The Boumerdes, Algeria, Earthquake of May 21, 2003

EERI Learning from Earthquakes
Reconnaissance Report

October 2003

This report was sponsored by the Earthquake Engineering Research Institute
with support from the National Science Foundation

Earthquake Engineering Research Institute
2003-04

The Earthquake Engineering Research Institute's participation in this reconnaissance effort and publication of this report was supported by the National Science Foundation under grant CMS-0131895.

This report is published by the Earthquake Engineering Research Institute, a nonprofit corporation. The objective of the Earthquake Engineering Research Institute is to reduce earthquake risk by advancing the science and practice of earthquake engineering; by improving understanding of the impact of earthquakes on the physical, social, economic, political and cultural environment; and by advocating comprehensive and realistic measures for reducing the harmful effects of earthquakes.

Any opinions, findings, conclusions and recommendations expressed herein are those of the authors and do not necessarily reflect the views of the National Science Foundation, EERI or the authors' organizations.

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Printed in the United States of America

ISBN #
EERI Publication Number 2003-04

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An EERI reconnaissance team was in Algeria from May 25 to June 5, 2003. The reconnaissance effort was greatly enhanced by the many Algerian scientists, engineers, and researchers who joined the team. The collaboration of the National Center for Research in Astronomy, Astrophysics and Geology (CRAAG) and the National Earthquake Engineering Research Center (CGS) is greatly appreciated.

This earthquake also afforded a unique opportunity to examine high resolution satellite imagery of the affected area. About a month after the earthquake, EERI acquired three sets of images — one a year prior to the earthquake, one immediately post-earthquake and a third image from a month after the earthquake. EERI members who are currently conducting research in remote sensing were given the imagery for further analysis. The insert summarizes some of the remote sensing team's findings. Further discussion and analysis will be available in a forthcoming report from the University of California, Irvine. While the imagery was not available for this reconnaissance team in the field, its potential usefulness as a quick analysis tool is apparent, and will be pursued in future events.

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Financial support for the EERI reconnaissance team and for the publication and distribution of this report was provided by the National Science Foundation (NSF) under grant No. CMS 0131895 to EERI's Learning from Earthquakes Program.

The in-kind support of RMS Inc. is also gratefully acknowledged.

Contents

Introduction

At 18:44 UTC (19:44 local time) on May 21, 2003 a strong, shallow earthquake of moment magnitude Mw=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 36.91N-3.58E (National Center for Research in Astronomy, Astrophysics and Geology — CRAAG), 7 km north of Zemmouri in the province of Boumerdes, about 50 km east of the capital city of Algiers (see Figure 1).

Damage was reported in an area about 100 km long and 50 km wide, centered on the city of Boumerdes. The hardest hit regions were in the coastal province of Boumerdes (the province immediately east of Algiers) and mainly in the cities of Boumerdes, Zemmouri and Thenia, as well as the eastern districts of the province 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 central districts of Belcourt, Bab-El-Oued and El-Casbah in Algiers.

The earthquake generated a tsunami observed as far away as the southern coast of Spain, but little or no damage was done locally.

The affected area is heavily developed and urban. The earthquake affected about 2.3 million people. As of June 14, 2003, there were 2,287 people dead, more than 11,000 injured, and about 800 people were still listed as missing. Total economic loss was estimated at US$5 billion. About 182,000 housing units (apartments and private houses) were damaged, of which more than 19,000 collapsed or were rendered uninhabitable. The earthquake left upwards of 120,000 people homeless.

This earthquake highlights the particular vulnerabilities of both large and megacities in the developing world. Had the earthquake struck any closer to the City of Algiers or had a larger magni-tude, the losses would have been much greater. It reminds us what can be expected in fu-ture earthquakes in large cities around the world. To better understand some of the causes of the extensive earthquake damage, and the challenges of reconstruction, a discussion of the political/social context is useful. Accordingly, we depart here from the normal orga-nization of an LFE report to provide background on Algeria's recent population dynamics and political situation.

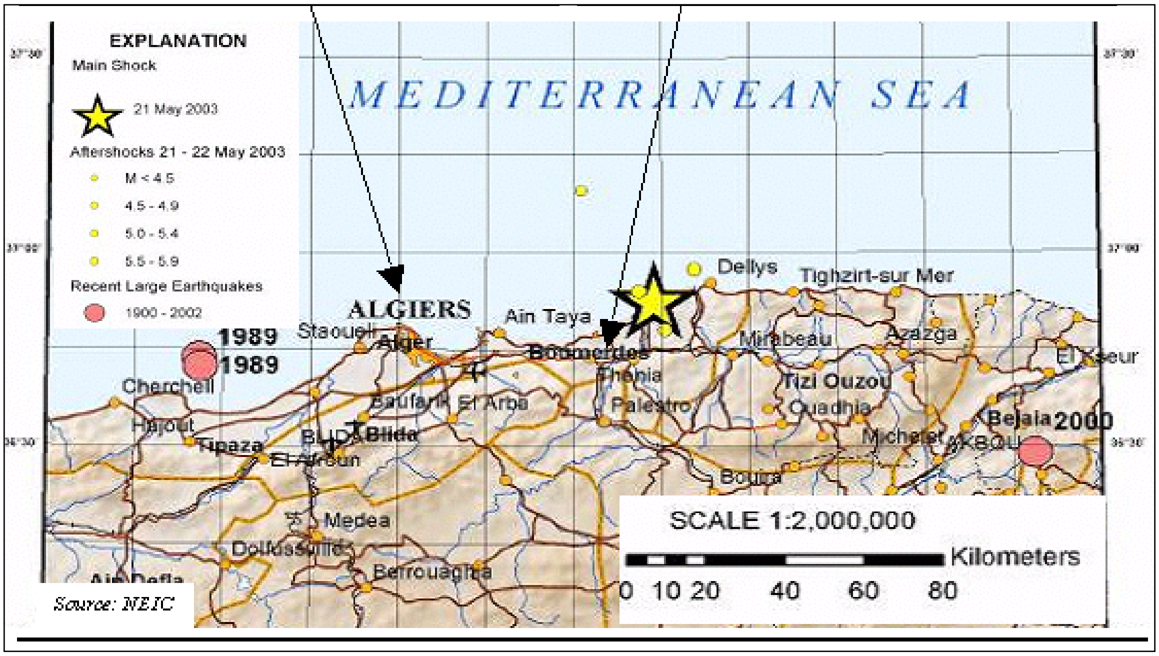


Figure 1 *Location of the May 21, 2003 Boumerdes, Algeria, earthquake. Also indicated in the map are recent earthquakes that have affected the region.*

Chapter 1

Urbanization of the Algiers-Boumerdes Region

Since gaining its independence from France in 1962, Algeria has experienced one of the highest birth rates in the world, with the population growing from less than 10 million inhabitants to more than 30 million. The increase in population, coupled with rural-urban migration, has resulted in a rapid growth in cities. The region of Algiers and Boumerdes has seen phenomenal urban sprawl, with more than 67% of the construction undertaken in the last 30 years. Furthermore, the society has been dealing with twelve years of rapid economic and institutional reforms, as the country changed from a state-controlled to a free-market economy. And for the decade of the 1990s, the country was in the throes of a civil war. All these factors have contributed to unregulated and uncontrolled growth as well as a certain level of social disorder.

The area directly affected by the earthquake is made up three distinct areas: 1) the eastern section of the Province of Algiers (21 jurisdictions out of 62), a mixture of beach cities with individual homes built on rich agricultural land and industrial cities with a predominance of collective housing; 2) the entire Province of Boumerdes, including the City of Boumerdes, created in 1958 to house administrative and higher-level research/academic activities; and 3) a few small colonial rural cities in the foothills of the Djurdura mountains, running through the adjacent provinces of Blida, Tizi-Ouzou, and Bouira.

The third area has seen little urban transformation compared to the first two, which have developed into a dense urban continuum extending between Route Nationale 24, running along the Mediterranean coast, and the new inland highway running from Algiers to Boumerdes. These two transportation corridors provide easy and efficient access to Algiers and have facilitated the development of the flatlands between Algiers and Boumerdes during the last ten years. Compared to the older neighborhoods of Algiers, which were choked by overcrowding, scarcity of land, and stiff government control over building construction, this newly accessible region offered ample land for construction and an administrative structure ready to meet the demand for housing.

The differences in the urban character among the damaged areas influenced the damage pattern and the social impacts associated with the earthquake. These differences will also undoubtedly affect the manner in which each area recovers.

Administrative Organization for Planning and Construction

In Algeria, four jurisdictional levels have had designated authority over land use management. At the national level, the land use plans are generated by the "Schéma National d'Aménagment du Territoire (SNAT). At the regional level, land use requirements are defined by the "Schéma Régional d'Aménagment du Territoire (SRAT). The requirements apply uni-formly to regions determined to be homogeneous. The area of these homogeneous regions varies from part of a wilaya (province) to several wilayas. At the local level, master plans are prepared by the cities (communes) that specify architectural and urbanization requirements (PDAU) as well as land use guidelines (POS). Finally, for an individual lot, a construction project must be certified as conforming to the local zoning requirements, and permits must be issued authorizing activities such as subdivision and construction. In addition, there are a number of technical requirements such as soil studies, architectural and design drawings, and technical control of construction that are specified in the building code.

Construction needs dramatically increased following Algeria's independence from France in 1962. The period from 1962 to 1990 was characterized by a soviet-style economy in which housing was planned by central government institutions and built by large state-owned contractors. The housing stock increased significantly in the period from 1974 to 1990, as major government funding was put toward relieving some of the housing shortage. During that time, the state also owned most of the housing stock, which was left from the French colonial era ("biens vacants"), and a significant proportion of Algerians were renters. The government invested little in maintaining this stock, and it deteriorated rapidly (Safar-Zitoun 1994a and b).

In 1990, political reforms were initiated in Algeria that had little respect for the regulations at the four levels of authority described above. In a few short years, Algeria went from a rigid state-controlled system to a free-market economy. The apparatus in charge of planning and construction was also reformed. The state relinquished most of its housing ownership by selling it to private individuals. The Real Estate Orientation Law of 1990 made it possible to convert agricultural land into private building lots. Land distribution was decentralized to local authorities, and land was quickly transformed into lots for private homes or multifamily housing. Construction was liberalized and quickly taken over by an emerging but, for the most part, unqualified private sector. The liberalization of the real estate market resulted in further increases in development mainly around the capital city of Algiers. Many towns grew from being small seashore vacation spots to large housing and commercial conglomerates, often in an ill-planned or unplanned manner.

During the civil war, local governments were not able to adequately perform their roles. Between 1991 and 1997, the electoral process was suspended so temporary administrators (DEC), rather than elected administrators (PAPC), were in charge, and blatant disregard for regulations was common practice. The temporary administrators seemed unaware of the potential risks that the country could incur from the shoddy land use and construction practices. During this period, non-adherence to construction requirements became the rule, and respect for regulations became the exception. There was inconsistent treatment of seismic requirements in the laws and regulations. Some laws referred to the necessity of addressing seismic issues, but the implementation regulations were not specific, especially when it came to the private sector and individually-built housing. Further, there were few laws identifying the responsibilities of different parties (architects, engineers, contractors). Finally, control during construction and final inspection of buildings was not systematic.

Prior to the 2003 earthquake, there was significant debate about the potential negative consequences of the withdrawal of the national government from the management of development in the country as well as the failure of state agencies to supervise construction of large housing developments, including those financed by the government. The vulnerability of the public housing stock, which was in an advanced state of degradation, was often mentioned. This debate was fueled by the heavy losses caused by recent earthquakes, which demonstrated the extreme vulnerability of the housing, and the lack of preparedness of the Algerian society in general. These concerns were again supported by the 2001 Algiers floods, which affected the inner neighborhoods of Algiers, and caused close to 800 fatalities and millions of dollars in material losses (Zerzour 2002; Kasmi 2002).

Academic reports discussed the exposure of the Algiers region to earthquakes and other disasters and called urgently for a comprehensive disaster management and disaster risk reduction program for the region (Allal 1999, Bendimerad 2000, El Foul 2002, Benouar 2002). Media commentaries and government studies warned against the increase in vulnerability caused by the illegal character of the construction.

The Algiers-Boumerdes Region

The earthquake damaged two areas with completely different urbanization processes: the badly planned and often illegally built neighborhoods in the eastern suburbs of Algiers, products of the speculative building boom of the nineties; and the city of Boumerdes, jewel of modern, planned urbanism.

Algiers and Vicinity

Up to 1990, development consisted almost exclusively of collective housing, but in recent years, the urban character has changed into two distinct zones: one of mixed habitation in the interior (more industrial) jurisdictions, and the other of private single homes along the coastal cities that are much desired for their real estate value (Safar-Zitoun 1997). Figure 2 shows the distribution of individual housing (in percent) per jurisdication in the Algiers province. This change was in great part the result of the liberalization of the real estate market. Huge demand for private housing from the residents of Algiers helped boost prices, creating a speculative market for private lots and housing.

Official data from the Algerian Ministry of Housing indicate that in the period between 1990 to 2002, 42.4% to 52.8% of the individual homes were built without a legal title document, and thus without a building permit. Figure 3 provides the geographic distribution of the "illegal" construction in the province. Individuals and families from a broad spectrum of society managed to acquire building lots, either bought from a private owner or allocated by the local authorities, and built houses for their own use or for resale at a premium. This situation was tolerated by government authorities, which were more concerned with providing housing than controlling the development and construction itself.

Typically, most landowners do not have the capital or the possibilitiy of bank loans to complete the construction of their homes in one stage. To accommodate the lack of funds,

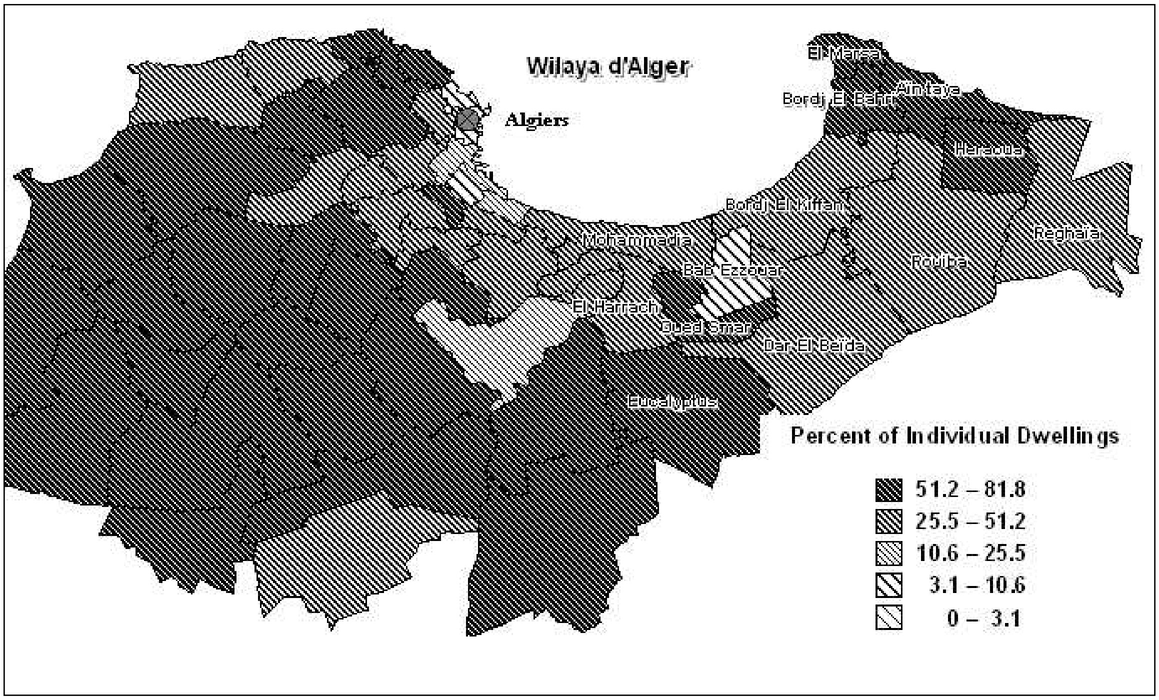


Figure 2 *Percentage of individual housing by city.*

the construction takes place in three stages: 1) a first floor, intended for commercial occupation, is first erected to help generate income to finance the rest of the construction. This would also establish a de-facto "ownership;" 2) a partial or full but unfinished second floor is added that would allow the family to move in; and 3) the rest of the construction was completed over time, sometimes by also adding a partial or full third floor.

This process of housing construction does not lend itself well to construction control. Of course, the process is also prone to corruption and personal intervention. The full list of actors, including the owners, the builders, and the administrators, are typically unaware of the need for construction controls or earthquake safety considerations. Despite repeated recent earthquakes in Algeria, the level of earthquake education in the general public is low. Building owners are much more knowledgeable about quality of tiles and faucets than they are about minimum earthquake construction requirements. This lack of attention to the quality of construction was a direct cause of the heavy damage to the housing stock. In one locality alone, more than 300 occupied houses were completely destroyed by the earthquakes.

Boumerdes

The city of Boumerdes was created in 1958, toward the end of the French colonial era, as part of a French administration economic reform plan for Algeria. It was intended to serve as an administrative and educational outpost for Algiers. This role was continued after independence, as the Algerian government located several research institutes and universities in Boumerdes. The rigorous planning process for Boumerdes has continued through the years. Several generations of construction styles sit side by side in this city: the first generation of buildings (built between 1959 and 1974) has bearing walls; the second

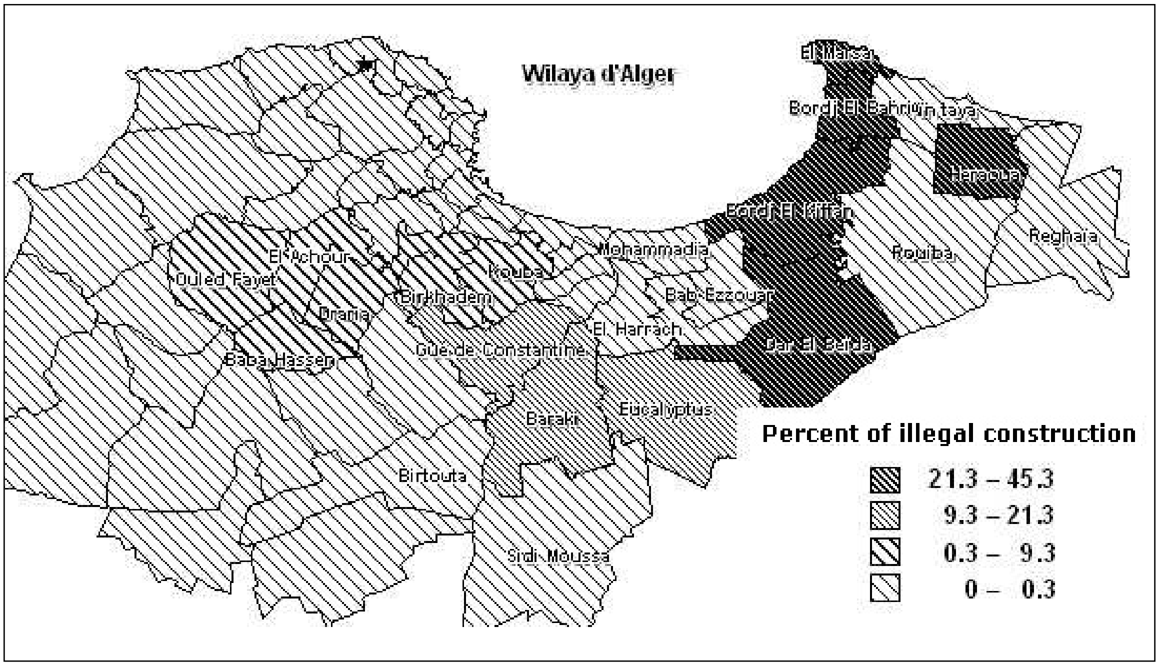


Figure 3 *Percentage of "illegal" construction by city.*

generation (built between 1974 and 1993) is primarily engineered multistory buildings built by large government-owned construction companies; and the third generation is characterized by a return to traditional construction methods using reinforced concrete beam-column and concrete slabs with brick partitions.

Boumerdes residents are for the most part middle and upper-middle class, working in government or colleges and research institutions. Close to one quarter of the population is college-educated, a ratio without equivalent elsewhere in the country, and in stark contrast to the rural area immediately surrounding the city. One can assume these differences in education will dictate different levels of involvement in the earthquake recovery process.

Chapter 2

Social and Economic Impacts

Social Losses

As of June 14, 2003, official estimates put the number of casualties at 2,287 dead, more than 11,000 injured, and about 800 people still listed as missing. The highest percentage of fatalities was registered in the county of Boumerdes, at 60.5%. In contrast, Algiers suffered 38.8% of the fatalities. The earthquake happened towards the end of the day on a weekday at the time when many women were at home getting ready for supper and many men were either just getting home from work or from the traditional post-work social hour at the neighborhood cafes. Part of the population was also just departing from mosques, having finished their evening prayers. A larger number of younger people than usual were in their homes to watch a popular European soccer game, scheduled to start minutes after the time of the earthquake. Hence, as more detailed data come out in the future, it will be interesting to see if the earthquake toll affected women and younger people more so than men.

The final number of unoccupied buildings/dwellings will not be known for several weeks, but official figures as of June 23 put the number of dwelling units (apartments and private houses) to be demolished at about 19,000. Upwards of 120,000 people were temporarily housed in 185 tent camps established by the government (see Figure A4 in the insert for an aerial image of such a tent camp). In terms of the permanent loss of housing, the damage was proportionally larger in the epicentral zone: Boumerdes had 17.6% of its housing destroyed, compared to 8.9% in Algiers.

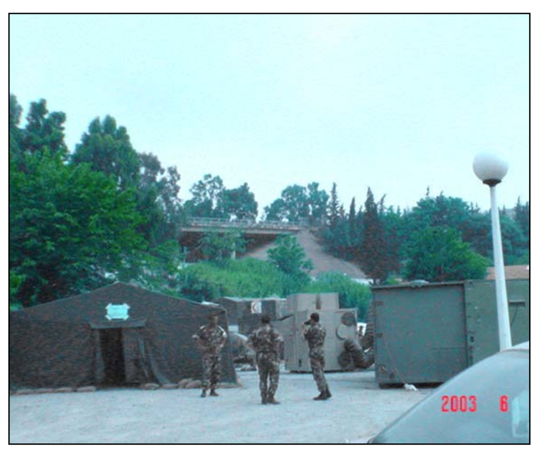
The difference in the urban development of Algiers and Boumerdes was reflected in the damage to the buildings. Earthquake damage in Boumerdes was mostly to institutional buildings and large planned apartment buildings. In contrast, in the eastern section of Algiers, a large proportion of the damage was found in the post-1990 hastily — and often illegally — built housing stock. A polarization of the population has been observed between those residents in legally constructed buildings and those in illegally constructed buildings, who will need to negotiate for their "rights" with local officials. This "legal" vulnerability is not synonymous with poverty or social vulnerability, but rather centers on the informal real estate market that contributed to redistributing land and allowing construction without efficient administrative oversight.

About 50% of the heath care facilities in the affected area were destroyed or severely damaged. The hospital in the municipality of Thenia in the epicentral region was destroyed (Figure 4), but the Algerian military established a temporary hospital at the same location (Figure 5). Of the 564 schools seriously damaged by the earthquake, 373 were primary schools, 119 junior high schools, and 72 were high schools. In addition to Algiers and Boumerdes, the schools in the provinces of Blida, Bouira, Tizi Ouzou, Tipaza, and Medéa were also damaged (see Figures 6 and 7). The library and other buildings at the University of Boumerdes sustained significant damage and remained closed. The University of Science and Technology, the largest university campus in the country, located in the district of Bab-Ezzouar in the eastern portion of Algiers, was also temporarily closed to allow for damage assessment and repairs.

Economic Losses

Preliminary estimates put the economic cost of the earthquake as high as US$5 billion, representing about 10% of Algeria's total GDP (for 2001). The rebuilding of the housing stock and infrastructure accounts for most of the cost, but some of it is also due to damage to industrial facilities, as a great number of them are located in the eastern districts of the province of Algiers. Major industrial complexes, including the truck factory SNVI of Rouiba, were put out of commission due to damage to buildings and equipment.


Figures 4a and 4b *Damage to Thenia Hospital*

Figures 5a and 5b *Temporary hospital to replace lost Thenia Hospital*

Figure 6 *First floor collapse of school building in Boumerdes.*

Figure 7 *Elementary school in Corso. Insufficient lateral resisting system.*

The water distribution system was also severely impaired; distribution of water in the affected area was ensured by mobile cisterns and distribution of individual containers. Repair of drinking water systems is estimated to cost about US$34 million, whereas the repair of transportation systems and other public work facilities exceeded US$30 million.

The government and private homeowners will assume most of the cost of the earthquake, as earthquake insurance is essentially nonexistent in Algeria.

Chapter 3

Geosciences

Seismotectonic Setting

Northern Algeria is located along the convergent plate boundary between Eurasia and Africa (Figure 8). 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 X), 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 (CRAAG 1994). All these events have been located in the Tellian Atlas (Figure 9), 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 (Meghraoui 1988, 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.

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

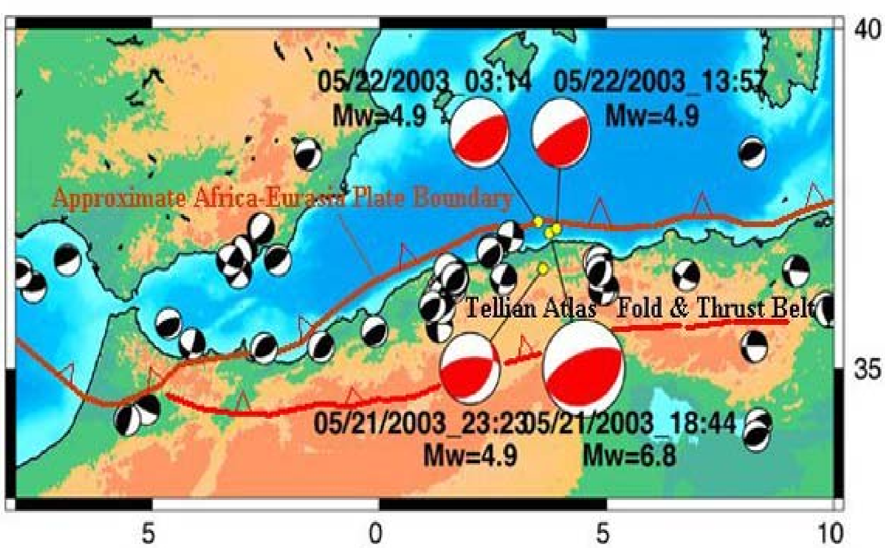


Figure 8 *Plate tectonic setting of northern Algeria.*

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 1996; Boudiaf et al. 1998). The Mitidja basin is bordered to the north by the Sahel anticline (Figure 9). 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 that 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 (Figure 9). 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. The 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, an offshore south dipping, fold-propagation blind thrust, is considered the source of the 2003 earthquake (Figure 9). 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) (Figure 10). Some of these earthquakes — for example, the earthquake of January 28, 1961 — occurred along the coastline. The historical seismicity

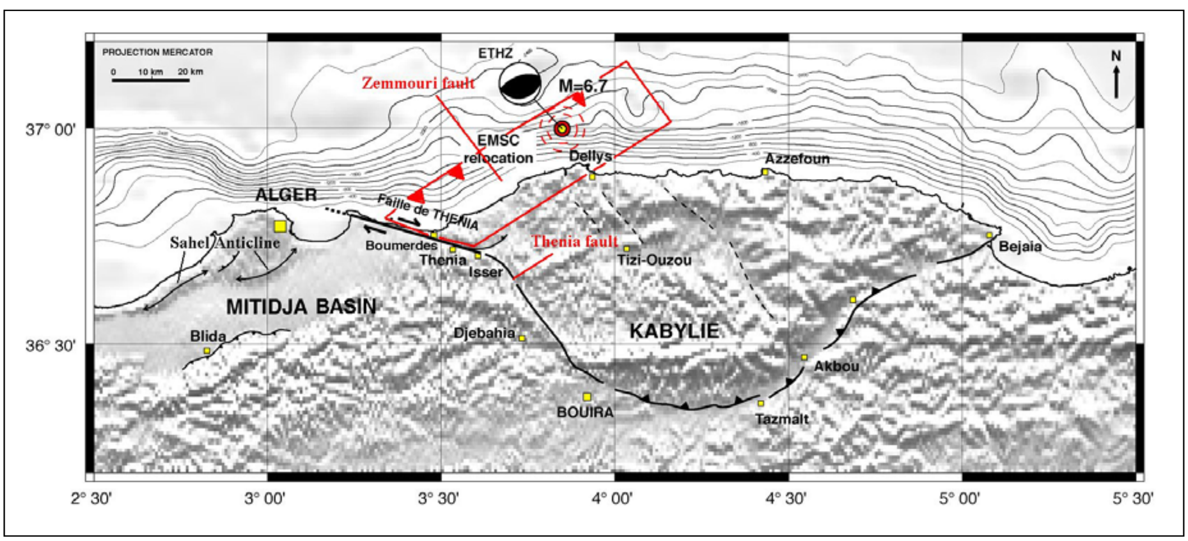


Figure 9 *Major active geologic structures in the Tellian Atlas region.*

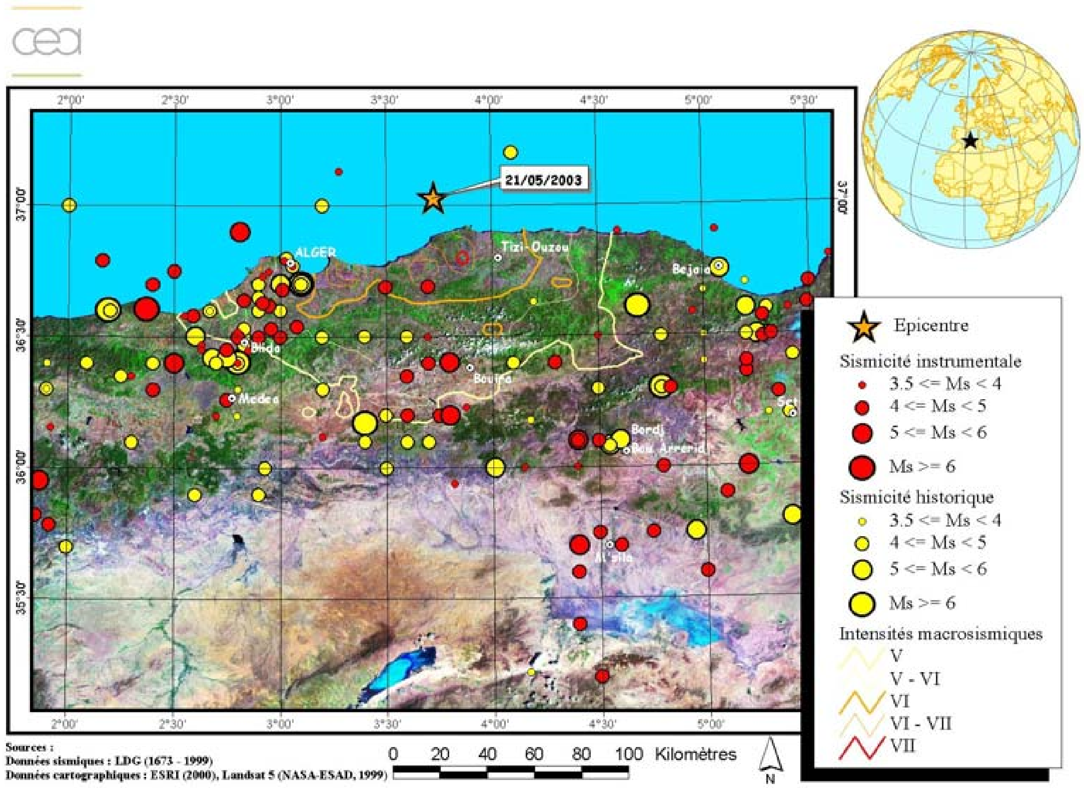


Figure 10 *Historical and instrumental seismicity, Northern Algeria.*

catalog reveals several large earthquakes in the Algiers region, including that of January 28, 1716 (I_o X), 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, in the present tectonic stress regime, 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 along the Zemmouri fault during recent geologic time is indicated by the series of uplifted and warped marine terraces along the coast around Zemmouri Al Bahari (Boudiaf et al. 1998).

Earthquake Parameters

The Boumerdes earthquake, with a maximum Modified Mercali Intensity (MMI) of X, caused significant damage in the region between Dellys and Algiers. The Algerian seismological network, operated by the Center of Research in Astrophysics, Astronomy and Geophysics (CRAAG), located the epicenter of the main shock 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 Center of Applied Research in Earthquake Engineering (CGS), which operates the strong

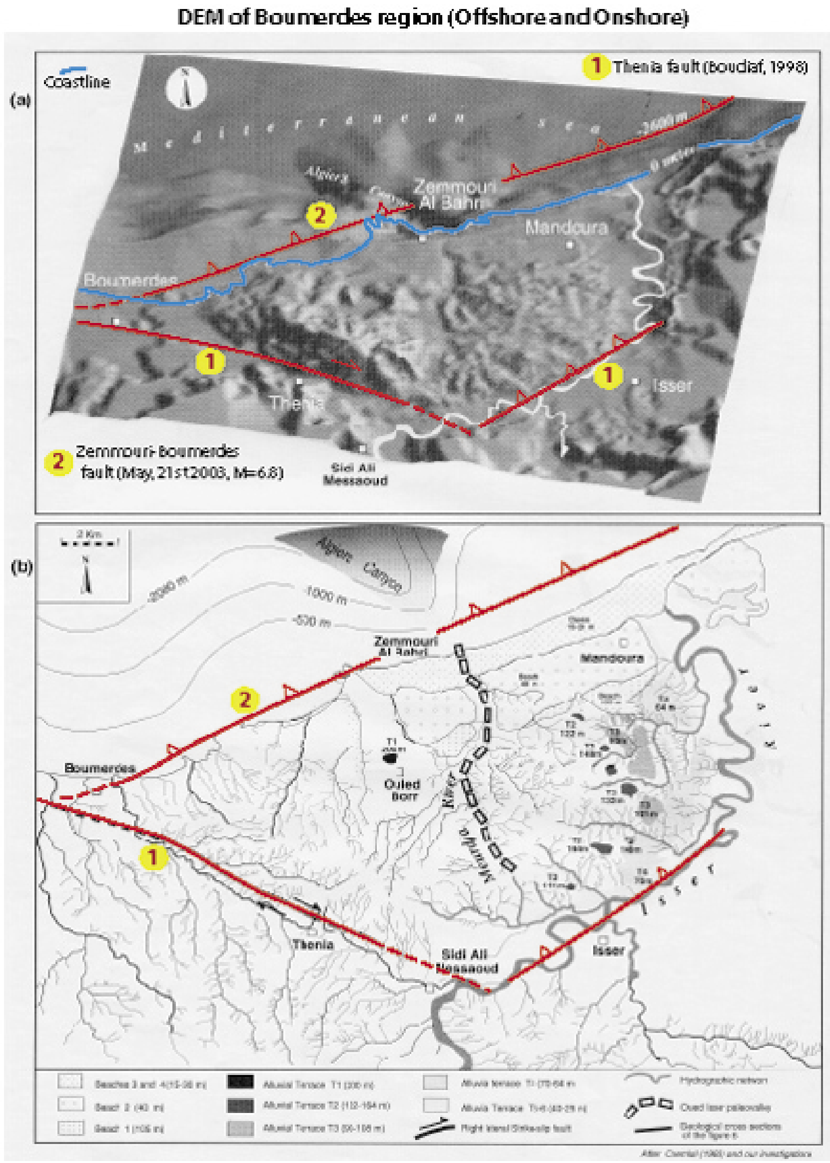
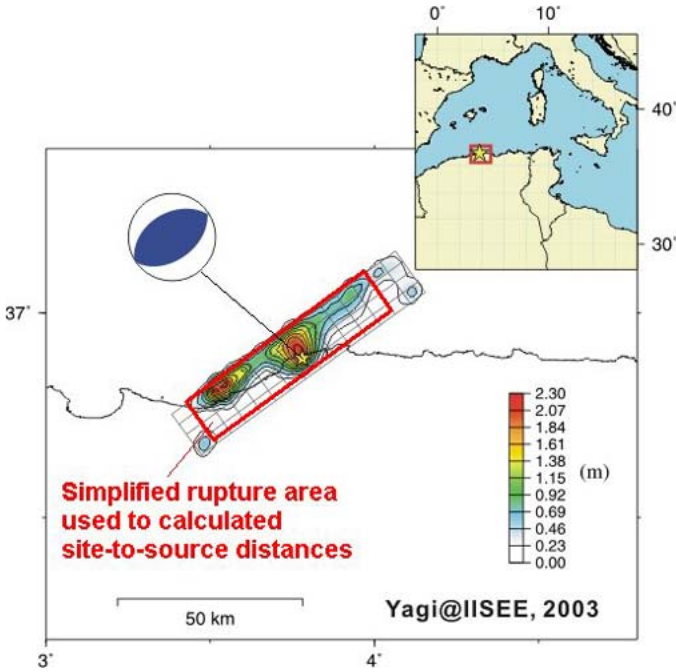


Figure 11
Preliminary assessment of rupture and location of Zemmouri Fault (from CRAAG):
1--Previously mapped Thenia/Isser Fault;
2--Modeled trace of Zemmouri Fault

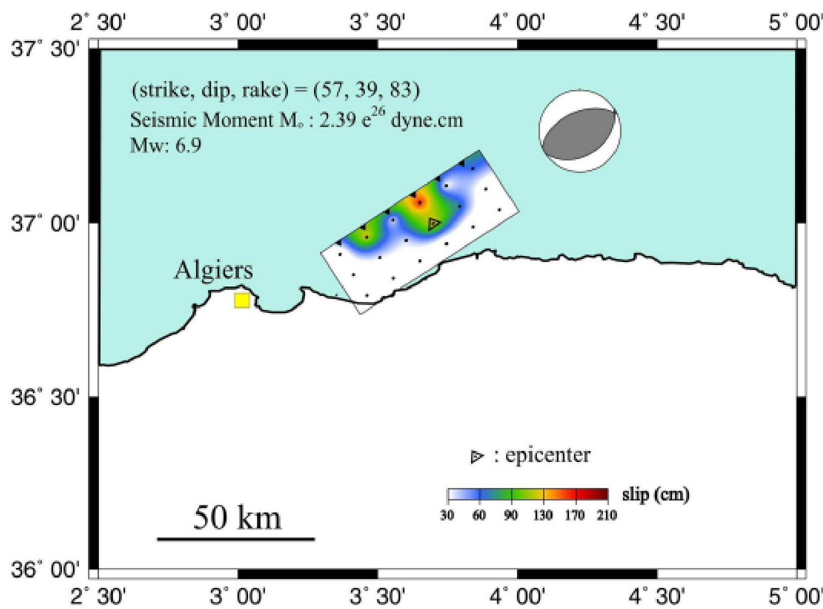
motion network in Algeria, computed an epicentral location of 3°53E, 36° 81N, and a magnitude of **M** 7.0, and strong motion duration of about 10 seconds. The U.S. Geological Survey reported a magnitude for the earthquake of **Mw** 6.8, which was later adopted by CRAAG.

The hypocentral depth of 10 km 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 were recorded in the six weeks following the mainshock, with two main events of M_L 5.8 on May 27 and 28, 2003. Aftershock sequence indicates a southwest-northeast rupture almost orthogonal to the previously mapped Thenia Fault (Figure 11).

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 U.S. Geolog-



Figures 12a and 12b
Fault Plane Inversion Models: (left) from Yagi, and (below) from DeLouis and Vallee



ical Survey location epicentral of 36.89°N, 3.78°E, **Mw** 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 was asymmetric and propagated 30 km to the southwest and 20 km to the northeast (Figure 12a). The rupture extended to the surface of the earth. Two asperities (large slip areas) are identified. The maximum dislocation is about 2.3 m at a distance of 25km southwest from hypocenter. DeLouis and Vallee (2003) developed a slightly different inversion slip model with a shorter rupture duration and higher maximum slip (Figure 12b). 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. The asymmetric nature of the propagation may have directed more energy towards the SW concentrating the damageability of the earthquake towards Zemmouri, Bourmedes 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 Dellys. These fractures are assumed to be a result of localized surface extension, and not fault rupture. If the 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. See Figure 13.

Geological investigations also revealed offshore effects such as uplift of the seafloor of at least 0.50m as shown in Figure 14, and minor landslides (Figure 15) and liquefaction along the coastline. Deformation of the seafloor resulted in a small tsunami that was recorded along the Baleric coast of Spain (Hébert 2003).

Ground Motion Records

The National Earthquake Engineering Research Center (CGS) operates and maintains Algeria's strong motion instrumentation network (Figure 16). Several of their instruments were triggered during the earthquake. The closest instrument to record the earthquake is

Figure 13 *Coseismic fractures oriented N20°. These fractures are located at the southwestern end of the main fault, which is situated in the Mediterranean margin. The inset image shows a NNE-SSW thrust fault.*

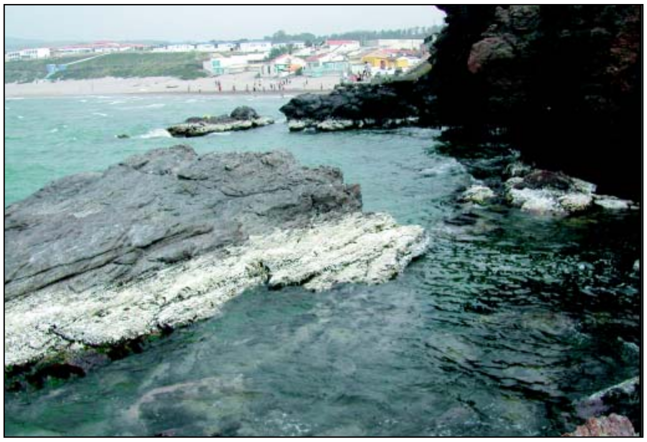


Figure 14 *Seafloor uplift of about 50 cm. The white level represents the thickness of alga that were under the water table be-fore the occurrence of the May 21, 2003, earthquake.*

Figure 15 *Induced landslide along the coastline from Boumerdes to Dellys.*

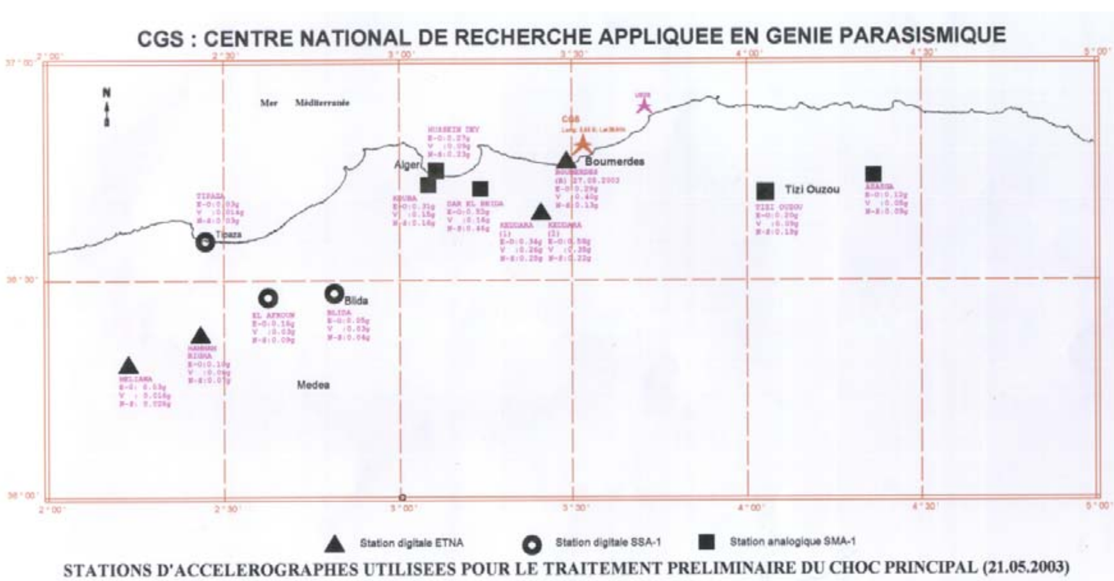


Figure 16 *Instrument location map and recorded ground motions.*

located about 20 km from the epicenter.

Following the mainshock, the network was augmented by a number of mobile accelerographs that enabled the collection of additional records from aftershocks, including the May 27, 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.

Table 1. Preliminary Strong Motion Data
May 21, 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

May 27, 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 made:

a) The E-W acceleration component was consistently larger than the N-S component for all recording stations.
b) There is evidence of significant vertical and horizontal motion in the epicentral region. This is supported by the fact that a concrete cap sitting atop a small brick

Figure 17 *Concrete cap thrown from its original location.*

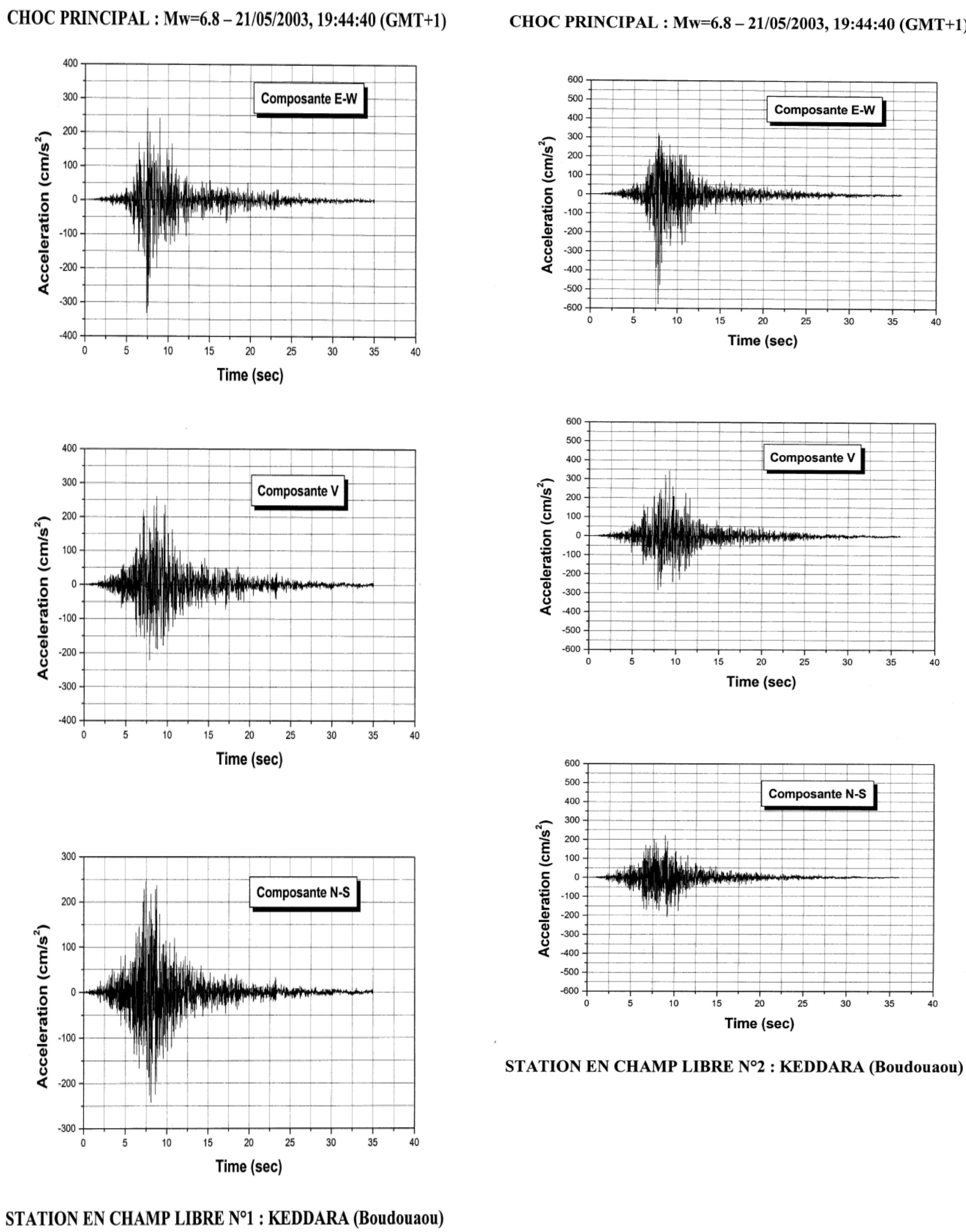


Figure 18 *Recorded acceleration time histories from Keddara 1 and Keddera 2 stations.*

transformer housing was lifted and thrown about 2 meters from its orginal position (Figure 17) in the epicentral city of Zemmouri. This indicates that the peak vertical acceleration exceeded 1.0 g in the region very close to the epicenter. A vertical acceleration of 0.40g was recorded during the M5.8 aftershock of May 27, 2003, on a mobile station at Boumerdes.

c) 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 also 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 Figure 18.

At the time of the preparation of this report, 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, may be reflected in terms of near-field directivity effects in the recorded 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).

A comparison of the recorded peak ground accelerations with those obtained from predictive attenuation relationships was undertaken. 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 Figure 19 and Figure 20, respectively. These are compared with the recorded horizontal components from the main shock. 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). These two models were compared, and only the rupture area with a significant to large slip was incorporated in the "simplified" rupture area model. This assumed rupture is shown in a bolder box within Figure 12a. This model was then used for estimating the seismogenic

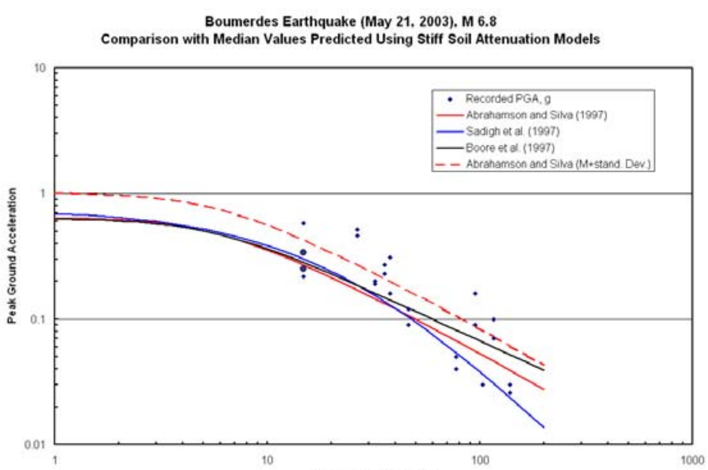


Figure 19 *Recorded PGAs compared to attenuation relationships for soil sites. The two circles represent the rock site at Keddara.*

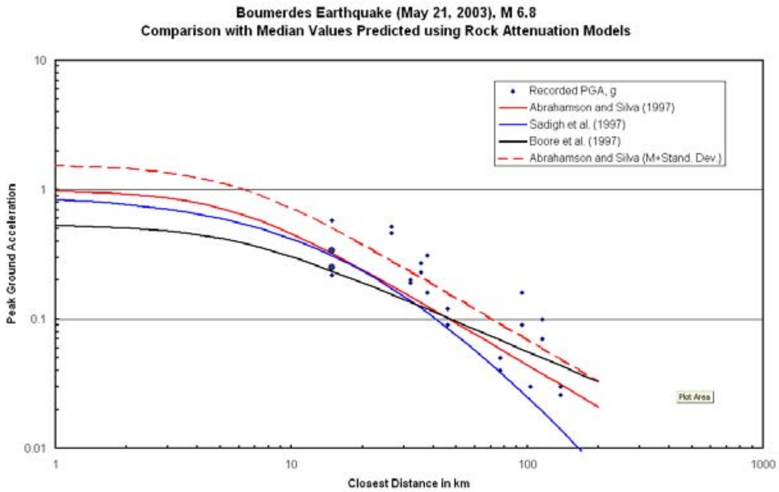


Figure 20 *Recorded PGAs compared to attenuation relationships for rock sites. The two circles represent the rock site at Keddara.*

distances between fault rupture and recording stations. These distances were used in the attenuation relationships above to calculate predictive ground motions. All the recorded data were plotted on both Figure 19 and Figure 20 because the site conditions are still not known for most of the sites at this time.

It can be seen that generally the PGAs from the main shock 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).

Seismic hazard studies for Northern Algeria indicate expected peak ground accel-erations of 0.16 g and 0.20 g for mean and worst-case values for a 475-year return interval (Peláez et. al. 2003). These values seem low considering the active tectonic setting of the region. Seismic experts who have worked in the region have indicated that these studies need to be updated (with increased PGA values) to include the previously unavailable 2003 Boumerdes earthquake data.

Geotechnical Observations

Much of the coastal area is characterized as a broad alluvial plain bounded by meta-morphic 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 relatively 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, 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 Figure 21. Some sand boils had a linear alignment; similar linear trend were also observed after the 1980 El-Asnam earthquake. Liquefaction near the river resulted in lateral spreading of each riverbank resulting in their moving inwards toward the river channel. Although not measured, several centimeters of lateral movement were estimated as illustrated in Figure 22 and Figure 23. Lateral spreading along the riverbanks caused movement of at least one electrical tower (Figure 22). Consequently, the lines sagged between the towers closest to the river channel and were pulled taught between

Figure 21 *Liquefaction-induced sand boils near Isser River.*

Figure 22 *Liquefaction-induced lateral spreading of the banks of Isser River.*

Figure 23 *Close-up view of tension cracks caused by lateral spreading of the river bank.*

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.

Near the town of Zemmouri, approximately 2 km from the surface projection of the modeled fault rupture area, multiple sites experienced liquefaction (Figures 24 to 26). 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, where the liquefied sand flowed into and filled an adjacent drainage ditch.

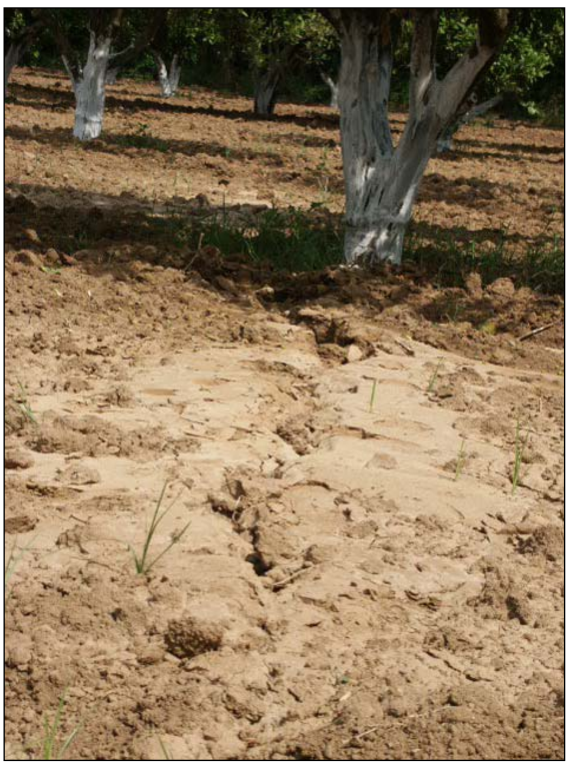


Figure 24 *Liquefaction-induced sand boils in an orange grove in Zemmouri.*

Figure 25 *Close-up of liquefaction-induced sand boils and sand vent in an orange grove in Zemmouri.*

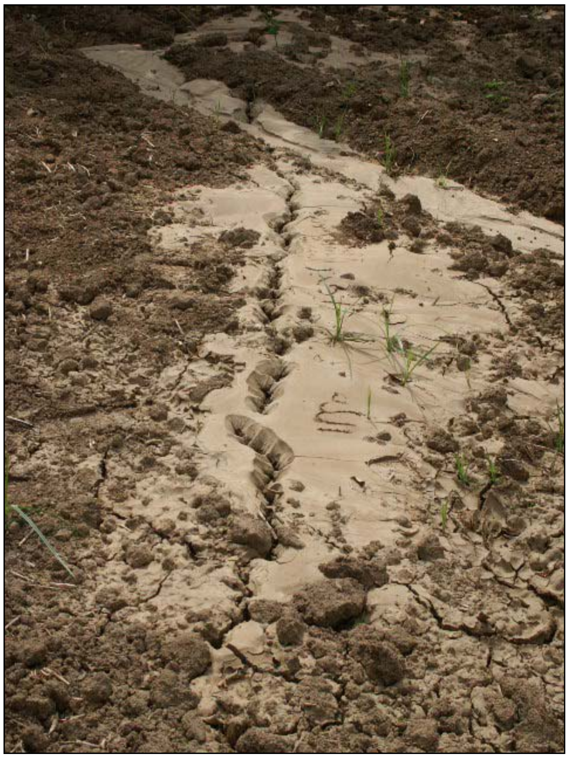


Figure 26 *Liquefaction-induced sand boils and sand flow into an irrigation ditch in Zemmouri.*

The earthquake caused permanent uplift along about 3 km of the coastline, with the maximum uplift of 0.6-1.0 m near Zemmouri. The offshore faulting and regional displacement triggered the seawater to withdraw 200 m to 500 m out from the shoreline along 80 km of the coastline for about 20 minutes (according to eyewitnesses). 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 to coastal Spain (Hébert 2003). In addition, submarine landslides (turbidities) severed major undersea communication cables.

Chapter 4

Buildings and Industrial Facilities

The most prevalent post-1960 multifamily residential construction type in Algeria is the reinforced concrete frame apartment building with hollow unreinforced brick infill walls, generally five to eight stories high. Private residential houses of the same construction type range from one to three stories. There are also buildings of precast reinforced concrete panels, tunnel-form shear wall concrete, or steel frame. Industrial construction consists mostly of light frame steel with masonry infills.

In 1981, after the 1980 El-Asnam earthquake, Algeria adopted its first seismic design code, referred to as RPA-81. In 1988, it was revised (RPA-88), and the most recent version is that of 1999 (RPA-99) (CGS 1999). The seismic zone classification ranges from 0 to 3, where 0 stands for no seismic risk and 3 stands for the highest seismic risk. The north central part of Algeria, including the provinces of Algiers and Boumerdes, is classified in Seismic Zone 2, with a seismic design coefficient of 0.15g for residential buildings. In late June 2003, about one month after the earthquake, the Algerian building code officials were seriously considering increasing the seismic design coefficient by 0.05g by moving these regions to Zone 1. However, based on the widespread damage, it is not clear that the seismic design principles were followed in recent construction, since similar failure mechanisms were observed in old and new engineered buildings.

Reinforced Concrete Frame Buildings

Extensive damage was observed in nonductile concrete frame and old unreinforced masonry buildings. The damage was due to inherent weakness in the structural system, design, seismic detailing, poor material quality, and unsound construction practices. The most commonly observed damage to reinforced concrete structures was in the form of partial or total failure of the first floor. Failures included shearing in columns with a clear indication of a strong beam/weak column approach, and minimal ductility, which are contrary to the seismic design requirements. Cracking of masonry infill walls was widespread. This damage resulted in human casualties and significant economic losses.

The column shearing occurred at the top of the ground floor columns. A classic case of edge column shearing in a residential building is shown in Figure 27. This resulted in the total disappearance of the first floor (Figure 28), or several floors pancaking (Figure 29). Also refer to Figure A5 in the insert for a satellite image of some of these failures, where building collapse is clearly visible. Most of the first floor column failures were also attributable to extensive openings and insufficient gravity load-carrying elements in the first floor, as is the case with the building shown in Figure 30. It is a typical practice here to use first floors for commercial activities, which essentially makes them soft stories.

The column shearing is also the result of poor seismic detailing. This is manifested by lack of transverse confinement (Figure 31) and improper longitudinal reinforcement joint connection. The failure is a combination of reinforcement buckling and concrete crushing. Lack of ductility and insufficient reinforcement in beams resulted in brittle failure, as shown in Figure 32. The extremely poor quality of concrete was another factor in the failures.

Other Structural Systems

Unreinforced infill masonry walls experienced the traditional diagonal cracking/crushing of concrete bricks, as shown in Figure 33. Load-bearing precast concrete buildings generally performed well, but in some buildings the connection of the precast panels failed at the anchors, and the panels fell to the ground (Figure 34). Tunnel-type shear wall concrete construction performed well. Many of these buildings in the epicentral region handled the shaking quite well because of their high shear capacity.

There were several four-story buildings close to the epicenter made of a combination of steel resisting frame with light-weight precast panels (Figure 35). These buildings

Figure 27 *Shearing of column at top of first floor of a residential building.*

Figure 28 *Total disappearance of the first floor.*

Figure 29 *Several floors pancaked.*

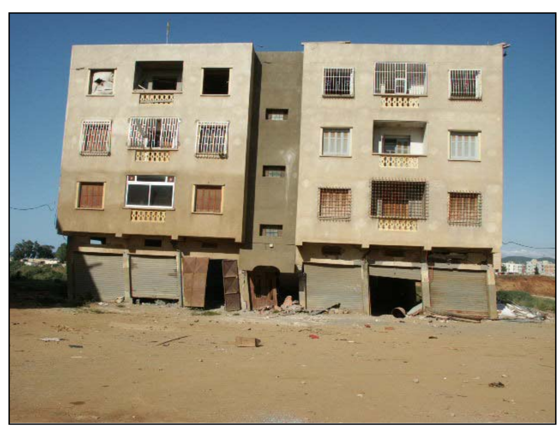


Figure 30 *Soft first floor with minimal masonry supporting walls.*

Figure 31 *Shearing of corner column due to lack of transverse confinement and poor seismic detailing.*

Figure 32 *Failure of beam at beam-column due to lack of development of reinforcement and insufficient ductility.*

performed adequately and showed no failure of the framing system or the building envelope. However, in some of them, the "X" bracing of the walls along the central corridor of the building buckled, pointing to an under-design. The modern high-rise structures designed to more stringent seismic requirements performed well. Even the building glazing systems performed well, with minor falling of glass panels in the high-rise building of Figure 36 located in Dar-El-Beida, the eastern neighborhood of Algiers, where several concrete buildings collapsed. Similar high-rise buildings in Boumerdes under construction sustained only light damage despite their close location to the epicenter (Figure 37).

Figure 33 *Failure of masonry infill walls.*

Figure 34 *Failure of precast façade elements in cast-in-place concrete tunnel buildings.*

Earthquake Design Requirements

The first Algerian seismic design code that included requirements for earthquake design specifications was developed in 1969 (PS69). It was not until the major earthquake that hit El-Asnam (Chelef) in 1980 that the Algerian government pushed for more comprehensive earthquake design practice. In 1981, with international assistance, especially from researchers at Stanford University, researchers in Algeria developed the first draft of what is known today as the Algerian Earthquake Design Regulations (RPA). The first printing of this design code appeared in 1983 (RPA83). It was supposed to be revised every five years.

With minor changes, another version appeared in 1988 (RPA88). Due to unknown circumstances, the next revised version of 1993 was not published. After several moderate

Figure 35 *No failure of steel-frame structure with lightweight infill panels.*

Figure 37 *11-story RC frame building in Boumerdes — no damage in resistant structure.*

Figure 36 *No failure of the glazing system of an R/C high-rise building.*

arthquakes (Oued Djer, October 1988; Tipaza, October 1989; Mascara, August 1994), lessons were learned and a newer version of RPA was developed in 1999. The RPA99 is the latest version of the Algerian Earthquake Design Regulations. Following are the two main rules incorporated in this design code:

- Provide the structure with minimum values of stiffness and strength to limit non-structural damage and to avoid structural damage with elastic behavior when subjected to a moderate earthquake.
- Endow the structure with a required level of ductility and energy dissipation capacity to allow for inelastic behavior with limited damage.

The RPA99 is used only for common construction. It does not cover special structures such as nuclear power stations, GNL (liquefied gas) plants, bridges, dams, or tunnels.

In the RPA99, three methods can be used to determine the structural post-elastic deformations caused by an earthquake. These methods are all based on the equivalent linear method using an elastic model where the seismic action is introduced as a response spectrum. These three methods are:

- the equivalent static method (see box on page 32),
- the spectral modal method, and
- the dynamic analysis using accelerograms.

Construction Quality

Most private residential houses and mid-rise buildings are designed and built by personnel with no training or knowledge of seismic design. In addition, concrete is often produced on-site with little quality control. Construction regulations control only government-built projects or private buildings used by the general public. In recent years, about 60% of housing has been privately built. There is also no licensing process for contractors, engineers, or architects. Heavy demand for housing from an ever-growing population has further degraded the quality of construction by pushing unqualified people into the construction industry. As mentioned on page 32, Seismic Zone 2 prescribes a seismic coefficient of 0.15g for residential buildings, but the ground motion from this earthquake far exceeded that threshold in a large area around the epicenter. Hence, even buildings in which seismic details were incorporated were not designed for the actual earthquake level.

Building Safety Inspections

The Controle Technique de Constructions (CTC), a government agency under the authority of the Ministry of Housing, undertook the building safety assessment surveys with 450 engineers. Building inspection teams were deployed in groups of two or three and were provided with a standard evaluation form (similar to the ATC-20 form) with which to report their findings and tag the building as either green, yellow, or red. These engineers

Base Shear Calculation Based on the Equivalent Static Method (RPA99)

Based on the Equivalent Static Method, the total seismic base shear V, in a given by the following equation:

$$V = \frac{A.D.Q}{R} W$$

Where :

1. **A**: Zonal acceleration factor, which depends on the seismic zone and importance of the building, given in the following table:

Group	ZONE		
	I	II	III
1A	0.12	0.25	0.35
1B	0.10	0.20	0.30
2	0.08	0.15	0.25
3	0.05	0.10	0.15

The territory is divided into four (4) seismic zones ranging from negligible or no earthquake effect to a severe earthquake as follows:

- Zone III: Severe earthquake ground motion. This zone includes the region of Chlef and Ain defla, west of Algiers, in the northern part of Algeria.
- Zone II: Medium earthquake ground motion. It spans all the northern region within a width of 100 km, parallel to the coastline, except the region of Tlemcen and Sidi Belabbes located in the north-west part of Algeria.
- Zone I: low earthquake ground motion. It includes the second 200-km-wide trench south of Zone II, including the region of Tlemcen and Sidi Bellabes.
- Zone 0: No or negligible earthquake ground motion, covering the southern region of Algeria, including the Saharan desert.

Buildings are classified with respect to their importance. Vital buildings, such as nation-al defense buildings, hospitals, or fire department facilities are classified in group 1A. Those with a great importance, such educational and sports facilities, are classified in group 1B. Those with medium importance are classified in group 2. Group 3 includes all buildings of lesser importance.

2. **D**: Mean dynamic amplification factor, which depends on the site class, damping correcting factor and the fundamental period of the structure. Sites are classified in four (4) classes, from rocky site (class 1, S1) to sandy soils (soft soil — class 4, S4). Of course the two first characteristic periods are associated with the site class.

3. **Q**: Quality factor, which depends on

- The redundancy and geometry of the elements of the structure
- The regularity of the structure in plane and in elevation.
- The quality of construction control.

4. **R**: Global structural behavior factor, which depends essentially on the bracing system used in the structure.

5. **W**: The effective seismic weight of the structure, including the total dead load and a certain percentage of the live load depending on the type of building.

had been trained in this task and had performed similar surveys in previous earthquakes. The survey teams were deployed in different jurisdictions and worked systematically from one neighborhood to another following a detailed deployment plan. The survey teams reported each evening to headquarters, where they discussed their findings with their supervisors. The inspection teams were coordinated by two command centers—one in Algiers and one in Boumerdes. The damage state definitions used by the teams are listed in Table 2.

Table 2: Definition States Used by Building Safety Inspectors

Damage State	Description	Comment
Level 1: No damage	Overturned furniture and broken glass.	
Level 2: Slight damage	Nonstructural damage such as cracks in interior partitions and ceilings.	Assume the worst-case scenario and provide a comment if necessary.
Level 3: Moderate damage	Important nonstructural damage and slight structural damage.	Assign Level 4 for cases where the crawl space failed and the structure is leaning after it dropped, even if the super-structure is still intact.
Level 4: Heavy damage	• Heavy nonstructural and structural damage. • X cracks in shear walls, and plastic joints in the beam-column connections.	Make sure to distinguish be-tween Levels 3 and 4. Consult other engineers in case of doubt.
Level 5: Collapsed structure or to be demolished	• A story disappeared • Building is leaning • Several plastic joints devel-oped in beam-column connections	

In the provinces of Boumerdes and Algiers alone, as of June 24, over 100,000 buildings had been inspected. The majority were residential, but others included office buildings, schools, hospital facilities, recreational facilities, commercial buildings, and industrial facilities. About 31,000 buildings were listed as heavily damaged or totally collapsed, and slightly less than half (about 49,000) were found to have little or no damage. Among the essential structures, 1,800 schools and 200 hospital facilities were inspected, of which 331 schools and 24 hospitals were heavily damaged or totally collapsed. The inspection results by damage states for the provinces of Algiers and Boumerdes are shown in Figure 38. The damage statistics are reproduced in Table 3.

Table 3 - Damage Statistics by Occupancy (as of June 23, 2003)

Residential Buildings (Apartments and Private Houses)	Public Infrastructure
Total damaged: 182,000 units	Total facilities damaged: 6,200
Algiers Province: 92,000 units	Non-Available
Boumerdes Province: 72,000 units	Non-Available
Other Provinces: 18,000 units	Non-Available
Number of dwelling units to be demolished: 19,000	Facilities to be demolished: 462

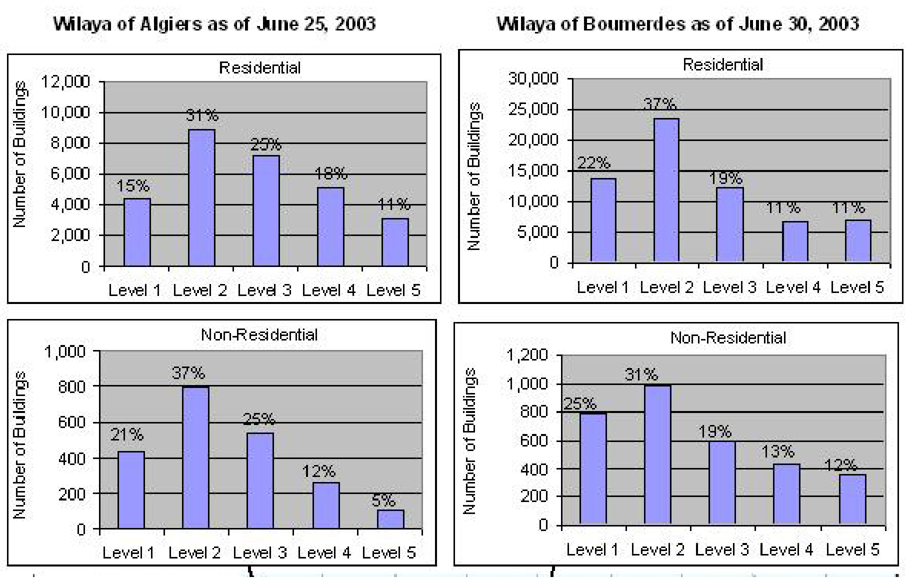


Figure 38 Damage statistics from building safety surveys (as of June 23, 2003).

Industrial Facilities

The major industrial area nearest to the epicenter is located along the highway corridor between Rouiba and Reghaia, about halfway between downtown Algiers and the city of Boumerdes. A preliminary survey shows that 276 administrative buildings within the inspected industrial facilities suffered damage with 10 tagged red, 64 orange, and 185 green. Eighteen industrial buildings within the inspected facilities were red tagged, whereas 10 were assigned orange, and 60 were marked green.

The SNVI, a truck plant, is the largest industrial facility in the area. Equipment suffered substantial damage, forcing thousands of workers to be sent home. Unanchored or poorly anchored machine tools and electric cabinets were over-turned or slid as shown in Figure 39. By contrast, equipment on vibration isolators performed well. Other industrial plants such as the Coca Cola plant, the milk plant Giplait, the hydraulics construction company ENAH, etc., in the Rouiba Industrial Zone also suffered damage to both the administrative buildings, industrial buildings, and equipment. The ENAH RC administrative building was severely damaged. On June 6, all employees and office furniture were already relocated to an older undamaged adjacent building.

A large RC grain storage silo approximately 100m long x 25m wide x 40m high in Corso, close to Boumerdes, was severely damaged. Several if its cylindrical cells were sheared in their lower sections (see Figures 40 and 41). Following the earthquake, this largest gain silo in Algeria was emptied for fear of explosion. Studies were already being planned in preparation for its repair.

There was no damage from fire following the earthquake because most building construction is concrete.

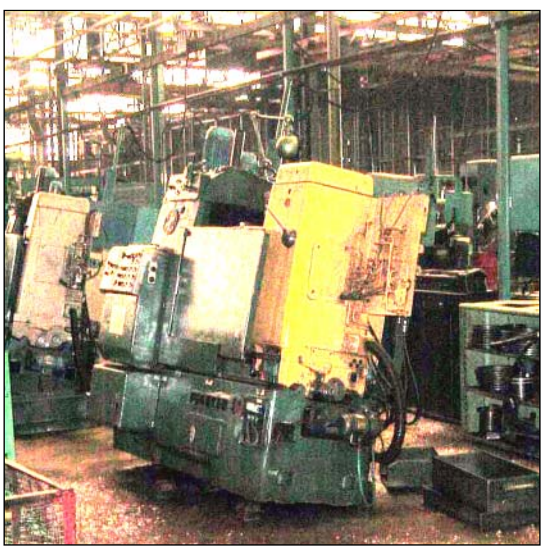
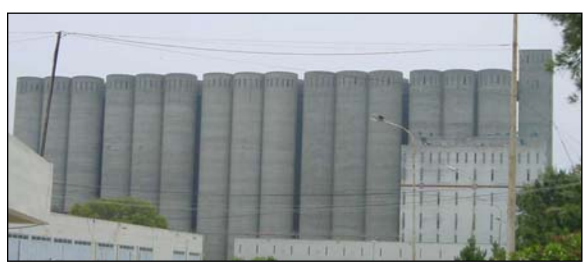


Figure 39 *Poorly anchored machine tool.*



Figures 40 and 41 *Severely damaged grain storage silo in Corso.*

Chapter 5

Lifeline Systems

Water[1]

Water treatment and distribution is the responsibility of the public company Algerienne des Eaux (EDA). In this area, water is either captured in dams or pumped from the ground. There are three dams in the earthquake-affected area: the Khedara Dam, the Beni Amrane Dam, and the Hamiz Dam. The Khedara 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 Khedara and Beni Amrane Dams and sensors were immediately installed on these two dams to monitor any further damage. As of June 8, 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 bloc 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.

A water treatment plant near Boudouaou, with a treatment capacity of 540,000 m3/day, incurred damage in each of the two 50,000 m3 reinforced concrete semi-buried rectangular reservoirs. The short RC columns sitting atop concrete walls and supporting the reservoir concrete slab were sheared at several locations, and the neoprene pads between the short columns and the slab slid.

In Reghaia, a recently built 1,000 m3 elevated RC tank was severely damaged and was subsequently demolished since it represented a collapse hazard. Ten other smaller elevated water tanks, 50-100 m3 in capacity, and the Ait Ouarzine Reservoir were damaged by the quake.

Four pumping stations in Rais Djinet and Tidjelabine were damaged and were out of service, and the distribution system was further affected by the widespread building damage. Several main lines were shut down, and entire neighborhoods were without running water for several days. As of June 8, 2003, some locations in the epicentral area were still without running water. For example, in Boumerdes the restoration was only at 70%. However, water was brought in by mobile cisterns on trucks and more was available from water tanks placed at fixed locations. Tent camps for the homeless were provided with water and either connected to the sewer system or provided with septic tanks.

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[1] Based on information from Mr. M. Terra of the Ministry of Hydraulics

Electricity and Gas[2]

Production, transmission, and distribution of electricity and gas is undertaken by the public company Societe Nationale d'Electricite et du Gaz (SONELGAZ). This company maintains its own specialized communication system and runs a permanent emergency center. Following the main shock, the gas lines were shut off and the natural gas-powered electric power plant in Ras Djinet was shut down. This power plant has four generating units and is designed to provide power to customers in the electric district of Boumerdes and a small fraction of customers in the Algiers district. The vibration isolators supporting the four units of this plant performed well (Figure 42).

There are four substations in the epicentral region. The Boumerdes station was put back into service on May 6, 2003, after the repair of two transformers. Similarly, the Si Mustapha station was put back on line the same date following the repair of its two transformers. As of June 8, the Reghaia station was still out and undergoing repair to a transformer. Finally, the Boudouaou station in Alger Est, with two 220/60kV transformers damaged, was scheduled to go fully back on line by June 14, 2003. Electricity was also provided to the tent camps erected in the four provinces affected by the quake. Progress in the restoration of the electricity and gas is plotted in Figure 43.

Telephone

Two companies operate the telephone network. Algerie Telecom, a public company, runs all the land line system and a portion of the wireless network. Djezzy, a privately owned company, runs the rest of the wireless market. Three communication centers of Algerie Telecom collapsed completely, one in El Harrach with 40,000 lines, and the two others in Zemmouri (see Figure 44) and Tidjelabine with 1,000 lines each[3]. The Algiers-Boumerdes optic fiber connection was also ruptured.

Figure 42 *Good performance of vibration isolators.*

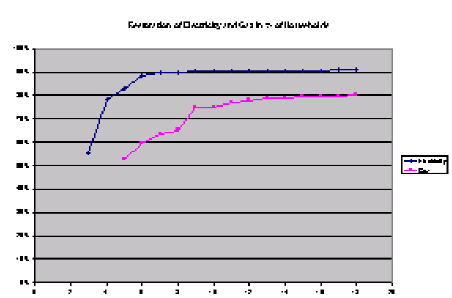


Figure 43 *Progress in the restoration of electricity and gas. Ninety percent of electricity was restored by the sixth day, and 80% of gas by the 14th day.*

[2] Based on information from Mr. M. Guitouni of SONELGAZ.
[3] Personal communication with Mr. Bara of Algerie-Telecom.

Figure 44 *Collapsed telecommunications center in Zemmouri.*

The wireless telephone network operated by Djezzy lost several roof-mounted antennae[4]. This resulted in the shutting down of communications for a few days. At these sites, either the building collapsed, or the anchorage of the antennae and associated equipment failed. Figure 45 shows typical equipment and light antenna damage at a site in Tizi Ouzou about 50 miles east of the epicenter.

As in other major disasters, the phone network experienced saturation immediately after the earthquake. This situation lasted for two to three days. Telephone service was restored domestically the day after the event except in areas where power was still unavailable, like Boumerdes. Algerie Telecom used mobile telecommunication centers with 7,000 and 9,000 lines to restore communications. It also opened several phone booths at tent camps, offering free calls to those left homeless, and dispatched six trucks with four wireless lines each to cover the remote areas. As of June 8, 2003, only about 8,000 customers in El Harrach remained without phones.

Communications with Europe were cut off because of the rupture of two cables, one running from El Djamila about 10 km west of Algiers to the island of Palma de Mallorca, and the other running to Marseille, France. The cable running to Palma ruptured 47 km offshore and was found 2.5 km west of its original location. During the repair of the cables, communications with Europe were diverted through neighboring Morocco and Tunisia, but with limited capacity.

Figures 45a and b *Typical anchorage failure of antenna.*

[4] Personal communication with Mrs. R. Amazouz of Djezzy

Transportation Systems

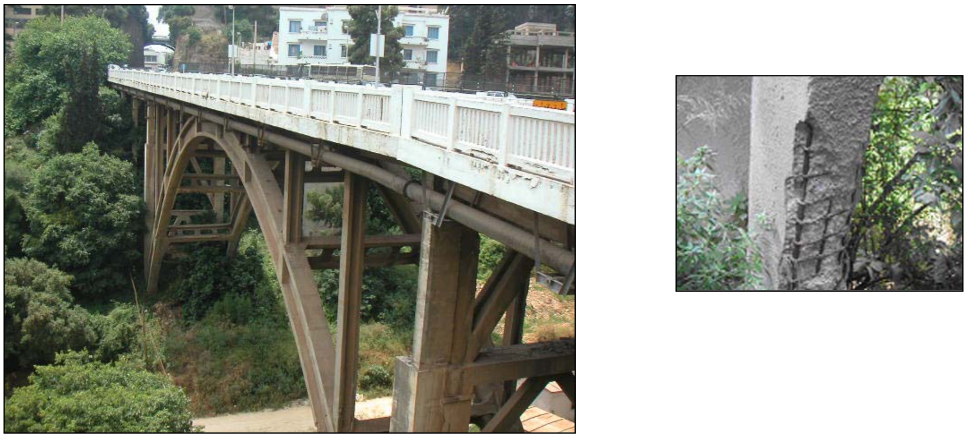
Bridges

Nearly all bridges remained fully functional. Most bridges are reinforced concrete. Damage observed was generally minor and included opening of expansion joints, some concrete spoiling at the bottom of the columns, and some failures of the transverse shear keys at the abutments. The bridge located in Boumerdes did not suffer any damage due to the earthquake, even though it is only about 10 km from the epicenter. According to a survey conducted by the Department de Travaux Public (DTP) (Ministry of Public Works), of more than 300 bridges in Algiers, Boumerdes, and other localities within a 60 km radius of the epicenter, only minor damage occurred to most bridges.

The major bridge affected was located between the city of El Harrach and Hussein Dey, less than 10 km east of downtown Algiers and about 50 km west of the epicenter. The bridge runs east-west on Route 5. It is composed of 18 spans and six frames; the frames are separated by expansion joints. The superstructure is composed of five simply supported steel girders on reinforced elastomeric bearings, and a continuous reinforced concrete deck. The substructure is composed of two-column bent connected by a bent cap. The last southeast frame had a skew angle of approximately 45 degrees. Due to the skew, the frame was subjected to a torsion that caused the outermost steel girder to fall out of the elastomeric bearing and land on the bent cap, which caused one end of the frame to move about 40 cm in the transverse and 20 cm in the longitudinal directions, and to drop by about 10 cm vertically (Figure 46). The eastbound lane was closed, but the westbound lane continued to carry traffic on both directions. The bridge was repaired a few weeks after the earthquake and put back into commission.

The Hydra Bridge, an arch bridge more than 100 years old, located in the southwest part of Algiers about 60 km west of the epicenter, sustained damage to the rib-arch connections and was closed to traffic (Figure 47). However, its closure did not affect traffic significantly because a duplicate bridge had been recently built next to it. More details of typical bridge failures in the epicentral area are shown in Figure 48.

Figures 46 a and b *Damage to Highway 5 Bridge.*



Figures 47a and b
Damage to the old arched bridge of Hydra.

Figures 48a and b
Typical minor, localized damage to bridge structures.

Ports, Harbors, and Airport

In the port of Algiers, the largest commercial port in the country, nine piers suffered damage (Figures 49 to 55). Investigations and studies were still being conducted on June 8, 2003, to assess the extent of the damage and the stability of the piers and to determine necessary repairs.

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 a few centimeters was noted near the quay walls. Depending on the pier location, the vertical offset of the quay wall with respect to the backland were reversed in direction from pier to pier as illustrated in Figures 49 and 50.

Lateral spreading was indicated by the opening of longitudinal tension cracks along the

Figure 49 *Differential settlement between the quay walls and backland, Port of Algiers (vertical offset toward the water).*

Figure 50 *Differential settlement between quay wall and backland, Port of Algiers (vertical offset away from the water).*

Figure 51 *Tension cracks longitudinal to the quay wall indicating lateral wall movement at the Port of Algiers.*

quay walls at the Port of Algiers, as shown in Figure 51. In many places the concrete pavement collapsed as a result of loss of ground support (Figure 52). Liquefaction created large cavities up to 2.5 m deep, mostly caused by the sand ejected from flowing boils (Figure 53). In these locations, port officials reported 3-m-high artesian flows that lasted for several hours.

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 (Figure 54 and 55). 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.

Figure 52 *Loss of ground support under concrete pavement at the Port of Algiers.*

Figure 53 *Cavity caused by loss of soil support due to liquefaction at the Port of Algiers.*

Figure 54
Settlement (>0.3 m) behind pier in the harbor of Zemmouri El-Bahri (close to the epicenter).

Figures 55a and *b*
Additional views of settlement behind pier in the Harbor of Zemmouri-El-Bahri

Algiers International Airport suffered damage to the main international terminal. The international check-in area was closed and has been temporarily relocated to a different building within the airport. The airport traffic control tower was also damaged and closed. Traffic control was accomplished from equipment set up in a temporary trailer.

Chapter 6

Response and Recovery

In Algeria, each province and municipality is required to maintain an ORSEC Plan (Organization de Secours), which specifies the procedures for emergency response. However, the ORSEC plans were developed many years ago and have not been updated, so they were of little use after the earthquake. Neither had there ever been a large-scale disaster exercise in the affected region. Furthermore, early underestimation of the earthquake's magnitude misled authorities about the severity of the earthquake. This was exacerbated by damage to phone communication lines, which impeded information coming from the affected zone about the extent of the disaster. The General Directorate of Civil Protection, the organization with responsibility for emergency response in Algeria (under the authority of the Ministry of Interior), dispatched teams to the area and coordinated the emergency activities with the local police and other authorities. A potential use of the high-resolution satellite imagery discussed in the insert is apparent here. If such imagery could be acquired immediately after the event, it could be used to help determine the severity and extent of the damage, even if other communication channels were not working.

Search and Rescue

As has been the case in many earthquakes in the past, local residents with the help of the local authorities (i.e., civil protection and public safety) were the first responders for several hours after the quake. The local population started digging into the ruins of the collapsed buildings to rescue their neighbors and family members. Personal cars were used to transport injured people to hospitals. Few of these local volunteers had any medical or rescue training.

In view of the tons of debris that needed to be cleared, these first responders were very frustrated; they had access only to their hands, shovels, and pickaxes. There is clearly a need for training and preparedness of community first responders, so they can participate effectively in search and rescue operations as well as first aid.

Teams from the General Directorate of Civil Protection and the Army started arriving in various locales four to eight hours after the main shock. Official teams started search and rescue (S&R) operations using sophisticated equipment and search dogs. They were helped by the local volunteers, who worked with them in moving debris and clearing sites. The support of the volunteers from the local population helped alleviate the work of the Algerian and international rescue teams. Together they achieved some success in saving lives, especially in the first 24 hours after the main shock.

The S&R operations lasted about one week. The priorities set for performing the search and rescue operations were established by a consultation process of the local people, the civil protection authorities and the police. In general, the rescue operations were directed first to apartment buildings and then to individual houses.

The Algerian S&R teams are well trained and have participated in several S&R disaster rescue missions from across the world, but the lack of heavy equipment hindered their operations. This issue should be taken into consideration in the planning of future search and rescue operations.

Shelter and Food

Immediately after the earthquake, the government established a national crisis commission to coordinate relief actions. Several other governmental institutions, such as the ministries of health, public works, housing, energy, and water resources, were activated to take care of matters that fell under their jurisdiction. The Ministry of Housing, through the Controle Technique de Construction (CTC), conducted building damage assessment and performed initial reinforcement of damaged buildings. The provincial authorities coordinated debris removal using equipment from both public and private sectors. Resources were brought in from all the other provinces in the country.

There are few humanitarian community-based organizations in Algeria. The Algerian Red Crescent Society and the Algerian Scouts deployed their volunteers to provide food, shelter, and support to the victims, including children. About 1,000 scouts were involved. Foreign countries also provided help in the form of food, medicine, tents, and blankets. About 120 aircraft landed in Algeria with relief goods in the first days after the earthquake. Several international organizations were in place a few days after the earthquake and provided additional resources and expertise in post-earthquake humanitarian relief operations.

Social Mobilization

Some residents in Boumerdes created an "association of the inhabitants of the 1200 lodgings neighborhood" to take charge of the food distribution and the allocation and placement of tents. The presence of many high-level public servants may have also been a factor in the effective organization of this neighborhood. Other types of social support systems quickly developed in larger cities — for example, mobilization through neighbors. Shortly after the earthquake, neighbors organized for protection and to take care of basic needs. Women typically took care of preparing food and ensuring basic sanitary conditions in the neighborhoods, whereas men where in charge of bringing supplies, guarding damaged buildings from intruders, and keeping in touch with the authorities. Younger people ran errands, kept an eye on the youngest, and gathered in groups in the neighborhoods. Similarly, groups formed around age groups and workplaces. Gathering along family ties was stronger in rural areas and in towns and villages. Leaders emerged from elders and local notables.

A certain amount of opportunism was also observed. Families that had not been affected by the earthquake, but were living in tenuous housing, such as shantytowns and sheds, built makeshift shelters to convince local officials they were earthquake victims and thus eligible for new housing. These makeshift shelters were often built in very visible places — road intersections, entrances to the cities — to serve as a constant reminder of their need for better housing.

Public Services

Shortly after the earthquake, injured people started to arrive at hospitals and clinics in the area or at hospitals in the adjacent provinces. They came in private cars or ambulances from the civil protection, hospitals, clinics, and private companies. The resources available were not adequate to meet emergency needs, so authorities brought additional medical resources from other provinces in the country. Many volunteers across the country went to hospitals to give blood for the victims.

Makeshift campsites grew up around damaged buildings. Many homeless people did not want to evacuate their camps to go to the shelters established by the army, civil protection, and NGOs. The victims wanted to stay by their buildings to keep an eye on their possessions and remain with their neighbors. However, after a couple of weeks, most victims went to the tent cities (see Figure 56) set up by the authorities because they were more secure, had electricity, and offered basic amenities. The country president promised that all homeless people would be sheltered before next winter, and preparatory work to install mobile homes was started in several places a few weeks after the event.

The authorities started large-scale debris removal about a week after the quake; however, the demand for site clearance exceeded the available resources. The government used equipment resources from the private and public sectors brought from all around the country.

The Ministry of Public Works was charged with repair of bridges and roads and with debris clearance in each province. The Algerian army provided assistance in the emergency operation as well as additional security. The army mobilized nearly 10,000 soldiers in the affected zones, and dispatched medical teams, public works personnel, and first-aid workers to join in the rescue and relief operations.

Ten days after the earthquake, a great many people were still sleeping in makeshift camps set up around damaged apartment buildings. The inhabitants were afraid that strong

Figures 56a and b *Tent cities erected by the government to shelter earthquake victims.*

aftershocks would bring down the damaged buildings, not without reason (see Figure 57). This phenomenon has been observed often in recent earthquakes and is understandable, but it makes the population stay out of their homes and apartments even in cases where only a little damage has taken place. A large number of people thus become homeless, significantly complicating humanitarian efforts.

Media Involvement

In Algeria, the radio, television, and some newspapers are state-owned, but there are several independent newspapers. The media responded quite effectively to the emergency situation by going directly to the disaster scenes, talking with victims about their needs and reporting the problems they were facing. The contribution of the media was significant in informing the public, staying in touch with conditions in the damaged ares, and maintaining contact with the victims. The effort of the media helped in reducing confusion and in providing some level of comfort to the population. The state-owned media, in particular, were important in collecting and disseminating information.

CRAAG has the responsibility of monitoring aftershock activity and collecting and disseminating scientific information about the earthquake. It communicated the information about the earthquake and the risk of aftershocks to various governmental agencies as well as to the news services. The information came in the form of public service announcements, round tables, and talk shows on TV and radio. The earthquake and its aftershocks (including two events of M5.8) spread confusion among the population in the capital city of Algiers, which was ill-prepared for this earthquake despite recent moderate events in the north-central part of Algeria.

Certain newspapers were critical of the emergency services on the basis that five days after the earthquake, there were still victims without adequate shelter, especially in remote villages. However, in the opinion of the EERI team, the authorities dealt with the emergency effectively considering that no formal plan was in place for doing so. Several factors worked together to aid emergency responders. Because the earthquake was near the capital city, government resources could be put in place very quickly. Furthermore, the transportation system remained almost intact, so relief could reach the victims without many obstacles. Because Algeria has been dealing with a civil war for many years, the civil protection and security organizations are at high state of readiness and were able to deploy their resources fairly fast. It was also helpful that it was late spring when the climate is dry and temperatures are comfortable both day and night.

Rebuilding and Relocating Housing

The issues related to rehousing the affected populations will undoubtedly be linked to their social status as well as to the political pressures they can put on the government. For now, the central government institutions have controlled the compensation and reconstruction processes. Compensation of homeowners who can prove legal ownership of their property will probably take place without much dispute; however, the process will be much more complex for those who "owned" or occupied housing without proper legal papers. Will those victims be able to benefit from informal structures and personal connections to acquire new properties? Experience in other disasters in Algeria and elsewhere suggests that it will be years before the situation is clarified for the illegal owners.

Reconstruction of damaged areas will pose technical as well as judicial problems of land availability. Will people be allowed to rebuild or will they be relocated? The role of local authorities in the decision-making process is likely to be curtailed by central governmental agencies. This is particularly true in the province of Algiers, where the availability of non-agricultural land is scarce; promised microzonation studies may further limit the availability of urbanized lots in the Algiers periphery. Moreover, the pressure on the authorities to act urgently might cause them to relocate large populations to areas far away from their original homes. A whole class of people such as teachers, factory workers, public servants, and small business owners may see their life greatly disturbed if they are moved far away from their work locations. Social science studies would be warranted in order to suggest a plan that will not exacerbate the trauma of a population that is already under significant distress. From past experience, rehousing victims can be time consuming because of all the associated social, legal, and economic issues.

Finally, one would hope that the process of developing options for rehousing will involve the affected communities. Despite the fact that local authorities have a small margin of political power (the president of the country promised housing before the end of the year) and are under extreme pressure to provide decent housing before winter sets in, they should not forget that the most sustainable solutions are developed with the active involvement of the community.

Figure 57 *Apartment tower in Reghaia heavily damaged in the main shock. This photo shows an evacuated tower three hours before its total collapse during the first strong aftershock (M5.8).*

Chapter 7

Conclusion and Recommendations

The earthquake of May 21, 2003, serves as yet another warning call about the risks faced by megacities throughout the developing world. Opportunistic access to land and unregulated construction significantly increase vulnerability in large urban areas, creating heavy material and human losses. Typically, the building inventory includes many weak and poorly constructed buildings that can collapse, as well as an older, brittle infrastructure, which performed poorly in Boumerdes and other past earthquakes.

Social issues can slow community recovery and destroy important social links. The issues of re-housing and compensation of the victims are very complex and can delay recovery from the earthquake for years. As observed in the Boumerdes earthquake, post-earthquake polarization develops between victims who have legal ownership of their property and those who do not. The first group is in a much better position to receive new housing and compensation for its losses, while the second group will need to negotiate its rights with the authorities. These conditions can derail government actions for rehousing the victims.

This situation is not specific to Algeria. In many developing countries where there is rapid, poorly controlled urbanization, societal vulnerability to earthquakes and other disasters keeps increasing alarmingly. Recent urban earthquakes such as those in Marmara, Turkey, in 1999 and Gujarat, India, in 2001 are reminders of this. Almost four years after the Marmara earthquake, many victims are still living in temporary housing, and many issues related to re-housing and compensation have yet to be resolved. Though the process of urbanization cannot be stopped, engineers know how to build earthquake-resistant buildings and protect communities from unnecessary risk to their lives and property. This knowledge needs to be urgently implemented in developing countries. Community preparedness efforts and mitigation practices can increase resiliency and decrease vulnerability to future events.

The EERI Reconnaissance team offers recommendations below related to urban earthquakes in complex environments and other recommendations specific to understanding the earthquake hazard and improving urban construction practices in Algeria and other developing countries.

Urban Vulnerability Reduction

- Undoubtedly the biggest issue facing large and megacities in developing nations is the existing building stock. In some cities, the inventory of weak and vulnerable buildings may number in the thousands. But retrofit of existing buildings often involves more than just technical issues — social, economic, and legal issues also loom large. A long-term strategy to integrate retrofit with urban renewal programs can provide the incentives for building owners to undertake retrofitting.

- Introduce minimum safety standards for new building construction. In particular, improvements are necessary in the design and construction of reinforced concrete frame buildings. Highly vulnerable nonductile reinforced concrete frame structures continue to be built in large numbers in highly seismic regions of the world. A more drastic solution consists of restricting building systems to shear wall structures. Attention should be given to the detailing of lateral-load resisting elements in soft-story conditions, short columns, and other adverse conditions.
- Lack of construction controls, code implementation, and code enforcement are major causes of damage. An effort should be made to train engineers, architects, contractors and other construction professionals in order to improve the state of the practice and include control functions in professional practice. Mechanisms for code implementation and code enforcement should also be introduced where they are lacking, such as in Algeria.
- Aging and vulnerable lifelines and weak public buildings contribute to heavy losses and complicate the ability to respond and recover quickly. Strengthening lifelines and public facilities should be on the mitigation agenda of governmental and utility agencies.
- The state of the art in repairing damaged buildings is not well established. The structural engineering solutions often rely on the personal capabilities and experience of the structural engineer in charge of the project. In the context of a country such as Algeria, where the structural engineering resources and training are very limited, there is ample room for mistakes. It would be prudent for the Algerian authorities in charge of reconstruction to establish a design and construction control process and to learn from other countries (e.g., Turkey or India) that had to deal with repair issues under similar circumstances in recent years.
- Awareness programs, preventive actions, and long-term mitigation policies will result in more responsible and capable institutions, more engaged communities, and a more aware civil society. Urban risk reduction must be viewed as a partnership between the government and its citizenship, but government has the responsibility to protect its citizens from avoidable risk.
- Post-earthquake housing is a major issue, requiring attention prior to the event and creative problem-solving after it. Housing in megacities is mostly in vulnerable building types, and the loss of many units contributes to social instability for years after the earthquake. Acceptable solutions for interim and replacement housing need to be researched prior to an event, so they can be implemented quickly.
- The Algerian government will assume the overwhelming portion of the losses from the Boumerdes earthquake. These funds will be diverted from economic development programs and basic social services. The government has announced the creation of a mandatory earthquake insurance system. Such systems exist in many countries and have proven efficient in providing a means to finance catastrophic losses.

Understanding the Earthquake Hazard

- The nature of the plate margin offshore from the Algerian coastline should be mapped and studied. Similarly, an investigation of the historical seismicity of the country and its relationship to the tectonic environment should be undertaken. Currently, the nature of risk to the city of Algiers itself is of utmost importance. Many questions about the hazard cannot be answered without understanding the offshore fault structures. Similarly, adequate levels of earthquake design for the region cannot be determined without accurate earthquake hazard mapping.
- Because of the still unknown seismic hazard in most of the northern regions of Algeria, as was the case for the Boumerdes region, it is prudent to raise the current seismic zoning by one level, while awaiting results from detailed microzonation studies.
- Geotechnical parameters should be taken into consideration in new construction. Other effects such as near-field conditions and directivity should be investigated and eventually introduced in the design procedures.

Urban Construction Practices

- Seismic code provisions should extend to privately-built structures, including single-family homes.
- Aggressive training programs for construction professionals should be undertaken. Similarly, earthquake engineering courses should be introduced in the university curricula for civil engineers and architects.
- A licensing process should be put in place to make sure that designers and contractors have necessary knowledge of the fundamentals of earthquake-resistent construction. Ultimately, only licensed professionals should be allowed to engage in the design and construction of buildings and other facilities. Meanwhile, authorities should introduce a system of third-party checking of design and construction under the supervision of the control company CTC.
- CTC's technical capacity should be enhanced to be effective in covering field as well as design review requirements. Specialized material and construction control laboratories should be set up to improve construction materials and practices.
- The process of improving the planning, design and delivery of construction in Algeria requires broad reforms, new government policies and significant resources. Sustained governmental action will be required in order to make progress in this area and impact changes in the long term.

Emergency Response

- Response plans should be developed to identify the resources needed to respond to a disaster. These resources include both necessary staffing and heavy equipment. Shortages of both hindered immediate search and rescue in Boumerdes.
- Training programs for local volunteers are important to reduce the life loss from an earthquake.
- Drills should be undertaken to test emergency response plans and keep them

current.

- GIS-based loss estimation tools should be developed. Such tools would allow ORSEC officers to estimate the location and extent of damage to lifeline systems, essential facilities, chemical facilities with hazardous materials, and high-density population areas, and would speed up response.

Further studies suggested for the various government and university centers

Research should be encouraged at the various Algerian research centers (CGS, CRAAG, CTC, CNERIB, ENP, University, LEM, etc.) to extract and document the lessons from this earthquake. Among the possible fields of investigation, the following are suggested:

- Survey building damage by construction type, year of construction, height, extent, failure mode, estimated ground shaking, and soil type. Such studies would identify potential improvements in the current seismic code. Of special interest is the performance of reinforced concrete moment-resisting frames with masonry infills. These studies would also allow the development of building vulnerability functions that could be useful in damage estimation studies.
- Study the performance of and retrofit techniques for colonial unreinforced stone masonry high-rise apartment buildings that make up most of the building stock in most downtown areas of cities in Algeria and several other Mediterranean countries. Without mitigation, these highly vulnerable structures will fail in future earthquakes of much larger proportions.
- Analyze the strong ground motion recordings and their relationship to earthquake mechanism, site effects, and other geophysical and earthquake engineering problems. The recorded ground motion should also provide a good base for developing attenuation functions for the north central region of Algeria.
- Study the site amplification effects in the alluvial plain as well as directivity and directionality effects, observed in the Boumerdes and other recent earthquakes.
- Study the dynamic response and resulting damage in some special structures such as the grain silos in Corso, the Khedara Dam, and the Isser Bridge.
- Study the sea withdrawal and the resulting tsunami, as this is a rare event in the Mediterranean Sea.
- Study how families and communities have been affected and how social structures have held up under stress.
- Study the potential social and economic effects of re-housing and relocating populations, and develop the least disturbing processes for relocation.

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Post-Earthquake Reconnaissance using Satellite Imagery: Boumerdes Case Study

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Note: *EERI's Learning from Earthquakes Committee and Information Technology Committee are investigating the uses of new technologies to assist in post-earthquake reconnaissance. The Algeria earthquake was an opportunity to look at the possible uses of satellite imagery, and the following report summarizes some of the potential of this technology. The LFE Program supported the acquisition of QuickBird scenes of the city of Boumerdes following the Algeria earthquake of May 21st 2003, and shared them with a number of EERI members conducting research on the uses of satellite imagery. We expect further reports from these members as they conduct their analyses. The following is a quick report prepared by colleagues at ImageCat and the University of Tokyo with supplementary funding provided by the Multidisciplinary Center for Earthquake Engineering Research (MCEER). Because these images were not available at the time the reconnaissance team went to Algeria, team members did not use the imagery and the discussion of its possible uses is thus not incorporated into the report. To enhance visualization, the images in this insert have been printed in color.*

Introduction

The use of remote sensing technology is becoming increasingly widespread following natural disasters. In the immediate aftermath of an earthquake, satellite imagery presents a regional overview of damage sustained. The location and extent of damage can be rapidly determined, facilitating the scaling and prioritization of relief efforts. Over time, the imagery can also be used for recovery monitoring. Figure I-1 shows the basic process.

Tiered Reconnaissance System (TRS)

The QuickBird satellite coverage of Boumerdes is seen in Figure I-2. The scene from April 22nd 2002 serves as a baseline case, depicting the city as appeared before the earthquake struck. The image from May 23rd--just two days after the event—shows damages. The image from June 18th reveals progress made with recovery efforts during the preceding month. These "pan-sharpened" images are a fusion of multispectral and panchromatic bands. The former band shows the ground surface in color, as it appears to the human eye. The latter band records additional surface details, showing features as small as 0.6m. The fusion process maximizes the distinguishing capability by optimizing spectral and spatial resolution.

The reconnaissance process uses a tiered approach. First, automated change detection algorithms offer a quick-look damage assessment. In simple terms, these algorithms compare images taken before and after the earthquake. Damage is detected in terms of changes between the images. Change detection algorithms have successfully been used to evaluate damage in cities affected in other quakes: the 1999 Turkey (Eguchi *et al*., 2000, 2002, 2003), 1993 Hokkaido, 1995 Kobe, and 2001 Gujurat earthquakes (Matsuoka and Yamazaki, 2002, 2003).

Figure I-3 shows the spatial distribution of severely damaged and collapsed buildings in Boumerdes, which were identified on the pan-sharpened QuickBird coverage using change detection algorithms. The areas highlighted in red and orange correspond with concentrated building damage. The scenes acquired before (4/22/02) and soon after the earthquake (5/23/03) were analyzed using the image processing software ENVI. A 9x9 pixel Laplacian edge detection filter was initially applied, followed by a 25x25 dissimilarity texture measure. The resulting images were differenced and the mean standard deviation plotted within a 200x200 window.

Within the tiered reconnaissance system, this quick-look assessment focuses on areas requiring more detailed inspection of building damage using visualization techniques. A visual comparison was drawn between enlarged views of the "before" and "after" pan-sharpened images, which were displayed side by side within the ENVI image processing environment. Due to the extremely detailed representation offered by QuickBird satellite imagery, severely damaged structures were readily identified (in blue), the distribution of which is mapped in Figure I-4. In addition to damage, Figure I-4 also shows the location of temporary tent camps (in green) housing displaced residents. Extraneous areas of change are attributable to isolated cloud cover in the "before" scene (in yellow) and changing conditions within the coastal waters.

Generally speaking, correspondence is high between the damage map in Figure I-3 and visually determined building collapse. Such close agreement reflects the distinctive characteristics of severe structural damage in high-resolution satellite coverage. Figure I-5 shows these definitive characteristics in greater detail. Collapsed apartment blocks are readily distinguished by the bright yet chaotic appearance of debris and piles of rubble. Where buildings have pancaked or toppled sideways, changes in shape and position are evident.

Remote sensing imagery has a further role to play in monitoring clean-up and recovery. Acquisition of extended temporal coverage, such as the image of 6/18/2003 in Figure I-2, allows for tracking progress with debris clearance and reconstruction. Figure I-6 shows the full temporal sequence for an area of apartment blocks in western Boumerdes. The first image illustrates the buildings prior to the earthquake, the second shows their collapsed state, surrounded by debris, and the third shows that the site has largely been cleared.

Ongoing Research

For several years, a multidisciplinary team at MCEER has been investigating how remote sensing technologies can improve response and recovery activities after major earthquakes. This research has focused on various aspects of damage detection, including the distinction between extreme damage and little or no damage; the quantification of damage states on a regional basis; and the assessment of damage sustained by individual buildings. In addition to the high-resolution QuickBird imagery employed for Boumerdes, damage assessment for previous earthquakes has utilized imagery from optical SPOT-4 and Landsat sensors, together with radar coverage collected by ERS-1 and ERS-2.

In addition to optical- and SAR-based damage assessment, researchers at the University of Tokyo and Japanese Earthquake Disaster Mitigation Research Center (EDM) have been exploring the mapping of urban damage using high-definition aerial television images (Hasegawa *et al*., 2000; Mitomi *et al*., 2002) and a surrogate indicator in the form of night-light data from the US Defense Meteorological Satellite Program (Hashitera *et al*., 1999).

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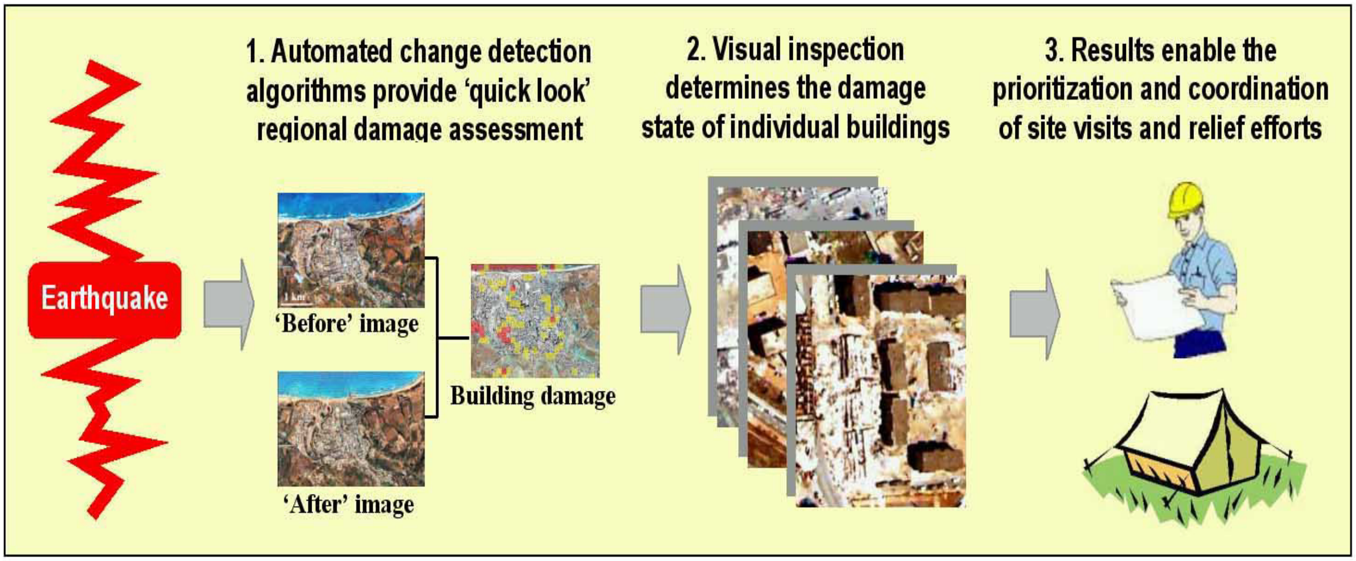

Figure I-1 - *Schematic representation of the Tiered Reconnaissance System (TRS). Satellite imagery is used to determine the location and extent of building damage, guiding the scale and prioritization of site visits and relief efforts.*

Figure I-2 **-** *QuickBird satellite imagery of Boumerdes, acquired before and after the May 21st 2003 earthquake. Images courtesy of DigitalGlobe, www.digitalglobe.com*

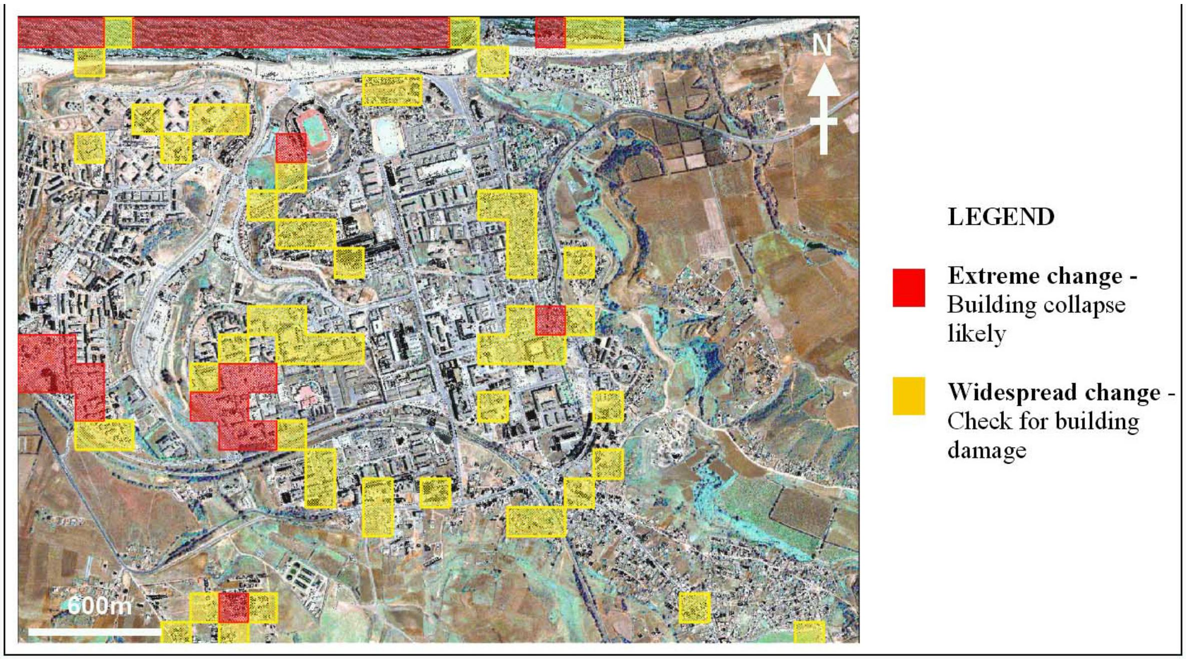

Figure I-3 - *Quick-look damage assessment for Boumerdes, obtained using change detection algorithms. Red and orange areas show changes which are primarily due to building damage or the establishment of tent camps. To aid visualization, results are overlaid with the panchromatic*

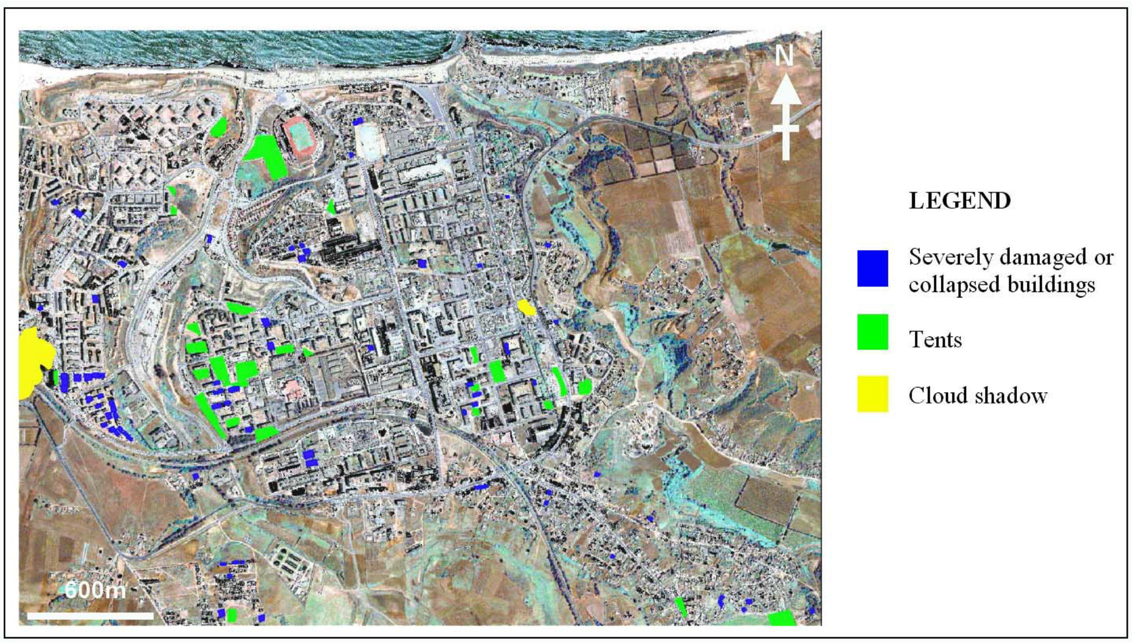

Figure I-4 - *Distribution of severely damaged/collapsed buildings and tent camps, identified using visual inspection. To aid visualization, results are overlaid with the panchromatic coverage from 5/23/03. Images courtesy of DigitalGlobe, www.digitalglobe.com*

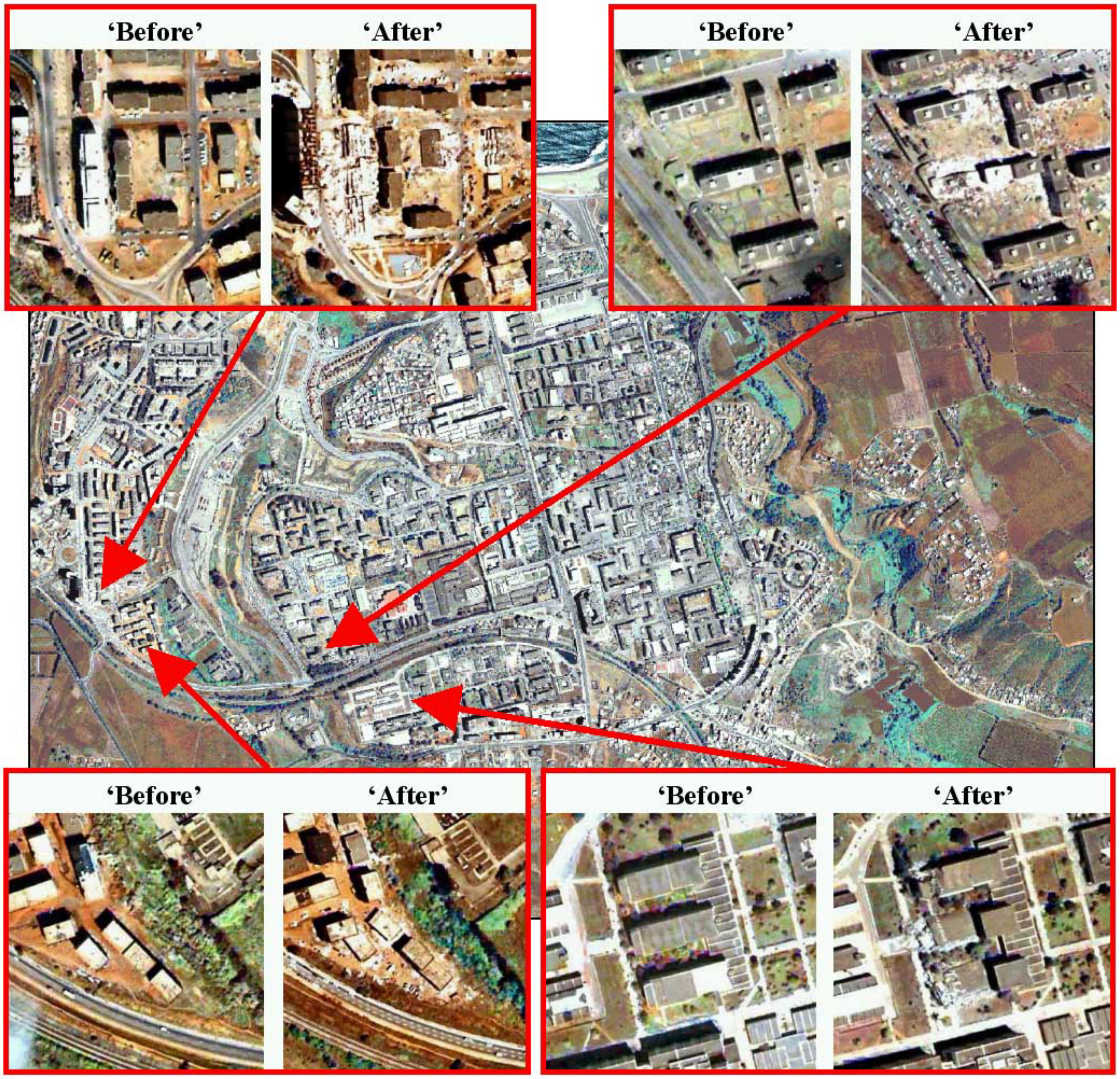

Figure I-5 - *Selected examples of building damage in the city of Boumerdes, identified by visual inspection of pan-sharpened QuickBird imagery, acquired before and after the 5/21/03 earthquake. Images courtesy of DigitalGlobe, www.digitalglobe.com*

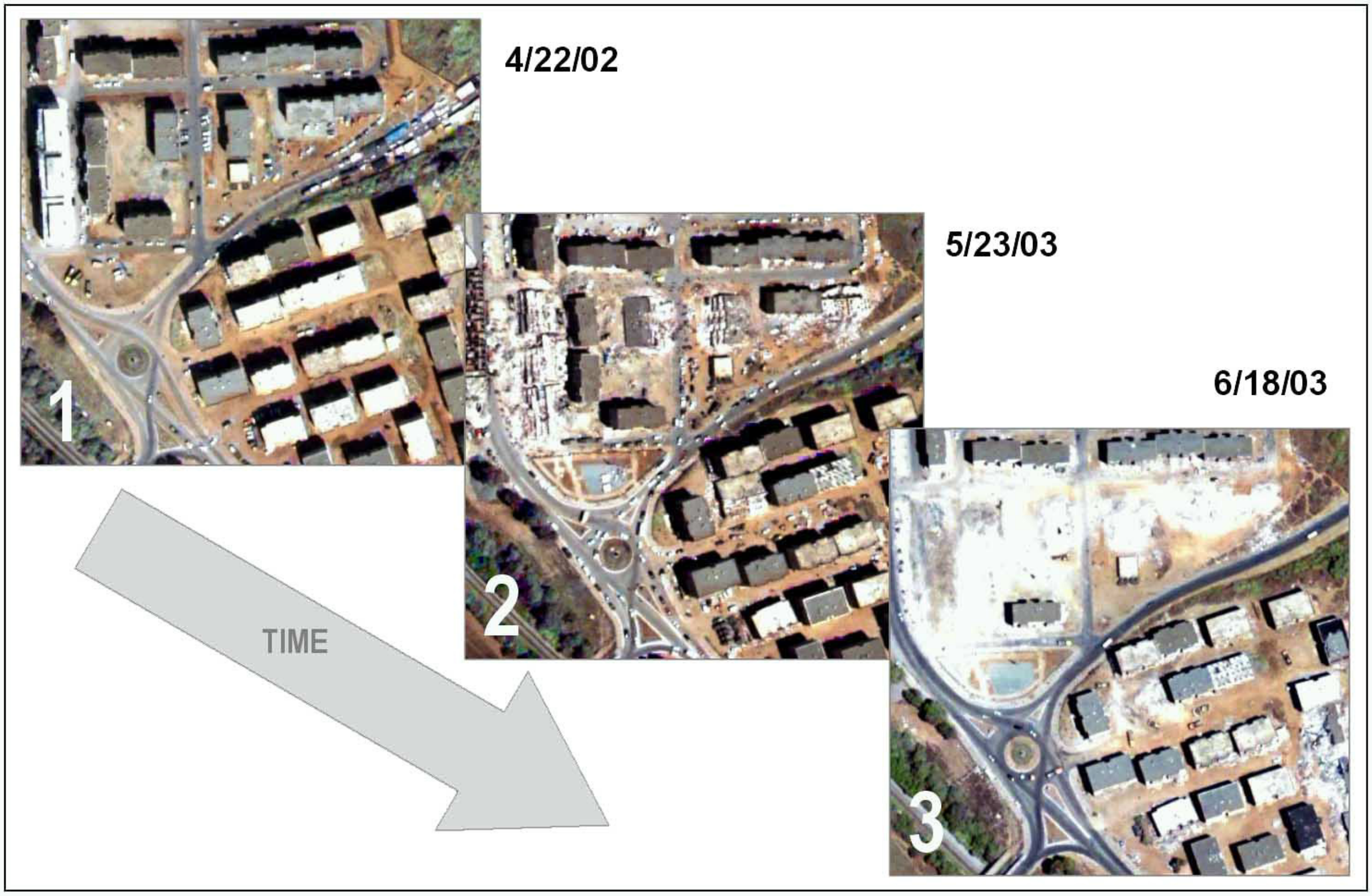

Figure I-6 - *Time sequence of QuickBird images, showing apartments in western Boumerdes (1) prior to and (2) soon after the 5/21/03 earthquake. Scene 3 was acquired on 6/18/03, and shows progress made with clean-up operations.*