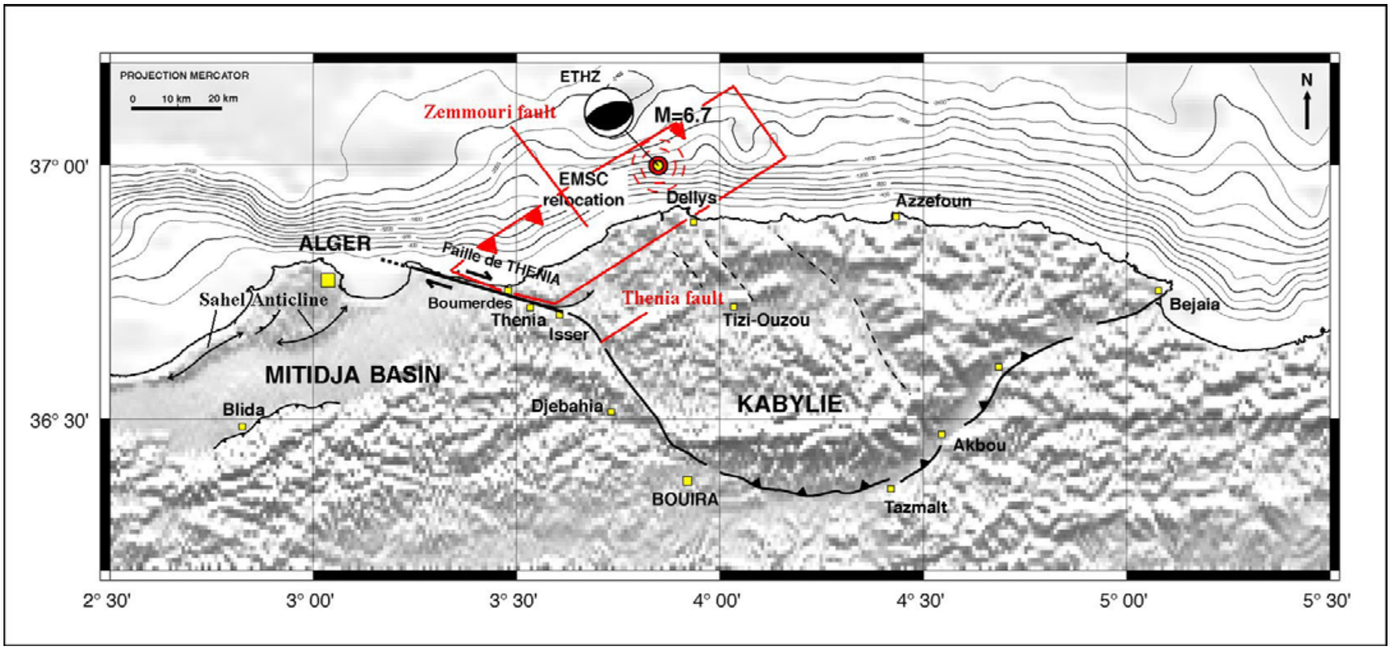
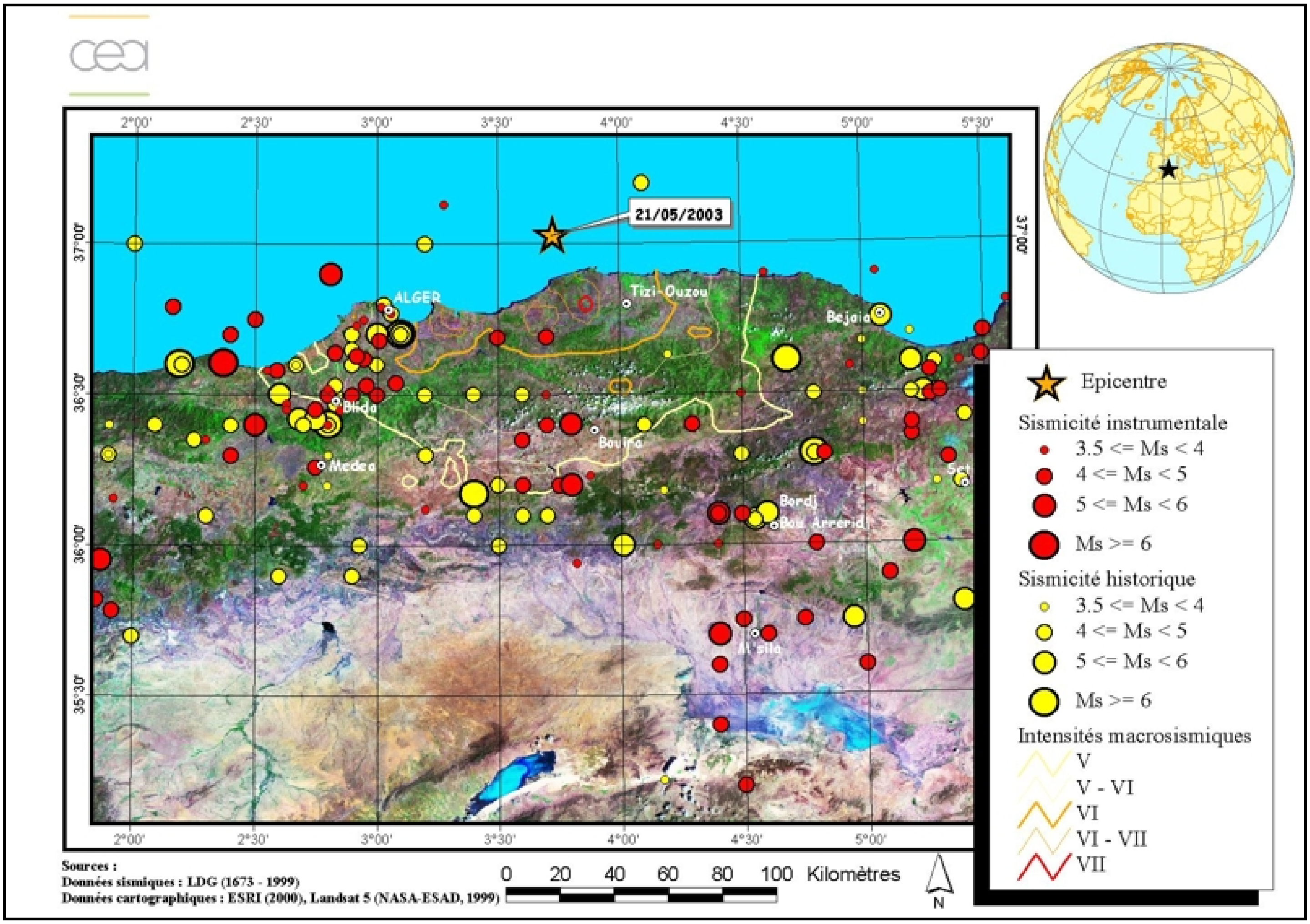


Fig. 3. Major active geologic structures in the Tellian Atlas region



Sources :
Données sismiques : LDG (1673 - 1999)
Données cartographiques : ESRI (2000), Landsat 5 (NASA-ESAD, 1999)

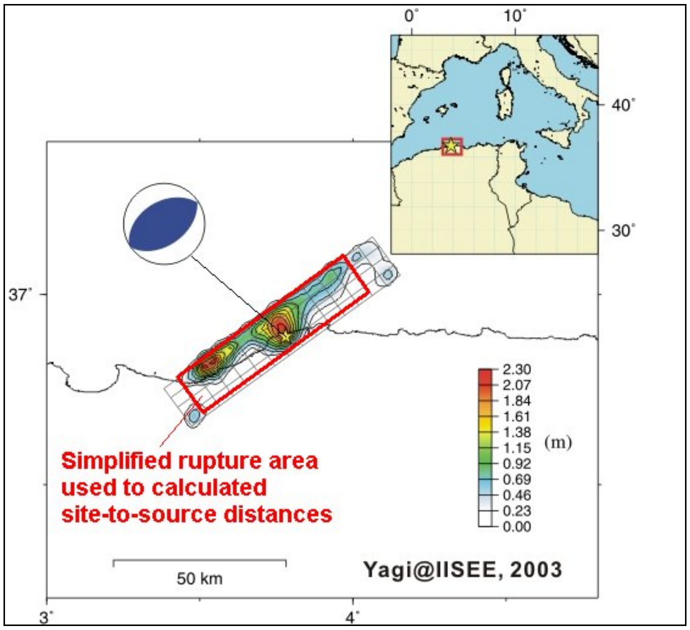
Fig. 4 Historical and instrumental seismicity, Northern Algeria

BOUMERDES EARTHQUAKE PARAMETERS

The Boumerdes earthquake (Fig. 3), with a maximum Modified Mercalli Intensity (MMI) of X, caused significant damage in the region between Dellys and Algiers. The Algerian seismological network operated by Center of Research in Astrophysics, Astronomy and Geophysics (CRAAG) located the epicenter of the mainshock on the Mediterranean margin at 36.91°N, 3.58°E. Using the time duration of seismic signals from the CRAAG stations, a Richter Local Magnitude (M_L) 6.2 was calculated. It must be noted that the National Earthquake Engineering Research Center (CGS), which operates the strong motion network in Algeria, computed an epicentral location of 3°53E, 36° 81N, and a magnitude of **M** 7.0, and strong motion duration of about 10 seconds. The U.S. Geological survey reported a magnitude for the earthquake of **M** 6.8.

A hypocentral depth of 10 km was determined, which is similar to that of most previous Algerian earthquakes. The focal mechanism corresponds to a northeast-striking thrust fault (N54°E), dipping 47°SE with a rake of 86°. Over 1,000 aftershocks occurred in the six weeks following the mainshock, with two events of M_L 5.8 on 24 and 28 May 2003.

Yagi (2003) used teleseismic body wave (P-wave) data recorded at IRIS stations for waveform inversion using the procedure of Fukahata *et al.* (2003). Using the US Geological Survey location epicentral of 36.89°N, 3.78°E, **M** 6.9, strike N54°E, dip 47°, and rake 86°, hypocentral depth of 10 km, and source duration of 18 s, the source process is characterized asymmetric bilateral rupture propagation. The main rupture mainly propagated 30 km to the southwest and 20km northeast (Fig. 5). The rupture extended to surface of the earth. Two asperities (large slip areas) are identified. The maximum displacement is about 2.3 m at a distance of 25 km southwest from hypocenter.



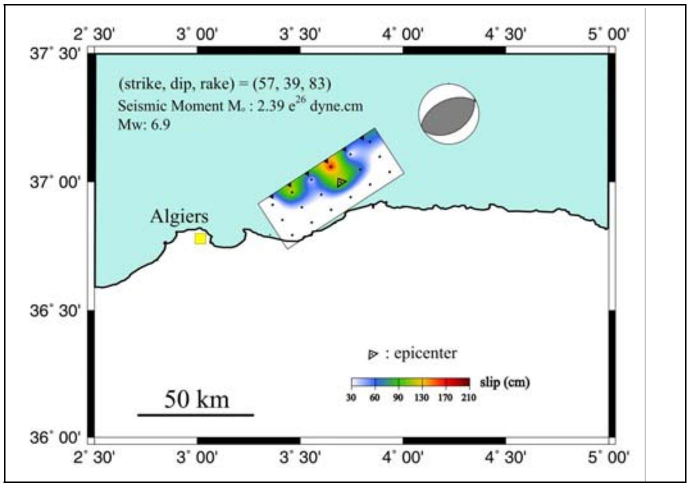


Fig. 5. Fault plane inversion models from Yagi (2003), left, and DeLouis and Vallee (2003), right. The red polygon on the left-hand map represents the simplified rupture area used in our ground motion analysis

DeLouis and Vallee (2003) developed a slightly different inversion slip model with a shorter rupture duration and higher maximum slip (Fig. 5). Both models however, show the same overall rupture geometry, with a major slip asperity in the area of the hypocenter, bilateral rupture, with a slight bias to the southwest, and the development of a secondary asperity (sub-event?) towards the southwestern end of the rupture plane.

Although the fault experienced bilateral rupture, the models of both Yagi (2003) and DeLouis and Vallee (2003) both indicate that the rupture pattern was slightly asymmetric with 30 km propagation to the SW and 20 km propagation to the NE. Due to this rupture propagation asymmetry, most of its energy was directed towards the SW. Thus, due to the directivity, the expected damage zone is oriented southwest towards Zemmouri, Boumerdes and Algiers.

SURFACE DEFORMATION

Surface fracturing was observed onshore in the epicentral area; in the area of Corso, in the port region of Zemmouri, and near Dellys. Fractures were observed on the Thyrrhenian marine terraces along the coast to the east of Algiers. The fractures were oriented N130° and N20° and were observed in unconsolidated Quaternary sediments discontinuously from Ain Taya to Zemmouri. These fractures are assumed to be a result of localized surface extension, and not fault rupture. If our hypothesis of the Thenia fault acting as a tear fault to accommodate differential slip is accepted, it is unlikely that slip along the Zemmouri fault can propagate to the southwest beyond the mapped trace of the Thenia fault.

Geological investigations also revealed offshore effects such as uplift of the seafloor of at least 0.50 m, and minor landslides and liquefaction along the coastline. Deformation of the seafloor resulted in a small tsunami that was recorded along the Balearic coast of Spain (Hébert, 2003).

GROUND MOTION RECORDS

The National Earthquake Engineering Research Center (CGS) operates and maintains Algeria’s strong motion instrumentation network (Fig. 6). Several of their instruments triggered during the earthquake. The closest instrument to record the earthquake is located about 20 km from the epicenter.

Following the mainshock, the network was augmented by a number of mobile accelerographs which enabled the collection of additional records from aftershocks, including the 27 May, 2003, **M** 5.8 aftershock recorded in Boumerdes about 7 km away from the epicenter. Preliminary information on recorded peak ground accelerations (PGA) provided by CGS is reported in Table 1.

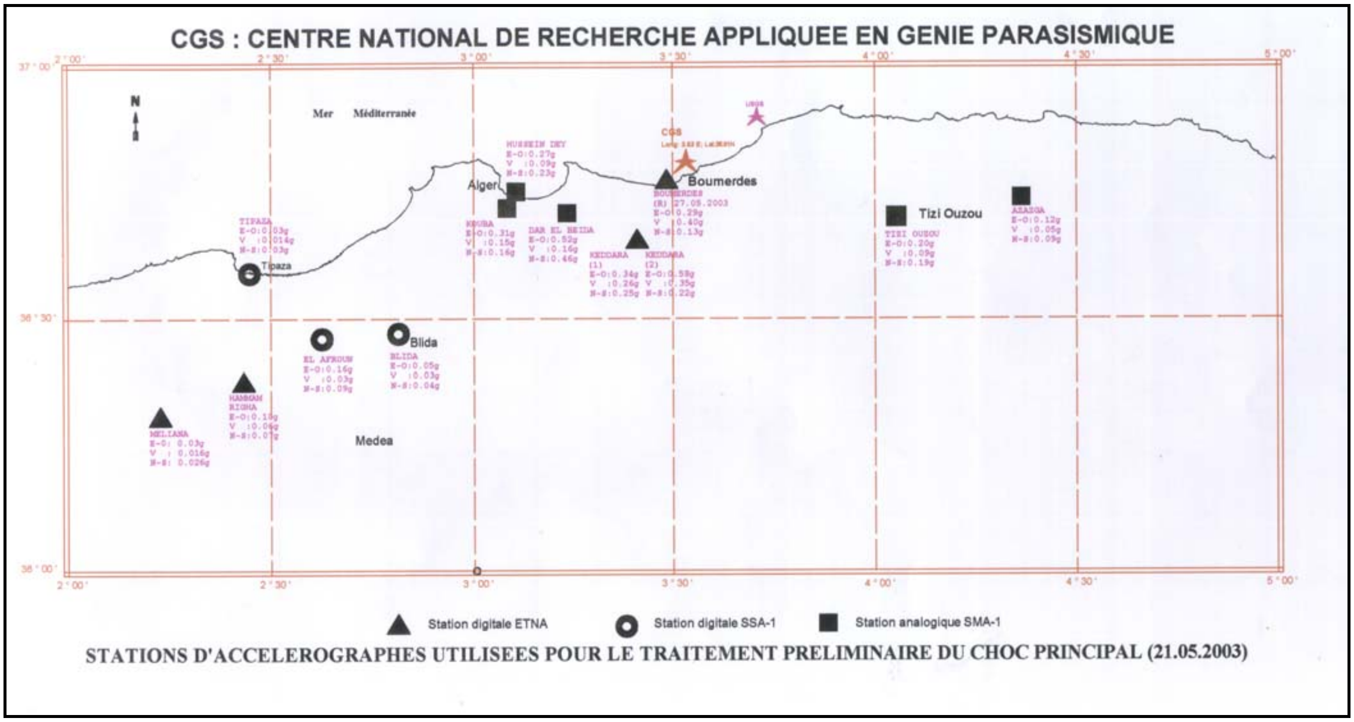


Fig. 6. Instrument location map and recorded ground motions

Table 1. Preliminary Strong Motion Data

21 May 2003 **M** 6.8 Mainshock

Station	Distance to Epicenter (km)	E-W (g)	N-S (g)	Vertical (g)
Keddara Dam 1	20	0.34	0.24	0.26
Keddara Dam 2	20	0.58	0.22	0.35
Hussein Dey	36	0.27	0.23	0.09
Dar El Beida	29	0.52	0.46	0.16
Blida	72	0.046	0.038	0.028
El Affroun	86	0.16	0.09	0.03

27 May 2003 **M** 5.8 Aftershock

Station	Distance to Epicenter (km)	E-W (g)	N-S (g)	Vertical (g)
Boumerdes	7	0.29	0.13	0.40

From examination of these data, the following preliminary observations can be made:

a) The E-W acceleration component was consistently larger than the N-S component for all recording stations.

b) Soil sites experienced higher accelerations than rock site as exhibited by the difference in motions between Keddara Dam 1 (rock) and Keddara Dam 2 (soil) sites, and by the high accelerations recorded in Dar El Beida (soil). The strongest ground motions were recorded at the Keddara Dam 2 (soil) site, located about 20 km southwest of the epicenter. The acceleration time histories from Keddara Dam 1 and 2 are shown in Fig. 8.

c) There is evidence of significant vertical motion in the epicentral region. This is supported by the fact that a concrete cap sitting atop a small brick transformer housing in the city of Boumerdes was lifted and thrown about 2 m from its original position (Fig. 7). This indicates that the peak vertical acceleration exceeded 1g in the region very close to the epicenter. A vertical acceleration of 0.40g was also recorded during the **M** 5.8 aftershock of 27 May 2003 on a mobile station in Boumerdes (Table 1).

Fig. 7. Concrete cap thrown from its original location

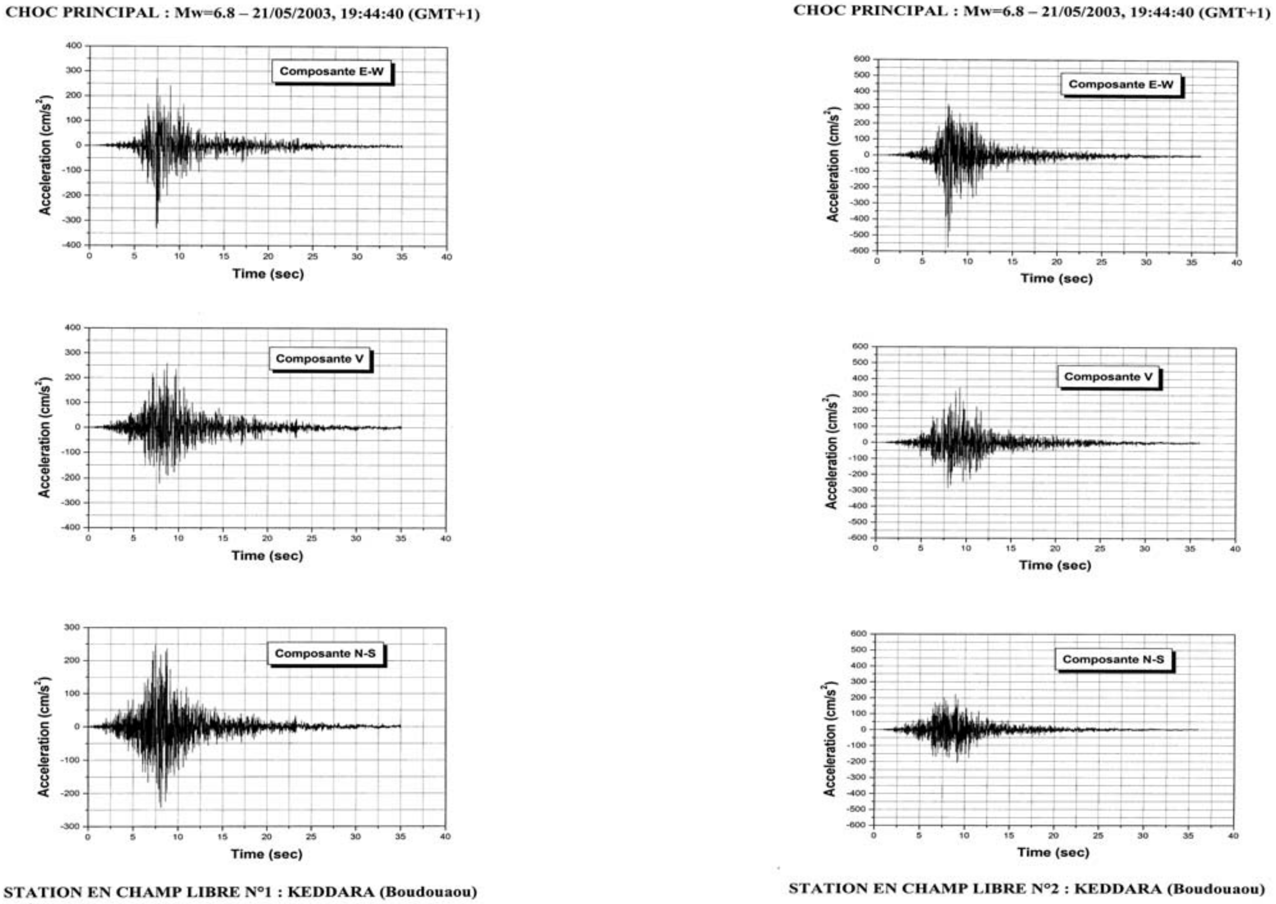


Fig. 8. Recorded acceleration time histories from Keddara 1 and Keddara 2 stations

At the time of the preparation of this paper, the digital records from strong motion stations were not available to perform response spectra analyses. The previously discussed bilateral fault rupture mechanism with energy release (slip) along the southwestern extent of the fault could exhibit near-field directivity effects in the recorded ground motions to the south and west of the epicenter. These effects would be expressed as large spectral amplitudes in the long period range in the south-east/north-west direction (fault-normal components).

We conducted a comparison of the recorded peak ground accelerations with those obtained from predictive attenuation relationships. The attenuation relationships used were Abrahamson and Silva (1997), Boore *et al.* (1997), and Sadigh *et al.* (1997). The reverse fault rupture style was used in the attenuation relationships. The attenuation relationships for both soil and rock sites were applied and are presented in Figs. 9 and 10, respectively. These are compared with the recorded horizontal components from the mainshock. The fault rupture dimensions used in this analysis considered a combination of the inversion models developed by Yagi (2003) and by DeLouis and Vallee (2003) (Fig. 5). These two models were compared, and only the rupture area with a significant to large slip was incorporated in our "simplified" rupture area model (the red polygon in Fig. 5). This model was then used for estimating the seismogenic distances between fault rupture and recording stations. These distances were use in the attenuation relationships above to calculate predictive ground motions. All the recorded data were plotted on both Figs. 10 and 11 because the site conditions are still not known for most of the sites at this time.

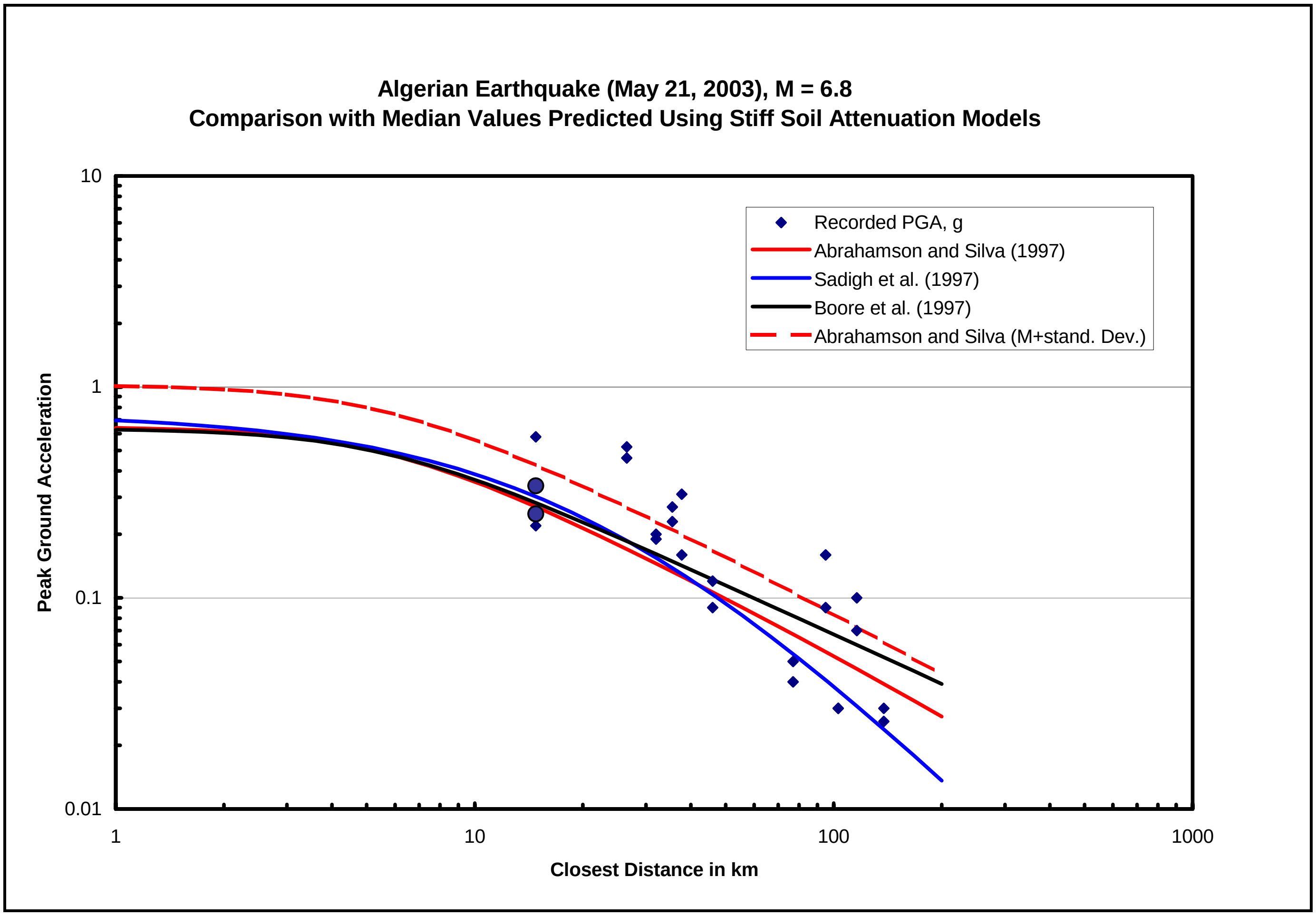


Fig. 9. Recorded PGAs compared to attenuation relationships for soil sites. The two circles represent the rock site at Keddara

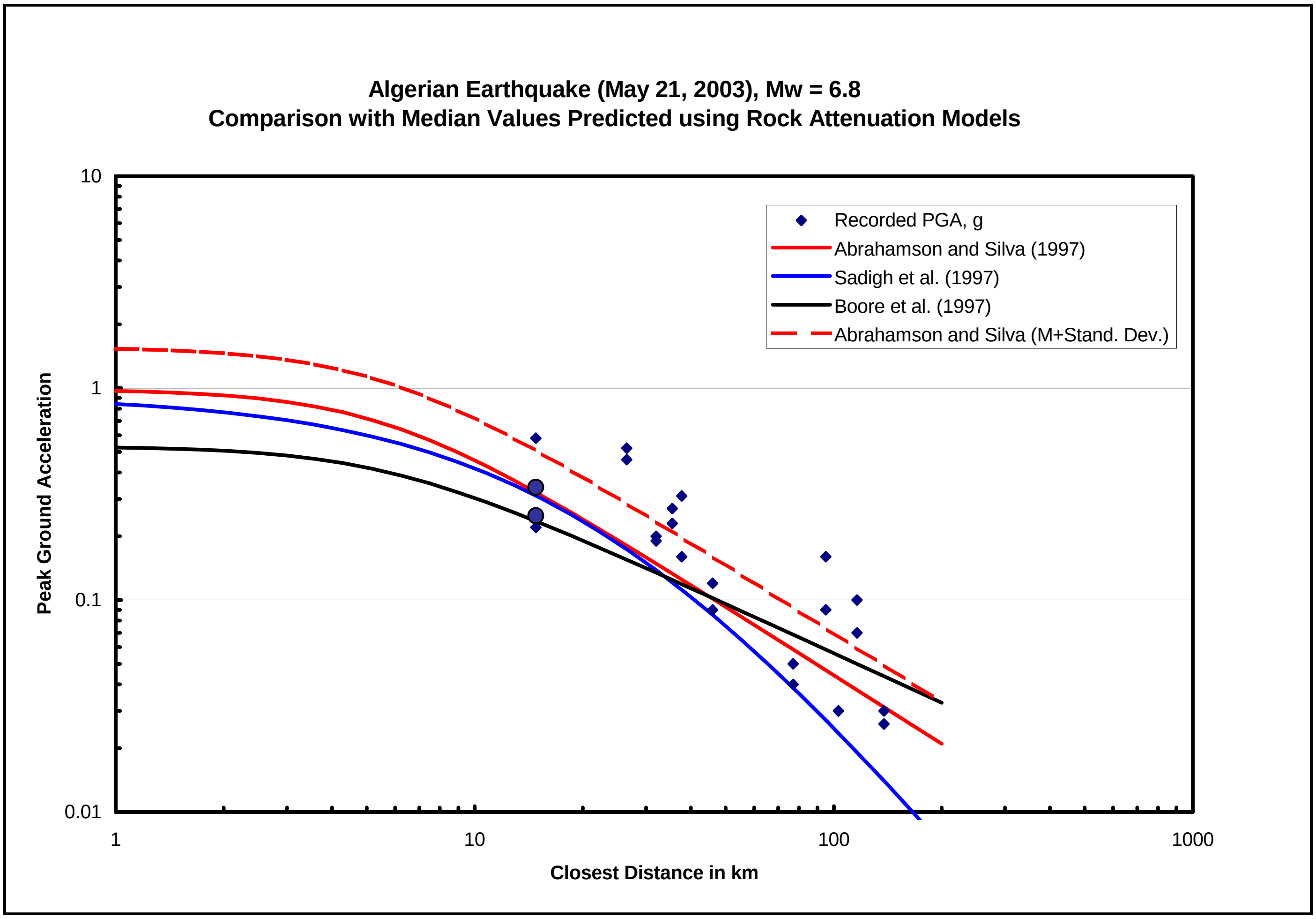


Fig. 10. Recorded PGAs compared to attenuation relationships for rock sites. The two circles represent the rock site at Keddara

It can be seen that generally the PGAs from the mainshock are higher than median values predicted by the three attenuation relationships. Furthermore, about half of the recordings are higher than the median plus one standard deviation values predicted by Abrahamson and Silva (1997).

Recent seismic hazard studies for Northern Algeria indicate expected peak ground accelerations of 0.16 g and 0.20 g for mean and worst-case values for a 475-year return interval (Montilla *et al*., *unpublished*). The authors indicate that these studies will be updated (with increased PGA values) to include the previously unavailable 2003 Boumerdes earthquake data.

OBSERVATIONS OF GEOTECHNICAL FAILURES

Much of the coastal area is characterized as a broad alluvial plain bounded by metamorphic rocks from the Atlas thrust belt to the south. The gently sloping alluvial plains have been uplifted by past earthquakes (Boudiaf *et al.*, 1998). Due to the semi-arid terrain, the groundwater levels are generally deep. Although the rainfall in April 2003 was over twice the average amount, the alluvial slopes appeared dry, indicating a deep groundwater table.

A few locations immediately adjacent to rivers and along certain portions of the northwest-facing Bay of Algiers have shallower groundwater levels, *e.g.*, the town of Ben Mered, on the southeastern coastline along the bay. Although it is probable that structural deficiencies were the main cause of damage, we hypothesize that the sandy soils underlying Ben Mered may have liquefied in areas of shallow groundwater and contributed to the damage in this region. Thus far, detailed damage reports are not available however, multiple incidences of liquefaction were observed during the field reconnaissance along the coastal cities and local creeks near the epicentral area.

Liquefaction and lateral spreading were present in areas near the Isser River and areas with extensive beach sand deposits.

Sand boils, sand vents, and lateral spreading were observed near the Isser River Bridge on Route 24, about 3 km west of Cap Djenet. Multiple sand boils were observed in the flat land near the Isser River as evidenced by the sand ejecta shown in Fig. 11. Some sand boils had a linear alignment; similar linear trend were also observed after the 1980 the El-Asnam earthquake. Liquefaction near the river resulted in lateral spreading of each riverbank resulting in them moving inwards toward the river channel. Although not measured, several centimeters of lateral movement were estimated as illustrated in Figs. 12 and 13. Lateral spreading along the riverbanks caused movement of at least one electrical tower (Fig. 13). Consequently, the lines sagged between the towers closest to the river channel and were pulled taught between adjacent towers. During a post-earthquake reconnaissance, only a few minor landslides and road cut failures were observed. No major landslides were observed. Ground cracking was reported in the fields on the west bank of Isser River north of Borj Menaiel.

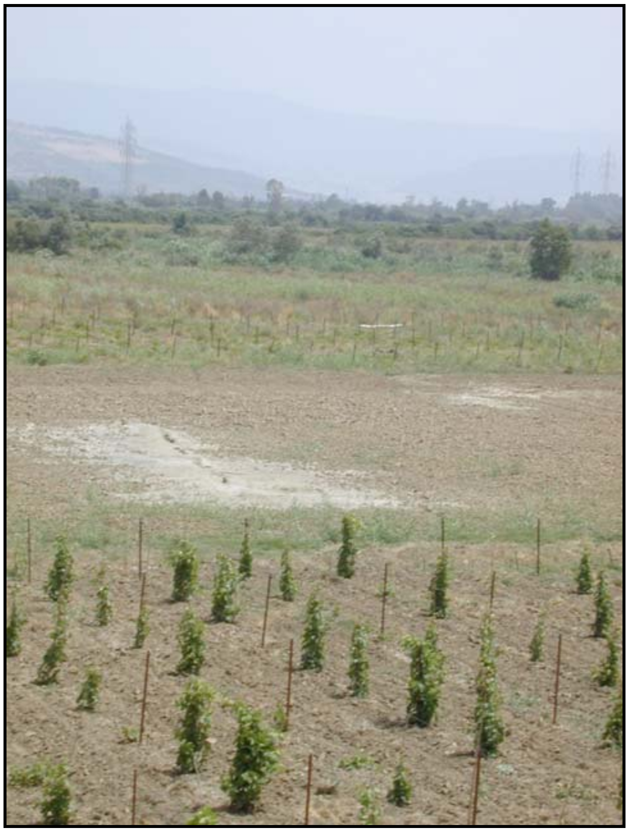


Fig. 11. Liquefaction-induced sand boils near Isser River

Near the town of Zemmouri, approximately 2 km from the surface projection of the modeled fault rupture area, multiple sites experienced liquefaction (Figs. 14 to 16). Based on the distance to the rupture plane and the anticipated near-field (<2 km) peak horizontal ground accelerations (PGAs) from the attenuation relationships, we infer that these sites experienced PGAs in excess of 0.70 g. An excessive amount of sand was ejected during the formation of the sand boils near Zemmouri (Fig. 16), where the liquefied sand flowed into and filled and adjacent drainage ditch.

Fig. 12. Liquefaction-induced lateral spreading of the banks of Isser River

Fig. 13. Close-up view of tension cracks caused by lateral spreading of the riverbank

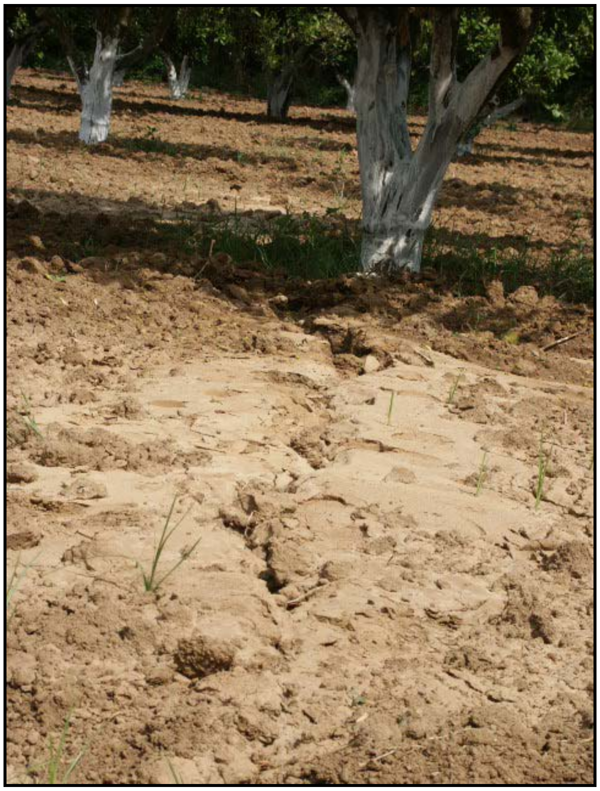


Fig. 14. Liquefaction-induced sand boils in an orange grove in Zemmouri

Fig. 15. Liquefaction-induced sand boils and sand vent in an orange grove in Zemmouri

Fig. 16. Liquefaction-induced sand boils and sand flow into an irrigation ditch in Zemmouri

Damage to Port Facilities

In the port of Algiers, the largest commercial port in the country, nine piers suffered damage (Figs. 17 to 21). Investigations and studies were still being conducted on 8 June 2003, to assess the extent of the damage and the stability of the piers and determine necessary repairs.

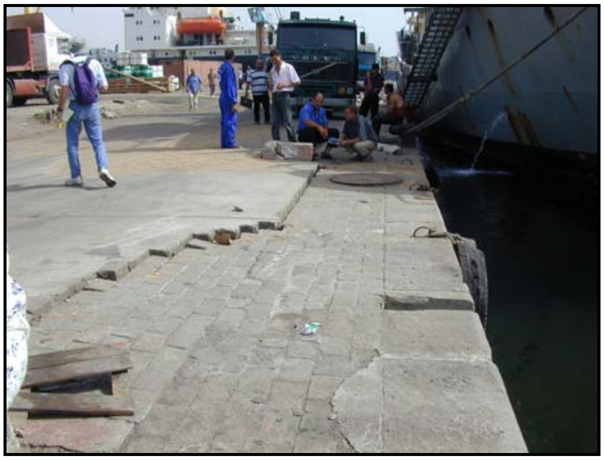


Fig. 17. Differential settlement between the down-dropped quay walls and backland, Port of Algiers

Liquefaction, loss of ground support, and lateral displacement (seaward movements) of the bulkheads were pervasive. Liquefaction-related vents and sand ejecta were observed in many locations behind the quay walls and within the container yards. Differential settlement of few centimeters was noted near the quay walls. Depending on the pier location, the vertical offsets of the quay wall with respect to the backland were reversed in direction from pier to pier as illustrated in Figs. 17 and 18.

Fig. 18. Differential settlement between quay wall and down-dropped backland, Port of Algiers

Fig. 19. Tension cracks longitudinal to the quay wall indicating lateral wall movement at the Port of Algiers

Lateral spreading was indicated by the opening of longitudinal tension cracks along the quay walls at the Port of Algiers as shown in Fig. 19. In many places, the concrete pavement collapsed as a result of loss of ground support (Fig. 20). Liquefaction created large cavities up to 2.5 m deep, mostly caused by the sand ejected during from flowing boils (Fig. 21). In these locations, port officials reported 3-m-high artesian flows that lasted for several hours.

Fig. 20. Loss of ground support under concrete pavement at the Port of Algiers

Fig. 21. Cavity caused by loss of soil support due to liquefaction at the Port of Algiers

The fishing port at Zemmouri El-Bahri, located in close proximity to the epicenter, suffered only minor damage from lateral spreading and soil settlement behind the quay wall (Fig. 22). The port of Dellys, further east of Boumerdes, was closed to commercial traffic for several days (only one pier out of five is served by commercial boats) due to damage to quay walls. The four fishing piers were re-opened a week after the earthquake.

Fig. 22. Settlement (>0.3 m) behind pier in the harbor of Zemmouri El-Bahri

The earthquake caused permanent uplift along about 3 km of the coastline, with the maximum uplift of 0.6-1.0m near Zemmouri. The offshore faulting and regional displacement triggered the seawater to with draw up to 500 m out from the shoreline along 80 km of the coastline for about 20 minutes. This local draw down is thought to have contributed to the lateral spreading observed at port facilities. Damaging tsunami waves were not observed locally, but a tsunami that traveled northward caused some moderate damage to south-facing ports on Majorca, in the Spanish Balearic Islands, about 300 km to the north, and coastal Spain (Hébert, 2003). In addition, submarine landslides (turbidities) severed major undersea communication cables.

Damage to Dams and Water Lines

There are three dams in the earthquake-affected area: the Keddara Dam, the Beni Amrane Dam, and the Hamiz Dam. The Keddara Dam is the largest and the closest to the epicenter. All of the reservoirs were at almost full capacity as the rainy season this year was exceptionally wet. Cracks developed on the Keddara and Beni Amrane Dams and sensors were immediately installed on these two dams to monitor any further damage. As of 8 June 2003, no leaks and no further damage were observed.

The 12-km-long and 2-m-diameter water line running from the Keddara Dam to the Boudouaou water treatment plant suffered damage at two locations in the station. A pipe failed at the interface of a rigid concrete block of the station and a pipe was dislodged from a pipe-to-pipe flanged connection. The line was flushed and repair was completed within 24 hours. In addition, multiple water line breaks were reported along the entire water distribution system.

CONCLUSIONS

Based on the preliminary review of the recorded PGAs, the ground motions recorded during the May 2003 Boumerdes earthquake are unusually high. The E-W components are consistently larger than the N-S components. The PGAs consistently exceeded the predicted median values from attenuation relationships developed for a seismotectonic setting similar to the western United States. Further analyses of the time-histories and spectral responses, in conjunction with the characterization of the recording site conditions, are recommended to investigate the reason for these high ground motions.

Extensive liquefaction and lateral spreading along creeks and at port facilities occurred at sites containing loose saturated sand deposits or hydraulic fills. Correlation with liquefaction potential prediction charts was not done at this stage because of the lack of site-specific information. Field investigations at sites where liquefaction occurred using both SPT drilling and CPT soundings is recommended in the next phase of study.

ACKNOWLEDGMENTS

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