The El Mayor Cucapah, Baja California Earthquake April 4, 2010

An EERI Learning from Earthquakes Reconnaissance Report

EARTHQUAKE ENGINEERING RESEARCH INSTITUTE

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The Earthquake Engineering Research Institute (EERI) is a nonprofit corporation. The objective of the EERI 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.

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EXECUTIVE SUMMARY

The 2010, M_w 7.2 El Mayor Cucapah earthquake occurred on Sunday, April 4, 2010, at 3:40 pm (PDT) in northern Baja California (BC), Mexico, and was located at 32.259ºN, 115.287ºW at a depth of about 10 km (6.2 mi), approximately 17 km (11 mi) WSW from Guadalupe Victoria, BC, 47 km (29 mi) SSE from Mexicali, BC, 51 km (32 mi) SSE from Calexico, California, and 180 km (120 mi) SE from San Diego, California. This is the largest event in the area since 1892, even larger than the M 6.9 earthquake in 1940. The earthquake was felt throughout Southern California, Arizona, Nevada, and Baja California, Mexico.

This report summarizes the observations from initial reconnaissance by all groups and individuals coordinated by EERI. This report emphasizes the effects of the earthquake on buildings, transportation infrastructure, water and wastewater treatment systems, non-structural aspects, some seismological aspects, agriculture and the initial economic impact. This report is a complement to the GEER report (http://www.geerassociation.org/Post_EQ_Reports.html) that emphasizes on all significant seismological, fault rupture, ground motion, tectonic, geologic and geotechnical aspects of the earthquake.

One of the most significant features of El Mayor Cucapah earthquake was the occurrence of widespread liquefaction over almost the entire Mexicali Valley, BC. Damage observed in some areas of Mexicali city can be attributed also to soil liquefaction, which induced lateral spread in numerous areas. Salient effects of liquefaction on buildings were movements and differential settlement of foundations leading to near collapse and collapse of hundreds of houses in Mexicali valley. Liquefaction and lateral spread caused the collapse of a railway bridge over the Colorado River. Liquefaction also destroyed extensive lengths of irrigation canals, and disrupted agricultural lands with sand “volcanoes” and ejecta spread all over the ground surface. Agriculture and, consequently, local and regional economies will be severely affected by this damage. This is a major lesson for the Imperial Valley.

Another significant feature of this earthquake was the effect on water and wastewater treatment systems particularly in Calexico and El Centro, California. As a result, some system components needed urgent repair to satisfy current and future demands, with the summer season approaching. Nonstructural issues were significant especially in some school buildings in Calexico and at a university campus in Mexicali. Collapse of nonstructural features could have resulted in potential fatalities had the school or university been in session during the earthquake. As of April 30, 2010, several schools were still closed and under repair.

Despite the magnitude and intensity of ground shaking, there were only two fatalities, both in the Mexicali Valley, BC. Most buildings and structures behaved as expected for this level of earthquake intensity, exhibiting in scattered cases severe damage and the rare collapse. Lessons from this earthquake include the need to develop and improve low-cost foundation systems for houses on liquefiable soil; to improve the seismic design of water and wastewater treatment systems; to improve the seismic design of nonstructural features of buildings, particularly hospitals and schools; to reduce the economic impact on agriculture; and to minimize economic losses.

ACKNOWLEDGEMENTS

Earthquake reconnaissance offers great opportunities to learn from earthquakes and develop and refine current seismic design methodologies. However it is recognized that this work is challenging and risky in terms of access, operations in unknown territories and guidance to sites of interest. Without local support our reconnaissance efforts could not have been possible.

We need to express our gratitude to a number of individuals and institutions especially in Baja California, Mexico who were instrumental and vital to our mission. Our thanks to Alfredo Escobedo, and Mario Rodríguez, Director and Deputy Director respectively of Civil Protection, Baja California, Mexico, and to Marco Sotomayor Amezcua, Director, and Alejandro Soto Castellanos both of Baja State Center of Control, Command, Communication, and Computing, and Lt. Col. Eusebio Villatoro, Director, Baja State Police. Our thanks also go to Estela Martínez, Mexicali Civil Protection Office for facilitating information and contacts. Mario Valdez, Director of the Buildings Division of the State Secretary for Infrastructure and Urban Development (SIDUE), was extremely cooperative and organized logistics and transportation for our reconnaissance mission in Mexicali city and valley. Also our recognition to other SIDUE personnel who escorted us and provided engineering information including Pedro Salazar, Sergio Montes, José Guadalupe Bautista, Carlos Reyes and others. Luis Mendoza, CICESE, was very helpful organizing logistics and providing local information. Data were gathered from the USGS and CISN reporting websites (http://earthquake.usgs.gov/ and http://www.scsn.org/). Select photographs were provided by local photographer Joseph Llausas.

Partial support for the reconnaissance and report preparation has been provided by the U.S. National Science Foundation to EERI's Learning from Earthquakes Program, under grant #CMMI-0758529.

TABLE OF CONTENTS

1 INTRODUCTION

On Sunday, April 04, 2010, at 22:40:42 UTC (3:40pm PDT), a magnitude M_w 7.2 earthquake occurred in northern Baja California (BC), Mexico. It was located 32.259ºN, 115.287ºW at a depth of about 10 km (6.2 mi), approximately 17 km (11 mi) WSW from Guadalupe Victoria, BC, 47 km (29 mi) SSE from Mexicali, BC, 51 km (32 mi) SSE from Calexico, California, and 180 km (120 mi) E from San Diego, California. This is the largest event in the area since 1892, even larger than the M 6.9 earthquake in 1940. Figure 1.1 shows an approximate distribution of intensities. The El Mayor Cucapah earthquake was felt throughout Baja California, Mexico; Southern California; Arizona; and Nevada.

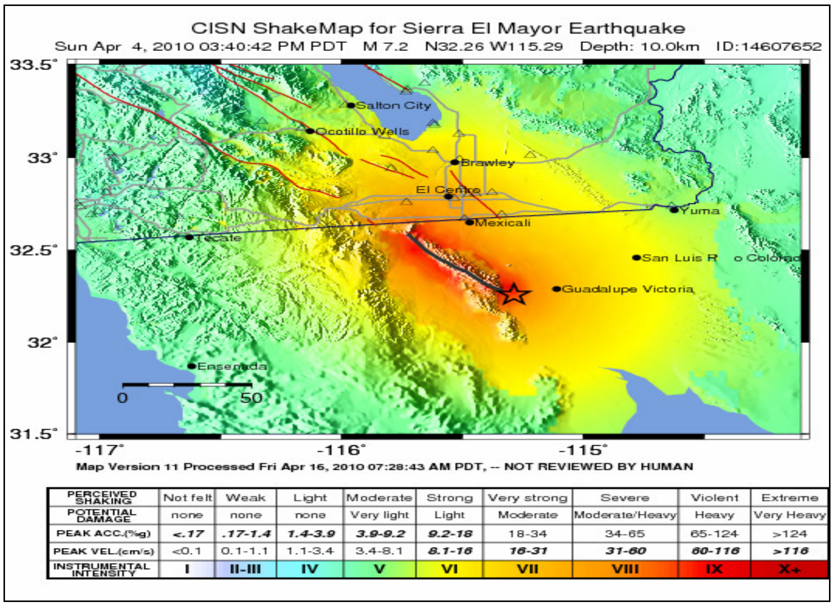

Figure 1.1: *Distribution of seismic intensities. Star shows location of epicenter (http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/ci14607652/#maps)*

The Earthquake Engineering Research Institute (EERI) immediately coordinated reconnaissance efforts to the affected areas. Kleinfelder, the University of California San Diego, California Seismic Safety Commission, Degenkolb, Exponent Failure, GeoHazards International, PSOMAS, Parsons, Simon Wong Engineers, and Tobolski/Watkins participated in these efforts. EERI organized a reconnaissance mission to Mexicali and surroundings, and closely coordinated efforts with GEER (Geo-Engineering Extreme Events Reconnaissance). Local authorities in Mexicali including the Department of Civil Protection, SIDUE (Secretary of Infrastructure) and CICESE provided support and facilitated the reconnaissance missions.

This report summarizes the observations from initial reconnaissance by all the groups and individuals coordinated by EERI. It emphasizes the effects of the earthquake on buildings, transportation infrastructure, water and wastewater treatment systems, some seismological aspects, agriculture and initial economic impact. A complementary report is available from GEER (http://www.geerassociation.org/Post_EQ_Reports.html), which emphasizes all significant seismological, fault rupture, ground motions, tectonic, geologic and geotechnical aspects of the earthquake.

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2 SEISMOLOGICAL ASPECTS

Because of the high seismicity of the area, it is heavily instrumented in the US by the United States Geological Survey (USGS) and California Geological Survey (CGS), as well as in Mexico by the Red de Acelerógrafos del Noroeste de México (RANM). Ground motions have been recorded as close as 16.2 km (10 miles) from the epicenter. The location and graphical display of PGA for the recording stations are shown in Figure 2.1. The epicenter, fault trace and Intensity Shake Map are also shown in this figure. Strong shaking on the order of 30% to 60% g lasting 10 to 15 seconds was recorded in the areas experiencing damage. The path taken by the Degenkolb Reconnaissance team, as measured by a portable GPS unit, is also shown in the figure in light blue. The data are plotted in Google Earth so that geographical data, such as mountain crests, are also shown in the figure.

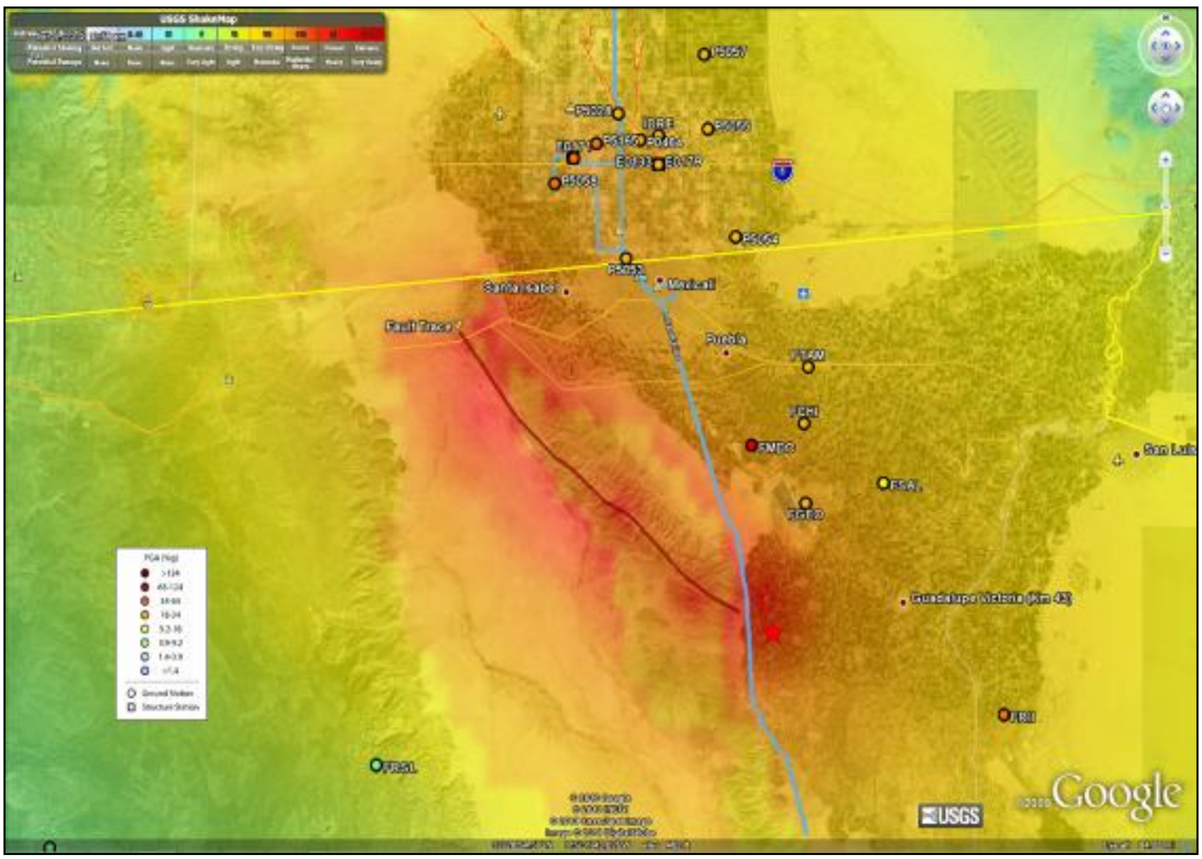

Figure 2.1: *ShakeMap and ground-motion recording stations (http://www.strongmotioncenter.org/cgi-bin/ncesmd/iqrStationMap.pl?ID=Calexico_04Apr2010)*

Please note that the peak ground acceleration in the horizontal direction (PGA) at the FMDO (Michoacan de Ocampo) site has been reported as 0.81g by the RANM. However, careful review of the actual ground-motion records appears to indicate that this measurement is in the vertical direction and that the PGA in the horizontal direction at that site is 0.53g. The ground motion records were measured at a representative number of sites, and the corresponding PGA are compared in Figure 2.2.

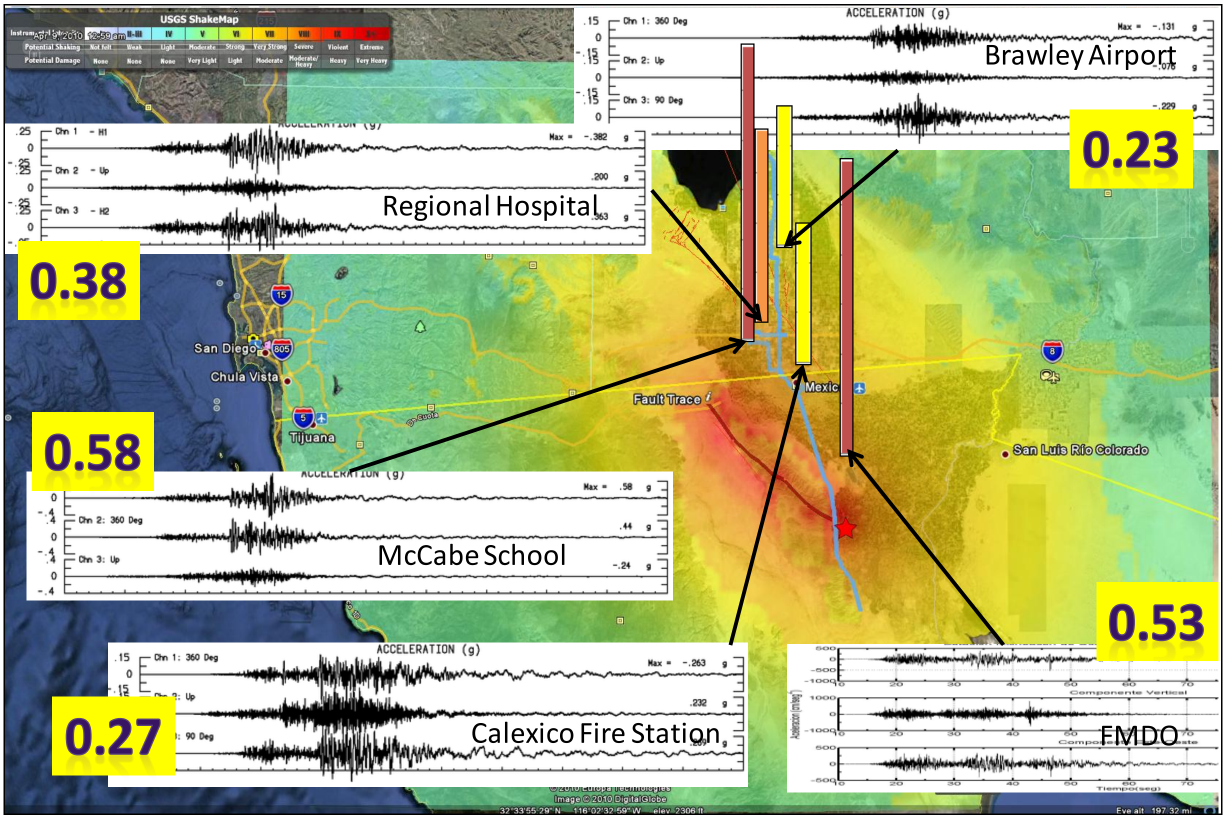

Figure 2.2: *Ground-motion records and PGA.*

The ShakeMap and PGA values shown in Figure 2.2 indicate that strong motion was felt quite uniformly at all points equidistant from the fault trace rather than just near the epicenter. This observation explains the dispersion in the plot of the PGA attenuation with epicentral distance, shown in Figure 2.3.

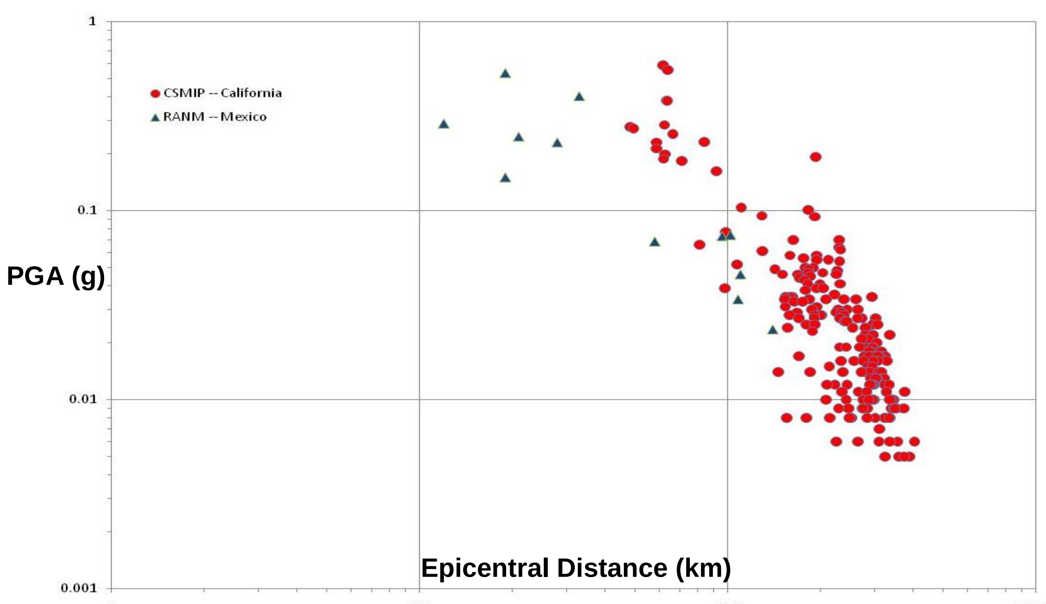

Figure 2.3: *PGA attenuation with epicentral distance*

Portions of the elastic response spectra for the ground-motion records shown in Figure 2.2 are shown in Figure 2.4. Please note that a digitized version of the FMDO record was not available for replotting in time for this report.

These response spectra at the individual ground motion sites represent the seismic characteristics of the site via the effective amplification. It is worth noting that even though the PGA at the two sites with the highest PGA are similar, 0.53g and 0.58g, the site characteristics amplified the response at the McCabe School site to peak spectral acceleration of 3.0g as compared to the 1.1g calculated for the FMDO site.

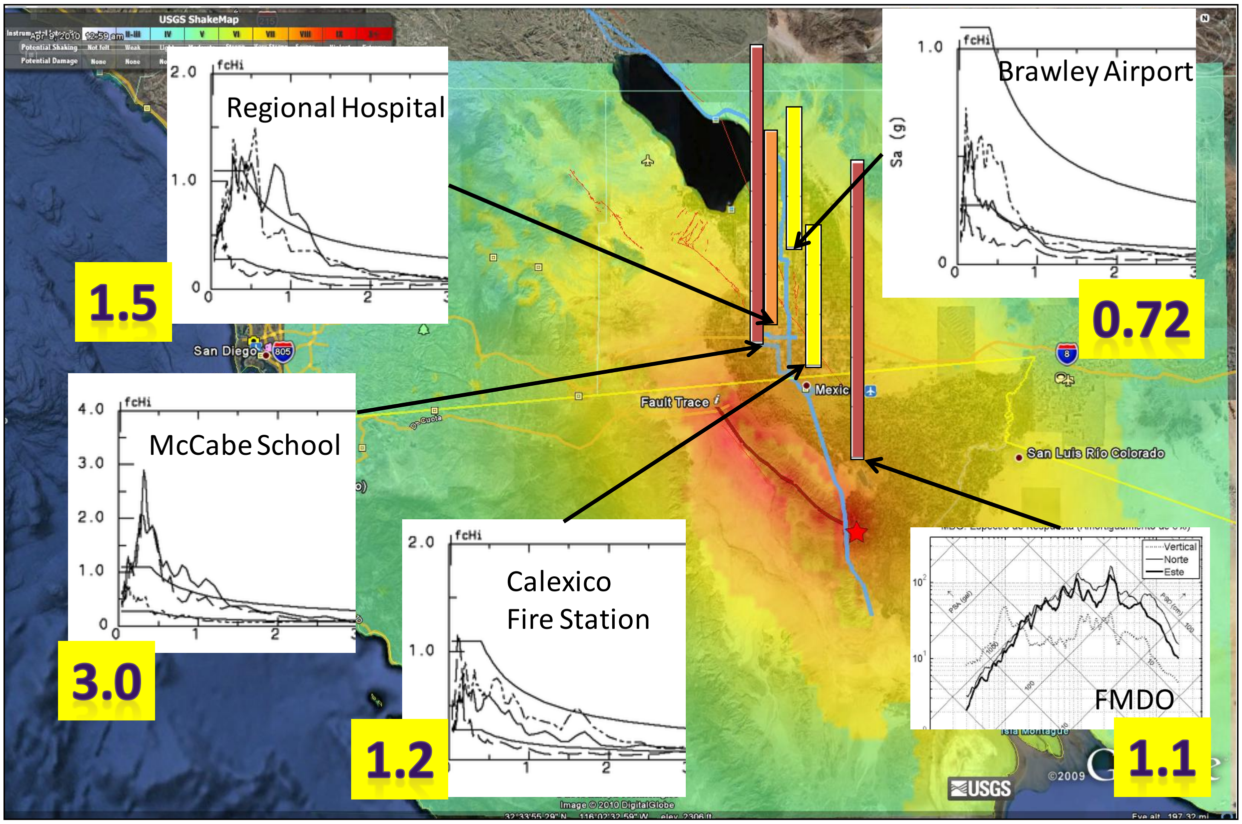

Figure 2.4: *Elastic acceleration response spectra showing maximum spectral accelerations.*

Figures 2.5 and 2.6 display some of the damage observed at sites near the USGS recording stations and near the epicenter, respectively. Specific descriptions of damage are contained in other sections of this report.

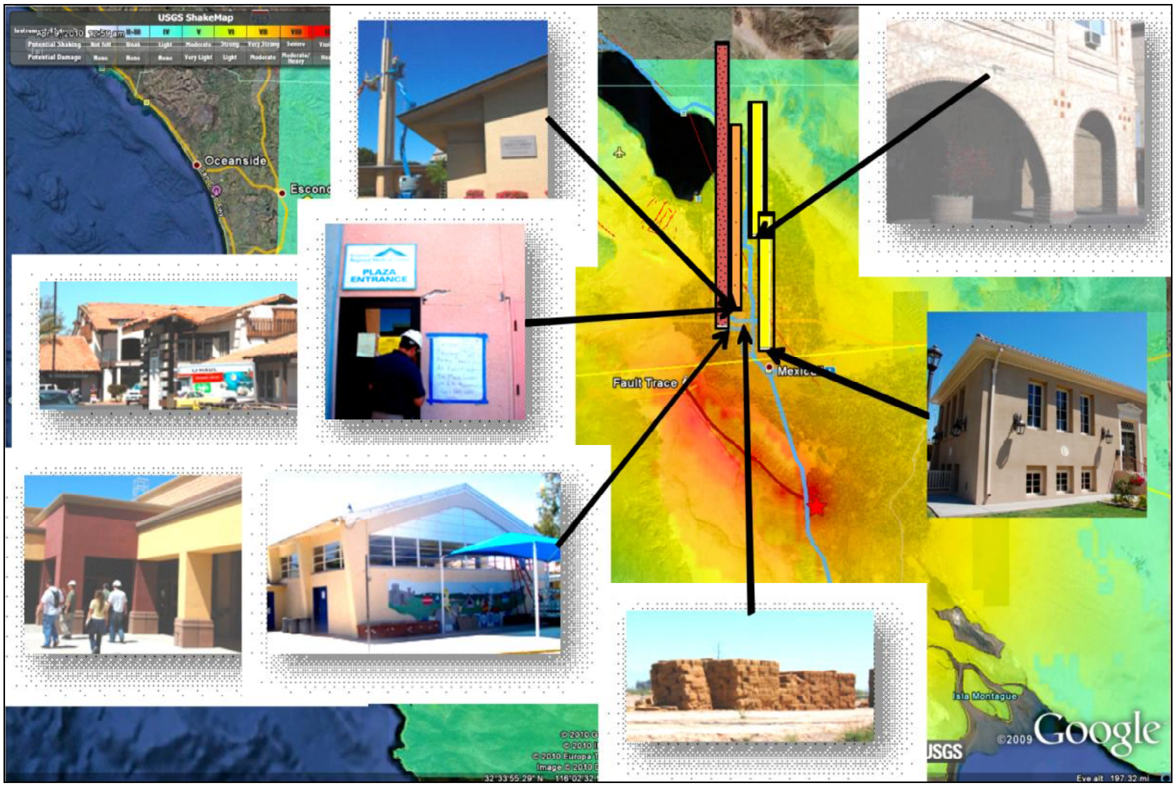

Figure 2.5: *Images of structures near the USGS strong motion recording stations in the cities of El Centro and Calexico.*

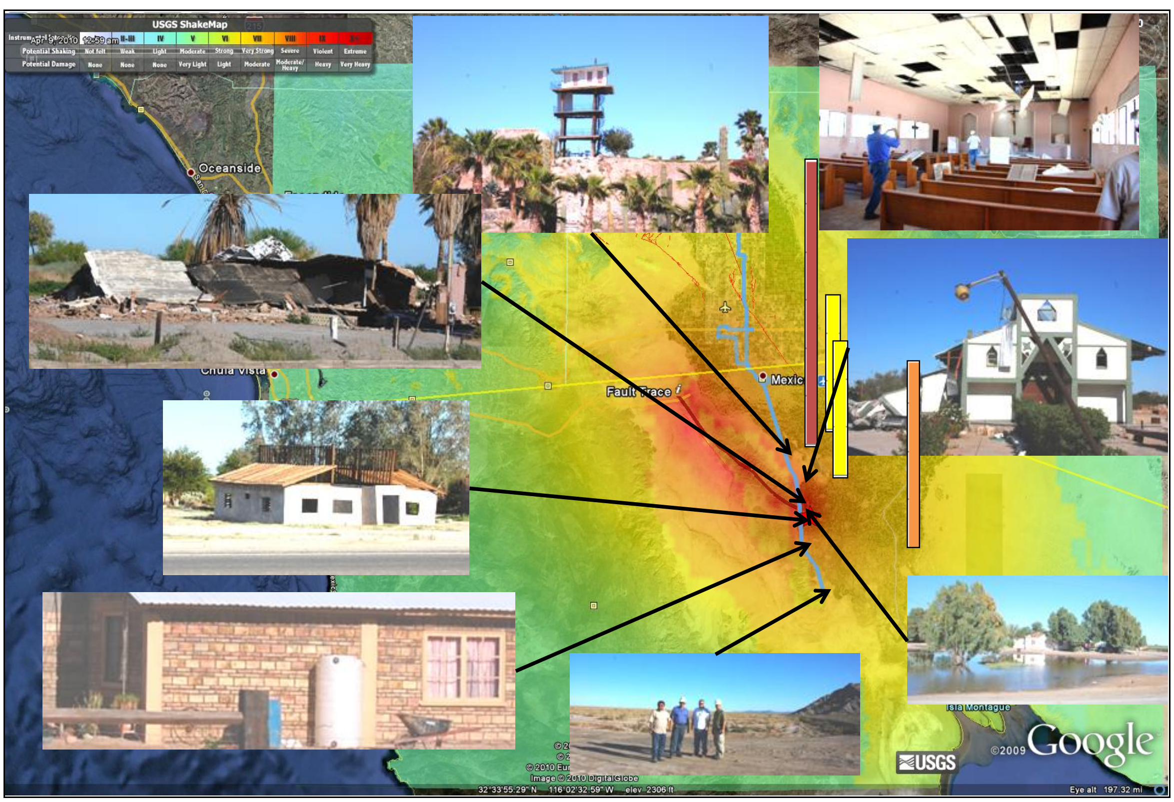

Figure 2.6: *Images taken at sites near the epicenter.*

A preliminary Probabilistic Seismic Hazard Analysis (PSHA) was performed on the McCabe School site to estimate the site-specific design spectra corresponding to different levels of seismic hazard. The results for three hazard levels (2%, 10% and 50% probability of exceedance) are plotted together with the recorded-motion response spectrum in Figure 2.7. The PSHA was performed using EZ-FRISK, with generalized estimates for site characteristics, such as shear-wave velocity and soil depth. The comparison indicates that this event was a significant event for the site, exceeding its design spectrum (both mapped values and site-specific) in the short period range up to 1 second.

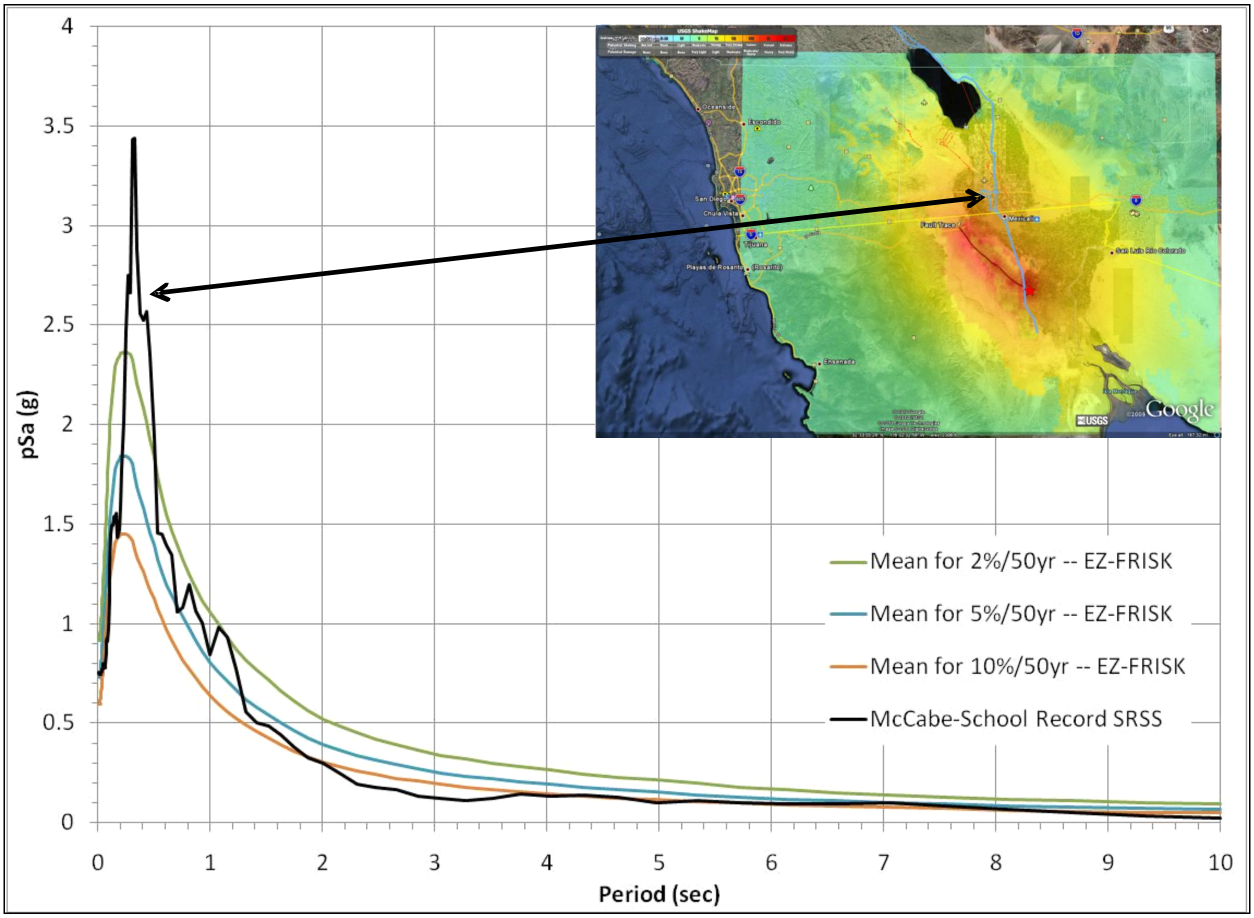

Figure 2.7: *Preliminary site-specific PSHA – El Centro - Array 11, McCabe School.*

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3 PERFORMANCE OF BUILDINGS

3.1 MEXICALI

Mexicali, Baja California Norte, Mexico is the city that suffered the most damage from this earthquake. Mexicali is located 47 km (29 miles) north of the epicenter. The city and its surroundings have a population of over 1 million residents. By comparison, Calexico and El Centro, the largest cities affected by this earthquake north of the US-Mexico border, have populations of approximately 30,000 and 40,000, respectively.

Mexicali houses many import/export companies within the city; however, most of the area outside the city is dedicated to farming. Most of the buildings in Mexicali are less than 2 stories and are composed of concrete frames with confined clay brick or concrete masonry in-fills. Outside of the city, there are still a great number of people living in adobe housing. A *Los Angeles Times* article dated April 12, 2010 reported that the earthquake collapsed a parking structure under construction, forced the evacuation of a hospital and damaged 5,200 homes. A firefighter in Calexico informed the reconnaissance team that his department had spent a good part of the week following the earthquake distributing food and water to the people of Mexicali.

Despite the reported damage in Mexicali, the city appears to be very resilient. The city did have some structural damage to its downtown area. However, with the exception of some school buildings in Mexicali, much of the structural damage occurred in retail areas rather than essential facilities. Several hospitals were evacuated in Mexicali after the earthquake; however, the reconnaissance team visited the hospitals and reported that the evacuation was mostly out of precaution rather than structural damage. The media has reported that only two people died in what is the largest earthquake the region has experienced this century. This earthquake, like many in the past, shows us that building code enforcement not only saves lives but also helps cities get back on their feet after a major seismic event.

3.1.1 Housing

During the trip to Mexicali, the lack of visible damage affecting the city was noticeable. The city was functioning as if nothing had happened. Very few buildings in Mexicali had visible cracks. However, while driving on Highway 5 towards the epicenter, more damage to residential housing was apparent. In speaking with residents, they reported damage to five neighboring communities: Zacamoto, Nayarit, Oaxaca, Cucapá, and La Puerta. They described homes that were destroyed by soil liquefaction and lateral spreading, and people affected by the earthquake were living in tents. There were rumors that the government will not let the residents re-build in the same areas due to fear of future soil failures. Aside from the reported damage caused by soil liquefaction and lateral spreading, some damage due to poor construction quality was observed. It was apparent that most of the older residential homes, especially outside of the city, are not engineered and therefore do not possess proper structural detailing. However, most of the newer homes had no visible signs of distress. Figures 3.1 and 3.2 show images of damaged and undamaged houses, respectively.

Figure 3.1*: Damaged homes in Mexicali.*

Figure 3.2: *Undamaged homes and resilience in Mexicali.*

3.1.2 Hospitals

Two adjacent hospitals in Mexicali's Centro Civico (Civic Center) area were partially evacuated following the earthquake, the Hospital General "5 de Diciembre" and the Hospital General de Mexicali (Figure 3.3). The Hospital General "5 de Diciembre" is a federal hospital, while the Hospital General de Mexicali is a state hospital. At both hospitals, portions of the ground floor were occupied and operational, while the towers were evacuated from the second story and above. A moderate number of patients were being treated in tents located outside. The chain of events that led to the evacuations was not entirely clear, however both hospitals were evacuated before government engineers inspected the facilities. Engineers inspected both hospitals and found the towers to be free from structural damage. Neither hospital appeared to have enough damage, structural or nonstructural, to create unsafe or disruptive conditions that would warrant evacuation or prevent re-occupation. However, the towers were not re-occupied nearly one week after the earthquake, and federal approvals had not yet been granted that were needed to re-occupy the evacuated portions of the buildings.

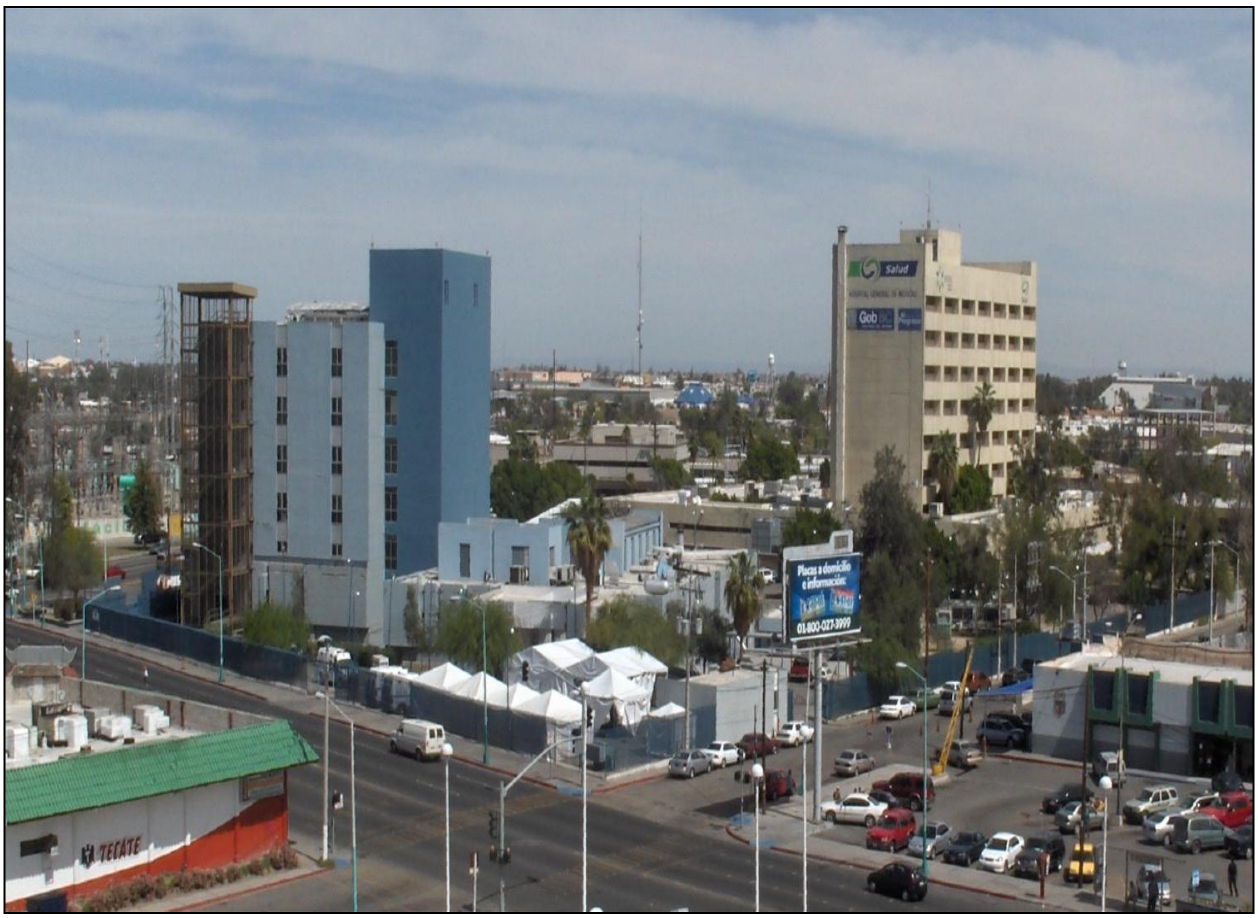


Figure 3.3: *Hospital General "5 de Diciembre" is the group of blue buildings at left, and Hospital General de Mexicali is to the right, most notably the taller building. Note the white tents for treating patients in the center foreground.*

3.1.2.1 Hospital General “5 de Diciembre”

The Hospital General “5 de Diciembre” has a six-story reinforced concrete frame tower building with brick infill, and several one- and two-story wings. No structural damage was observed, but damage to exterior cladding, interior finishes, suspended ceilings, and mechanical equipment was visible. Damage to exterior cladding was concentrated in the first two floors, as shown in Figure 3.4. Suspended ceiling damage was minor, with most damage occurring adjacent to walls. Some medical records fell from shelves, but pharmaceuticals and supplies stored on open shelves did not fall (Figure 3.5).

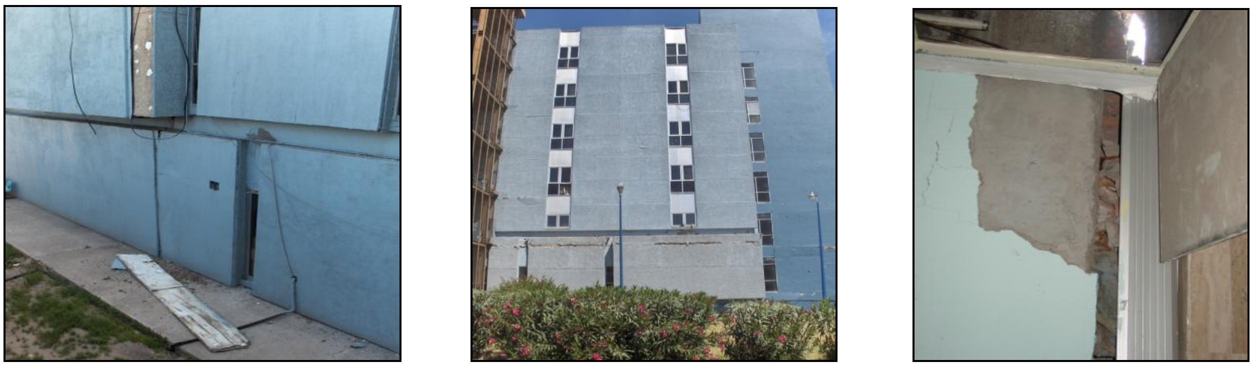


Figure 3.4: *Fallen exterior cladding panel (left); cladding damage (center); and finish damage due to differential motion at joint between tower and single-story east wing (right).*

Figure 3.5: *Soffit and suspended ceiling damage (left), a few fallen medical records files (right), both in tower ground story.*

Most of the hospital’s mechanical equipment was undamaged, with a few exceptions. HVAC equipment in the yard at the back of the hospital was damaged, in part due to a water tank located on top (Figure 3.6). In the main mechanical room, several tall, thin tanks toppled and broke pipe connections, and a large boiler almost slid off its supports (Figure 3.7). The emergency generator was running during the reconnaissance team’s visit, so it was apparently either undamaged or had been quickly repaired. The bulk oxygen tank was well-anchored and undamaged.

Figure 3.6: *Buckled HVAC unit in mechanical yard (left); toppled tanks in basement mechanical room (right).*

Figure 3.7: *Unanchored boiler (left) in basement mechanical room nearly slid off support (right).*

The hospital tower was evacuated following the earthquake, and remained evacuated nearly one week later despite inspection by government engineers who found no structural damage. The single story wing houses the Intensive Care Unit (ICU), and team members were told that it was not evacuated because there was no other option for providing intensive care. Nurses working in the ICU reported that a single monitor fell from its shelf during the earthquake; there was no other damage to medical equipment. The elevators had not been inspected or used since the earthquake, so their status was unknown.

3.1.2.2 Hospital General de Mexicali

Mexicali's General Hospital has a six-story tower with a reinforced concrete frame with brick infill, and several low-rise wings. The tower's structural members are very large; columns at the fourth story were observed to be more than 1.2 m (4 ft) across, and beams were at least 1 m (3 ft) deep. The frame has brick infill with small lightly reinforced concrete beams and columns included in the infill walls to keep the masonry from having to span large distances. The small concrete members may not be connected to the frame, and a space (often filled with Styrofoam) is provided at the top of the infill wall to decouple it from the beam. The tower is on a mat foundation.

No structural damage was observed in the tower. One of the wings, on the east (rear) side of the hospital had minor damage due to earthquake-induced settlement. The earthquake caused approximately one inch of new settlement of the wing relative to the tower. An official with the state health agency reported that poor soil underlying the east wing was a known issue and that settlement was ongoing, and that even before the earthquake the hospital had decided to replace the wing. Others who visited the building also learned that the top two floors of the tower have not been in use for some time, in an effort to reduce gravity loads and prevent further settlement. Two additional floors of the tower (the 2nd and 4th) are currently undergoing renovation and were not occupied at the time of the earthquake, minimizing the disruption caused by the evacuation. In these areas, the structural framing was exposed, and no structural damage was observed.

Figure 3.8: *Plaster damage in stairwell (left); finish damage in wing with settlement (right).*

Nonstructural damage was not observed in the tower, except for some fallen plaster in the stairwells and minor damage to finishes at the ground floor (Figure 3.8). There was some minor damage to HVAC equipment on the roof of the single-story wings, but repairs had already been made. One elevator was operating and in use, and had been “re-leveled”. The hospital had moved the Neonatal Intensive Care Unit to the ground floor from the tower; this was not due to equipment or systems damage.

3.1.3 UABC Campus

The Mexicali campus of the Universidad Autónoma de Baja California (UABC; 32.6320°N, 115.4444°W) is located approximately 44 km (27 miles) NE of the epicenter of the earthquake. The university was established in 1957 and had 16,000 students in 2007. The campus located in Mexicali is considered the primary campus; however, other UABC campuses are located in

Tijuana and Ensenada. The Mexicali campus has four main institutes: agricultural science, veterinary science, engineering and social research. Additional areas include architecture, humanities, law, medicine, political sciences and sports. Access to the interior of several buildings was limited due to the unknown extent of structural damage at the time of the reconnaissance visit. Where interior access was possible, significant nonstructural damage was observed. A survey of 11 buildings was conducted with the locations and facility usage noted in Figure 3.9. A detailed summary of each building follows along with English translations of the facility name.

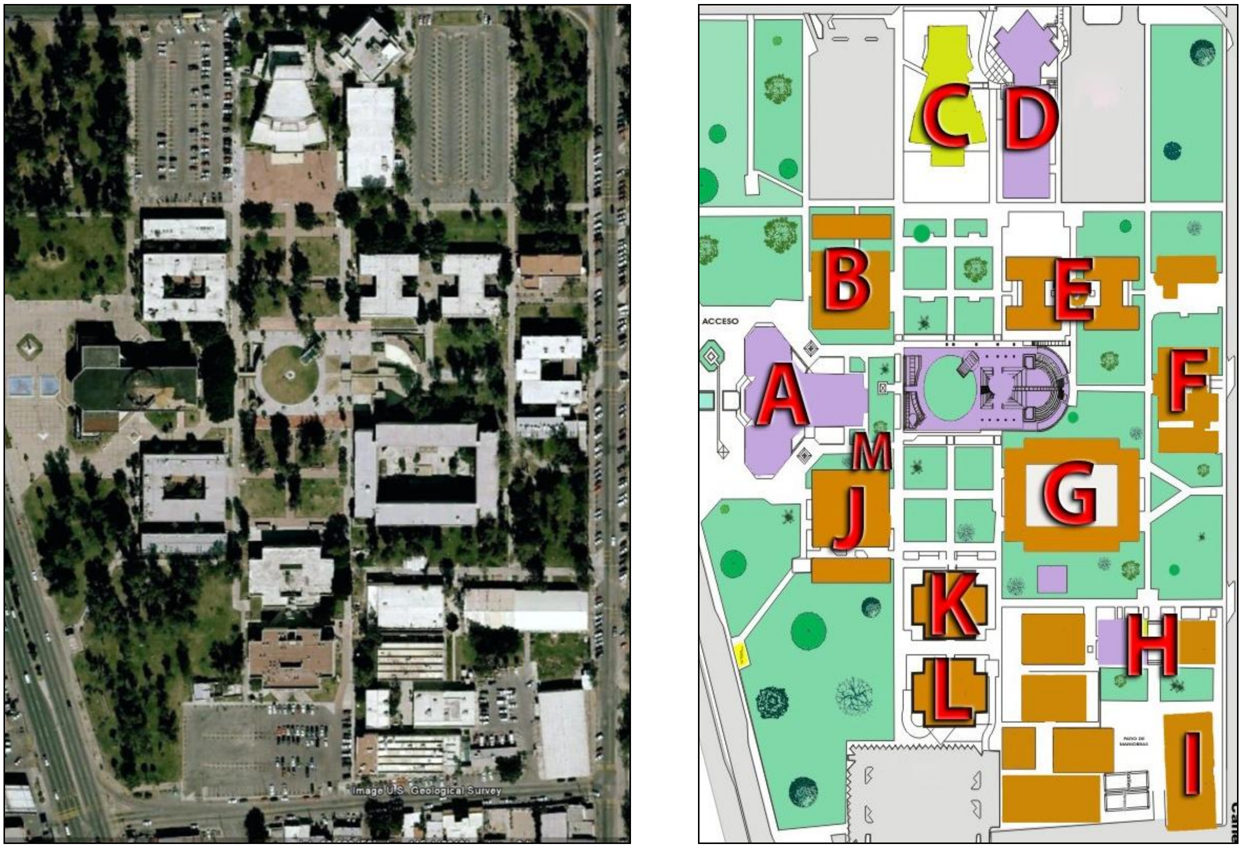


Figure 3.9: *UABC's Mexicali campus location; Satellite view from Google Earth (left); Campus map indicating locations of inspected areas (A-M) (modified from http://campus.mxl.uabc.mx/) (32.6306°N, 115.4442°W).*

3.1.3.1 Library Building

The library is located in the north section of campus (D in Figure 3.9). It is a two-story reinforced concrete frame with unreinforced brick infill walls built around 1988 (Figure 3.10a). The cross sectional dimensions of the north exterior columns were measured to be 0.5 m x 0.5 m (1.6 ft x 1.6 ft). Joint deterioration and shear cracking in the infill walls was observed (Figure 3.10b). The cracks revealed the column reinforcing details: #8 longitudinal bars and #3 stirrups spaced at 23 cm (9 inches) on center. Some bars were spliced at the upper third of the column, which was the location of shear failure. Gaps in the infill wall showed a single width brick thickness (Figure 3.10c). In the northwest corner of the library the column reinforcement was discontinuous at the second floor slab (Figure 3.11a), which resulted in significant joint deterioration during the earthquake. The building suffered extensive exterior damage (Figure 3.11b). Shear cracks were found in two columns on the north side of the building caused by the short-column effect (Figure

3.12). The damage appeared most prevalent in the north-south direction. Access to the building's interior was restricted, however, lights were on and most bookshelves were standing upright, as observed from the exterior.

Despite the severity of the acceleration in the area, the number of books which fell off the shelves was moderate. Some damage was observed due to pounding at the location of expansion joints between different buildings.

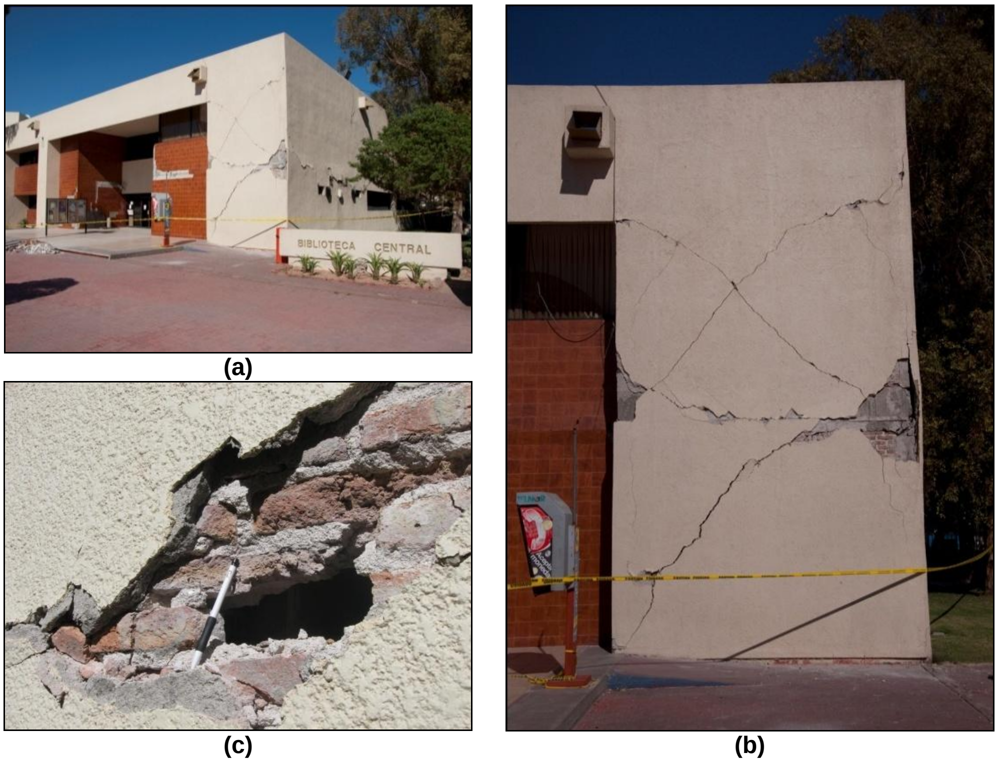


Figure 3.10: *Library at the Mexicali campus of UABC; (a) building overview and entrance from the southwest corner; (b) shear cracks in the brick infill panels; (c) single width unreinforced brick wall (32.6337°N, 115.4442°W) (Building D in Figure 3.9).*

Figure 3.11: *Library at the Mexicali campus of UABC; (a) poor reinforcement detailing at the northwest corner, (b) detail of discontinuous longitudinal column reinforcement in northwest corner (32.6337°N, 115.4442°W) (Building D in Figure 3.9).*

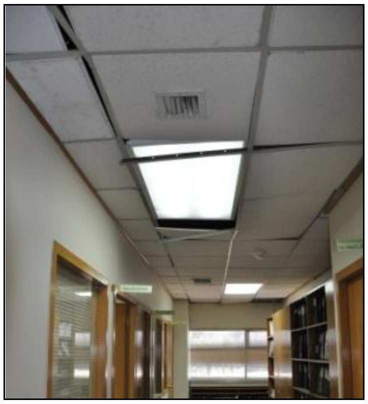
Figure 3.12: *Severe shear cracks in exterior reinforced concrete column.*

3.1.3.2 Rectoria (Office of the Rector and other administration)

The administrative building, denoted as A on the campus map (Figure 3.9) is shown in Figure 3.13a. The function of this building is to host the office of the campus rector, other administrative business and campus security. The interior of this building is dedicated to office space. An interior inspection was conducted of this structure. This structure is a three-story building, whose load resisting system appeared to be a concrete frame with infill. The front of the building presents a large open area with a heavy cobblestone façade, which was significantly damaged (Figure 3.13b). Similar damage to the stone façade was observed at the west end of the building. Interestingly, with the exception of significant glass damage, interior nonstructural components presented only moderate damage, given the severity of structural damage. For example at a given floor only 20% or so of the ceiling system was damaged (Figure 3.13c). Although the services for the building were not turned at the time of the reconnaissance team's visit, no significant damage was observed in the basement area to any of the mechanical, plumbing, or other units or their connections or piping (Figure 3.13d).

(a)

(b)



(c)

(d)

Figure 3.13: *Administrative building at the Mexicali campus of UABC; (a) building overview (b) damage at front entry façade, (c) moderate interior damage, and (d) typical service equipment in basement in good condition (32.6337°N, 115.4442°W) (Building A in Figure 3.9).*

3.1.3.3 Engineering Building

The Engineering Building is a reinforced concrete moment frame infilled with reinforced hollow concrete masonry units. The partial-height infill walls were isolated from the reinforced concrete columns with gaps thus preventing the occurrence of the short-column effect. The east and west sides of the building have confined masonry enclosure walls constructed of hollow concrete masonry units. Figures 3.14 through 3.17 show different aspects of the damage to this building.

Figure 3.14*: Partially collapsed infill panel at fourth story*

Figure 3.15: *Damage in enclosure wall on the northwest side.*

As early as of Monday 4/5/2010 (the day after the main earthquake), the UABC administration had mobilized crews to start clean up and repair work as they were about to start the new school year and did not want to delay significantly the beginning of the classes. As a result some exterior wall partitions were not observed at the Engineering Building, which collapsed due to out-of-plane forces and inadequate anchorage, because the walls had already been removed. These walls had some restraint in the form of steel angles at the vertical wall ends and some small braces at the top of wall; however, the wall itself was not strong enough to resist out-of-plane forces when restrained at the few support points. In addition, there were some very large cracks observed in the masonry infill of the stair shaft and some pounding damage observed along the building joints. The main lateral load resisting system for this 4-story building appears to be reinforced concrete moment frames with masonry infill walls in the transverse direction and concrete shear walls in the longitudinal direction. Some spalling was observed at the base of columns.

Figure 3.16: *Engineering faculty building at the Mexicali campus of UABC: Exterior damage on east wall*

Figure 3.17: *Collapsed wall (north side on 4th floor) (32.6321°N, 115.4439W°).*

3.1.3.4 Computer Science and Electronics Laboratory Building

This building is a two-story moment frame with partially grouted masonry infill. This building had parapet failure as well as masonry wall failure at one side of the entrance at the second story level. Because the damaged portion was already cleared at the time of the reconnaissance visit, it is not certain if it was due to lack of out-of-plane anchorage or caused by excessive shear. There were many windows broken at the main entrance. A very noticeable pattern of horizontal cracks was noted at the joint locations. Figures 3.18 and 3.19 show damage to the building.

Figure 3.18: *Damage to UABC Computer Science and Electronics Laboratory Building.*

Figure 3.19: *Damage to UABC Computer Science and Electronics Laboratory Building. Shear cracks are very visible at the masonry walls near the wall ends.*

3.1.3.5 Architecture Building

This three-story reinforced concrete moment frame has unreinforced hollow concrete unit masonry infill panels along the perimeter (32.6326ºN, 115.4431ºW). Several bays are partially infilled up to 50%-70% of the column story height. There are no separation joints between columns and infill panels. Shear cracks formed in one column of the building perimeter as a result of the short-column effect. Diagonal and sliding cracks formed in the masonry infill panels. Figures 3.20 through 3.22 present the damage to this building.

Figure 3.20: *Severely damaged infill panels and plaster.*

Figure 3.21: *Shear cracks in the infill panels and in a short column.*

Figure 3.22: *Damaged infill panels and plaster.*

3.1.3.6 Edificios C y D (Office Buildings)

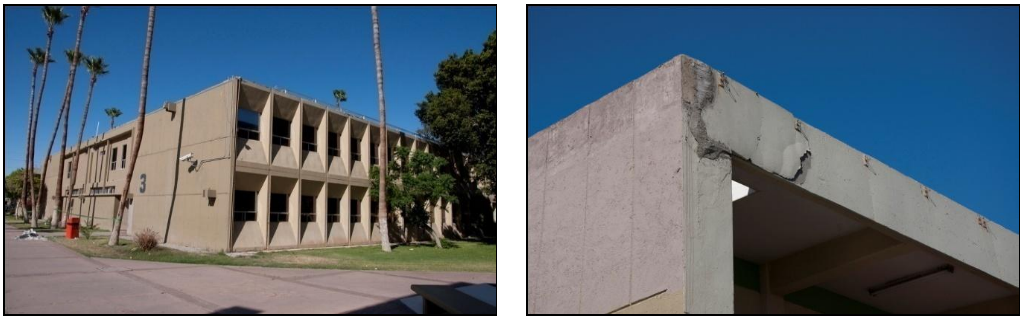
Two office buildings of similar configuration are located in the center of campus (E in Figure 3.9). Both of the buildings are I-shape in plan. The buildings are two-story reinforced concrete frames with reinforced concrete masonry unit (CMU) walls (Figure 3.23a). Exterior damage was observed to be more substantial on the west building. The only structural difference noted was that the CMU infill in the eastern building ran the entire height of the building (Figure 3.23b). In the western building, shear cracking was observed in second story columns and within the CMU walls. The south side masonry units were damaged in the out-of-plane (north-south) direction (Figure 3.23c). Interior access to the building was restricted, but ceiling tiles were observed to have fallen.

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

Figure 3.23: *Office buildings at the Mexicali campus of UABC: (a) west building (looking east); (b) out-of-plane failures of the reinforced CMU in the west building; (c) east building (full building height infill) (32.6330°N, 115.4439°W) (Building E in Figure 3.9).*

3.1.3.7 Facultad de Derecho (Law Faculty, North and South Buildings)

The north law building is denoted as B on the campus map, whereas the south law building is denoted as J in Figure 3.9. These two-story buildings appeared to be modern construction with masonry infill walls (Figures 3.24a and 3.25a). Building B exhibited very limited concrete spalling on the exterior of the building; an example of a beam-column connection is shown in Figure 3.24b. In contrast the exterior of building J on both the east and west faces was observed to be peeling away at the roof and second floor levels from the structural core (Figure 3.25b). Interior ceiling damage in building J was observed from the exterior to be significant (Figure 3.25c). Access to both buildings' interiors was prohibited.



(a) **(b)**

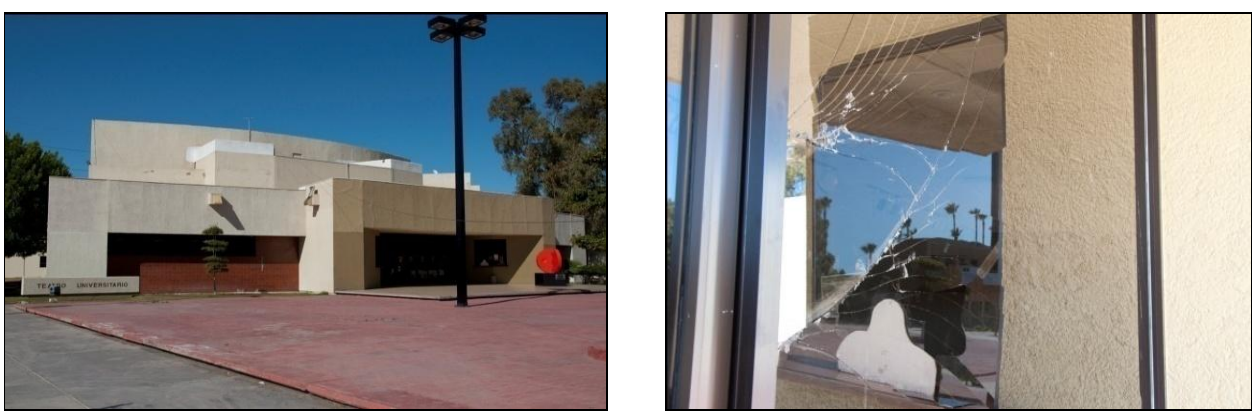
Figure 3.24: *Law building (north) at the Mexicali campus of UABC: (a) building overview from the southwest corner; (b) spalling on the concrete frame in the northwest corner on the second floor (32.6330°N, 115.4453°W) (Building B in Figure 3.9).*

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

Figure 3.25: *Law building (south) at the Mexicali campus of UABC: (a) building overview from the northeast corner; (b) peeling away of the east front face and (c) extensive ceiling damage in the interior (32.6320°N, 115.4453°W) (Building J in Figure 3.9).*

3.1.3.8 Teatro Universitario (University Theatre)

The university theatre is denoted C on the campus map (Figure 3.9). This reinforced concrete frame building with infill walls is irregular in plan (Figure 3.26a). The building experienced only minor exterior damage, with concrete spalling and fractured glass windows at the entrance as shown in Figure 3.26b. No access was allowed to the interior of the building, however, lights were on and a few ceiling panels were missing in the front foyer.



(a) **(b)**

Figure 3.26: *The university theatre at the Mexicali campus of UABC: (a) the front entrance to the building; (b) broken window on the front entranceway held in place by the film (32.6338°N, 115.4447°W) (Building C in Figure 3.9).*

3.1.3.9 Laboratorio de Ingeniería Industrial (Industrial Engineering Lab)

In the lower southeast corner of campus (I in Figure 3.9), another one-story building with a steel frame and CMU infill houses the industrial engineering laboratory (Figure 3.27a). While no exterior damage was observed, an interior assessment found extensive ceiling tile loss (Figure 3.27b). The ceilings were typically damaged at their interface with ducts and lighting fixtures. The building was still operational and personnel were in the offices.

(a) (b)

Figure 3.27: *Industrial engineering laboratory building at the Mexicali campus of UABC: (a) building overview; (b) ceiling failure in computer lab (32.6308°N, 115.4431°W) (Building I in Figure 3.9).*

3.1.3.10 Laboratorio de Electrónica y Computación (Electronics and Computer Lab) and Instituto de Ingeniería (Engineering Institute)

The electronics and computer laboratory and the Engineering Institute buildings are of like construction, located at the southern end of the campus, and denoted as buildings K and L, respectively, in Figure 3.9. Not depicted in Figure 3.9, however, is a new addition that had recently been constructed connecting these two buildings on their east ends. The new addition was isolated from the other two existing wings and interestingly interior damage was observed to be more significant. The north entrance of building K suffered significant shear and horizontal cracks and throughout this building structural and nonstructural damage was extensive (Figure 3.28). Similar observations were noted in Building L to the south; however, the front (south) entrance did not sustain nearly as much damage as the northern main entrance of Building K. Both of these structures are frame buildings with partially grouted masonry infill. The CMU appeared to have limited connectivity with the primary frame system (Figure 3.29). Infill wall damage, to all buildings, but particularly in the new annex building, was extensive, and often left large regions of exposed areas at the perimeter (Figure 3.30).

(a) **(b)**

Figure 3.28: *Electronics and Computer Lab at the Mexicali campus of UABC: (a) exterior damage at north entrance; (b) extensive interior ceiling system damage (32.6314°N, 115.4447W°) (Building K in Figure 3.9).*

(a) **(b)**

Figure 3.29: *Interior damage in the Electronics and Computer Lab at the Mexicali campus of UABC. Limited connectivity between CMU and primary structural frame (32.6314°N, 115.4447°W) (Building K in Figure 3.9).*

(a) **(b)**

Figure 3.30: *Damaged CMU infill in the new eastern annex building connecting buildings K and L on the Mexicali campus of UABC (32.6314°N, 115.4451°W).*

3.1.3.11 Sliding of Unanchored Transformers North of Building J

Three transformers denoted as TR-07, TR-08, and TR-09 from south to north respectively in Figure 3.31 are suspected to have slid significantly in plane during the earthquake. The transformers are located north of building J, as M in Figure 3.9. The transformers appeared to be liquid-filled. Figure 3.32 shows a sliding displacement of TR-07 to the east approximately 25 mm (1 inch). Although the anchorage could not be observed from the outside, it is suspected that the transformers are unanchored based on the large sliding displacement of 25 mm (1 inch). The transformers bear directly on a concrete pad with a rough surface. Figure 3.33 shows the outline of the transformers before and after sliding. The average sliding displacement of the center of gravity was approximately 25 mm (1 inch) in the east-west direction coupled with a maximum rotation of approximately three degrees clockwise. The weight of the transformers is estimated as 27 kN (6000 lbs), 22 kN (5000 lbs), and 13 kN (3000 lbs) respectively for TR-07, TR-08, and TR-09. Sliding of the transformers indicates strong shaking occurred at the site with a large enough peak ground acceleration to overcome the static friction between the transformers and the concrete pad, possibly coupled with vertical accelerations.

Figure 3.31: *Liquid-filled transformers (32.6323°N, 115.4451°W).*

Figure 3.32: *Movement of transformer TR-07 of approximately 25 mm (1 in) (32.6323°N, 115.4451°W).*

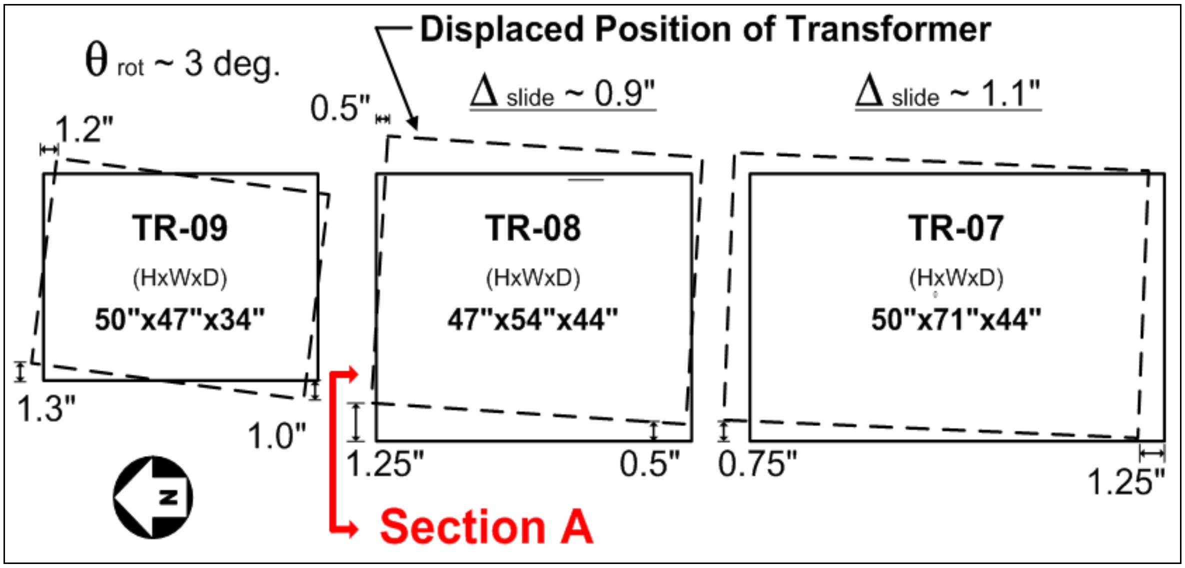


Figure 3.33: *Suspected movement of liquid filled transformers (1" = 25 mm) (32.6323°N, 115.4451°W).*

3.1.4 Civic Center

Critical federal, state, and city government buildings are located in the Centro Civico (Civic Center), Figure 3.34. The Centro Civico is located in the heart of Mexicali. Based on a visual observation of the exterior of the buildings, most of these buildings suffered only minimal structural damage. Most of these buildings are of late 1970s vintage construction.

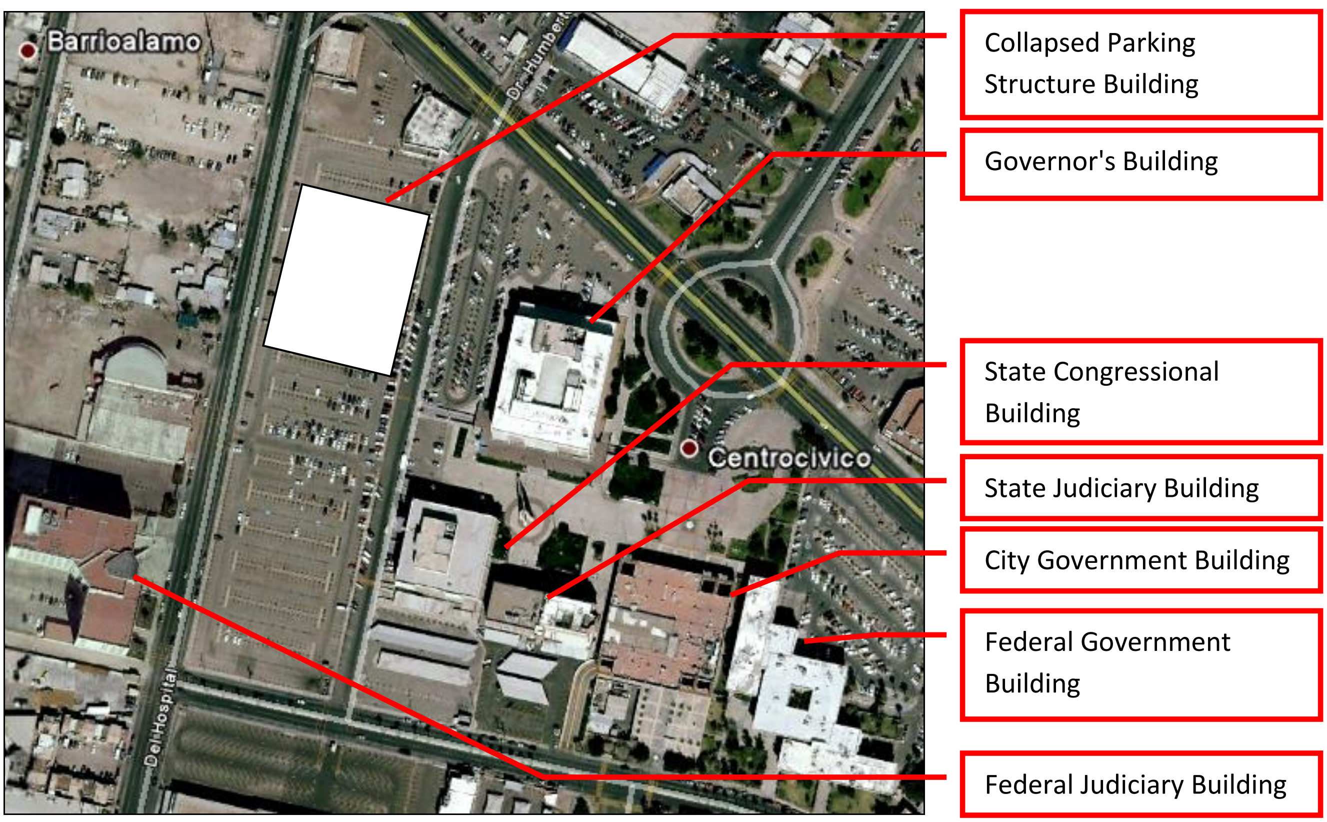


Figure 3.34: *Aerial view of Centro Civico (courtesy of Google Maps).*

3.1.4.1 Governor's Building

The Governor's building is a five-story structure with two penthouses and a footprint of approximately 55 m by 72 m (179 ft by 235 ft). The top two stories are offset approximately 9 m (30 ft) from the lower two stories. There is also a 14 m by 27 m (45 ft by 89 ft) diaphragm opening at the center of the building (Figure 3.35). The building is founded on drilled piers. This building contained an accelerometer at the roof level and at the lowest level. The reconnaissance team was unable to access the room that housed the instrument at the roof; however, the team did observe the instrument at the lowest level. It seems to be that no records were obtained.

A visual inspection was performed to observe the interior damage. The damage appeared to be primarily nonstructural. It was noted that some ceilings may have been damaged due to the vertical displacement of above-ceiling mounted mechanical units (Figure 3.36). The damaged ceilings of the Governor’s office had been removed and replaced. It did not appear that diagonal wires had been installed in the new ceiling.

Additional nonstructural damage was observed at the penthouse level of the Governor's building (Figure 3.37). It appeared to be a pattern of damage in the north/south direction.

Figure 3.35: *Governor's Building: Exterior west elevation illustrating vertical plan irregularity.*

Figure 3.36: *Governor's Building: A conference room in the Governor's office with the ceiling repaired on the left. On the right, a ceiling damaged due to excessive vertical displacement of an isolated mechanical unit mounted above the ceiling.*


Figure 3.37: *Governor's Building: On the left, a partition wall at the penthouse level has displaced approximately 150 mm (6 inches) out-of-plane in the north direction. On the right, mechanical units at the penthouse are supported temporarily due to damaged anchorage. The longitudinal axis of these units was oriented in the east/west direction.*

3.1.4.2 State Congressional Building

The State Congressional Building is a four-story concrete frame building with a penthouse and a footprint of approximately 45m by 45m (150 ft by 150 ft). The building appeared to be retrofitted with exterior concrete shear walls in the east-west direction. Observations were limited to the exterior of this building (Figure 3.38).


Figure 3.38: *State Congressional Building: Damage observed at the exterior penthouse walls. This photo was taken during repair of the exterior north and east walls.*

3.1.4.3 State Judiciary Building

This concrete frame three-story building with a penthouse has a footprint of approximately 58 m by 25 m (189 ft by 80 ft). Observations were limited to the exterior of this building (Figures 3.39 and 3.40).

Figure 3.39: *State Judiciary Building (right background) and City Government Building (left background) with the Civic Center Monument in the foreground.*

Figure 3.40: *Displaced rooftop units at the City Government Building (left) and at the State Judiciary Building (right). The mechanical unit on the State Judiciary Building has displaced in the northerly direction.*

3.1.4.4 Centro Civico Parking Structure

This precast concrete parking structure (32.64116ºN, 115.47745ºW) suffered a partial collapse during the earthquake. The building was under construction; the precast units had been placed on the building, but the diaphragms had not been cast. The building is a 4-story plus ground floor precast concrete parking structure (Figure 3.41), with cast-in-place shear walls acting as the lateral-force resisting system (Figure 3.42).

Precast double-tee units, connected through non-composite diaphragms, are used to form the floor system. According to the designers, the "PCI Connection Manual" specifications were followed. For financial reasons, the construction of this building was interrupted several times. Erection of the precast concrete units took place at the end of December 2009, but only the central bays (ramps) were completed with the diaphragm. Construction resumed on March 22nd, 2010, when concrete was poured on the first-floor lateral-bays. When the earthquake struck, the central bays suffered no damage (Figure 3.43). The precast units, which were erected but not connected through the diaphragm, bent the perimeter frames outwards (visible in Fig. 3.42) and collapsed on top of each other (Figure 3.44).

Figure 3.41: *View of the partially collapsed parking structure in Mexicali.*

Figure 3.42: *Perimeter precast frame (front) and interior cast-in-place shear wall (back).*

Figure 3.43: *Central bays resisted the earthquake without damage.*

Figure 3.44: *Lateral bay double-tee units collapsed on top of each other.*

3.1.5 Churches

About 32 km (20 miles) south of the US border, there is a church named Nuestra Senora de la Merced. The church suffered partial collapse due to the earthquake (Figure 3.45). According to members of the church, the church building had been incrementally constructed over the past 50 years. The church is constructed of concrete frames with confined brick masonry infills and a steel deck roof over steel framing. It had a small concrete tower in the front that collapsed causing damage to the lower roof and walls. The tower seemed to have some reinforcing that was not properly developed into its supporting columns. There were also some partial out-of-plane masonry infill failures at the rear gable wall of the building and severe damage to the interior ceiling (Figure 3.46). The loss of the church was a big loss to the community. Despite severe localized damage to the steeple tower and infill brick in a rear wall, the main structural system remained stable. The small tower that collapsed could be rebuilt by properly supporting it all the way down to the foundation. The masonry infill could also be strengthened and rebuilt. Aside from this church, there were no reports of damages to other churches.

Figure 3.45: *Exterior view of church showing collapse of tower.*

Figure 3.46: *Ceiling falling (above) and collapse of infill walls (below).*

3.1.6 Instituto Salvatierra Secundaria

The private high school, Instituto Salvatierra Secundaria (32.65203 ºN, 115.45230 ºW), consists of two buildings, built in 1958 and 1992, respectively. The newer structure did not experience any damage and is not discussed here. The structure built in 1957 is a two-story masonry-infilled RC frame, which has some columns along the building perimeter retrofitted by steel jackets around the upper third of the column height adjacent to windows. Clay and concrete masonry units were used for the infills.

Severe damage was observed in the bottom story of the 1958 structure, which had shear cracks in the columns and infill walls. The shear failure of the exterior columns can be attributed to the short column effect introduced by the partial-height infill walls. The inspection of the severely cracked columns indicated inadequate shear reinforcement, which consisted of 6 mm (1/4 in) diameter stirrups spaced at 28 cm (11 in) at the damaged region. The exposed concrete inside some of the damaged columns indicated poor concrete quality including poor consolidation and the use of smooth aggregates. The retrofitted columns performed satisfactorily but in some cases had damage below the jacketed portion. The masonry infills were damaged by a combination of severe diagonal cracks and bed-joint sliding. Figures 3.47 through 3.51 show damage to the school building.

As a result of the severe structural damage, the school was not operational at the time of the reconnaissance visit.

Figure 3.47: *Shear failure of exterior unretrofitted bottom story column.*

Figure 3.48: *Steel jacket retrofit of a short column between partially infilled bays.*

Figure 3.49: *Column confinement – 6 mm (1/4 in) diameter stirrups spaced at 28 cm (11 in).*

Figure 3.50: *Poor concrete consolidation and smooth aggregates.*

Figure 3.51: *Damage to clay masonry infill next to a retrofitted column.*

3.2 CALEXICO

The city of Calexico was founded in 1900 and incorporated in 1908. The downtown area of Calexico is centered at the border crossing and consists of rows of neighboring buildings with open store fronts. The buildings are unreinforced masonry with wood roofs that have typically been refinished with layers of plaster over the years. The city is 51 km (32 mi) north-northwest of the epicenter, and has a population of about 27,100. There are not many tall buildings in the city and the tallest ones are around three stories.

3.2.1 Downtown

At the time of the reconnaissance (within one week after the earthquake), an area of nine square blocks of downtown Calexico had been closed to the public due to extensive red-tagging. The outline of the approximate restricted area can be seen in Figure 3.52. The overall damage observed in this area included leaning and collapsed parapets, cracking at store front walls and columns, broken windows, some fallen soffits, and partial out-of-plane failure of unreinforced masonry (URM) walls. Assessment of the entire area of damage was not feasible due to the restricted access. Figures 3.53 through 3.63 illustrate the damage in Calexico downtown. There were two cases of collapsed or partially collapsed roofs and Figure 3.56 shows at least one of the partial collapses. Although no building from the distance observed appeared to have severe damage in the closed area, the close proximity to neighboring buildings that may have collapse potential could still pose a threat.

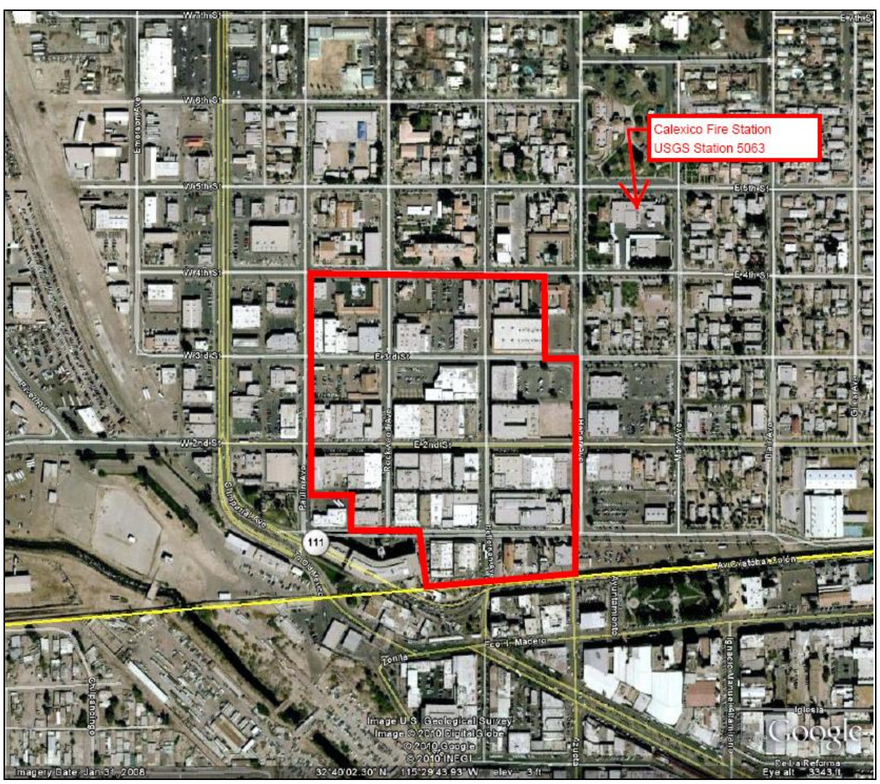


Figure 3.52: *A satellite map of downtown Calexico. The area outlined in red shows the portion of the city that was off limits to the public after the earthquake (courtesy of Google Earth).*

Figure 3.53: *A view of 3rd Street in downtown Calexico looking towards the east. Damage to the two-story building on the left side of the photo is shown in Figures 3.56, 3.58 and 3.59.*

Figure 3.54: *A view of 1st Street in downtown Calexico looking towards the west. A separation in the joint at the parapets at the Kress sign can be seen from here.*

Figure 3.55: *A view of 2nd Street looking towards the west.*

Figure 3.56: *A close-up view of a partially collapsed roof. Cracking at the top of the column in the foreground can also be seen (32.666696ºN, 115.496730ºW).*

Most of the cracking occurred at the joints between buildings and at the columns of the open store fronts. The cracking and spalling of the plaster sometimes exposed some of the original brick and/or older layers of plaster underneath. It was sometimes difficult to tell if the damage was concentrated in the layers of plaster or if structural damage occurred beneath.

Figure 3.57: *Column cracking at the store front.*

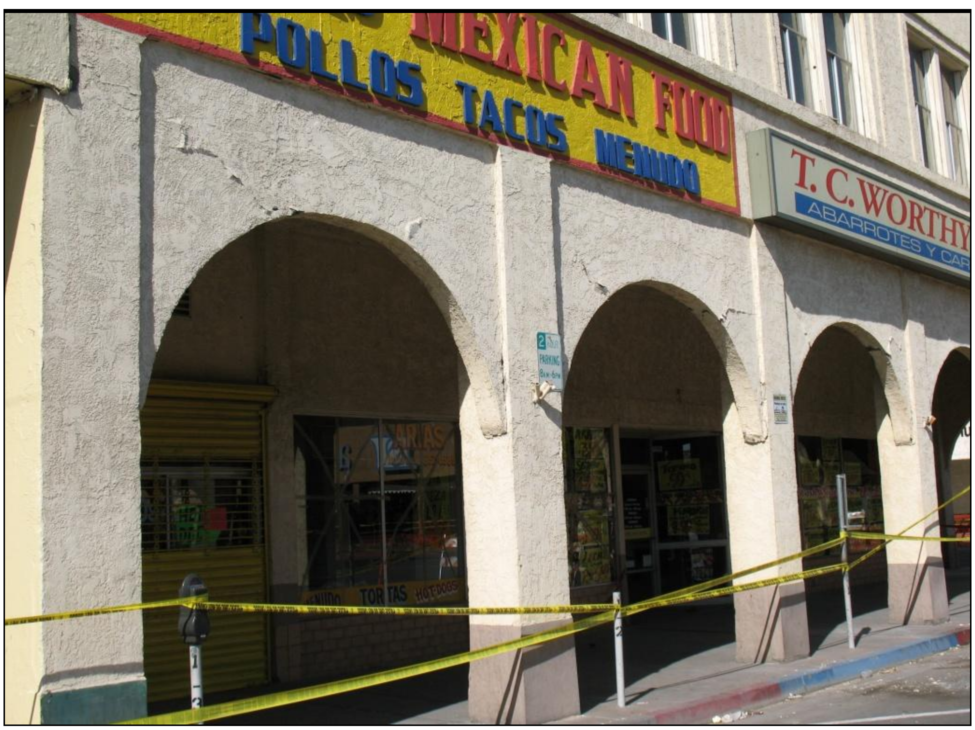


Figure 3.58: *Diagonal cracking at arches.*

Figure 3.59: *Wall cracks just below the floor line.*

Figure 3.60: *Wall cracks and spalled plaster.*

Figure 3.61: *Cracking at the building joint.*

Figure 3.62: *Parapet damage.*

(a)

(b)

Figure 3.63: *Typical damaged glass store front in downtown Calexico (images courtesy of professional photographer Joseph Llausas - taken April 5, 2010).*

The historic Hotel De Anza (32.66886 ºN, 115.49532 ºW) is a wood frame building with plaster exterior and interior walls with a few masonry trim and chimney elements built in 1931 and currently being used as senior housing. It was evacuated and red-tagged due to the earthquake. It is immediately north of the restricted area. Cracks at the exterior of the building can be seen, most of which occur near the floor lines (Figures 3.64 and 3.65). The large areas of removed exterior plaster is not necessarily earthquake damage, but was most likely removed for inspection or repair.

Figure 3.64: *The front of the Hotel De Anza building.*

Figure 3.65: *The sides of the Hotel De Anza building.*

This structure had little load resistance, with its core consisting of wood framing and plaster overlay (Figure 3.66) and was therefore extensively damaged during the earthquake. At the time of the team's visit it was red tagged pending further inspection (Figure 3.67a). Most of the visual exterior damage is concentrated on the west side of the building. A wide diagonal crack appeared between the first and second stories in a shearing dominated mode terminating at the arch, denoted (1) on Figure 3.67b. One vertical crack spanning the entire height of the building (2) is located just west of the tower section, demonstrating that the tower section remained intact with the eastside of the building. Smaller horizontal cracks (3) were found on the west side at the upper floor levels. No extensive damage was found on the east side of the building, however cosmetic damage is noted on the chimney on the east wall (Figure 3.67c). Interior damage was extensive and consisted of wide cracks localized at doors and arches as well as within stairwell regions (Figure 3.68).

Figure 3.66: *Wood wall with plaster overlay construction of the Hotel de Anza in Calexico (image courtesy of professional photographer Joseph Llausas - taken April 6, 2010). (Note: the region on the left was exposed by contractors during post-event inspection.)*

(a) (c) (b)

Figure 3.67: *Damage observed at the Hotel de Anza within the city of Calexico, CA: (a) overview of front entrance; (b) significant cracks sustained just west of the tower section (1 = diagonal crack, 2 = vertical crack and 3 = horizontal cracks at floor levels); (c) chimney damage on the east wall (32.6689°N, 115.4956°W).*

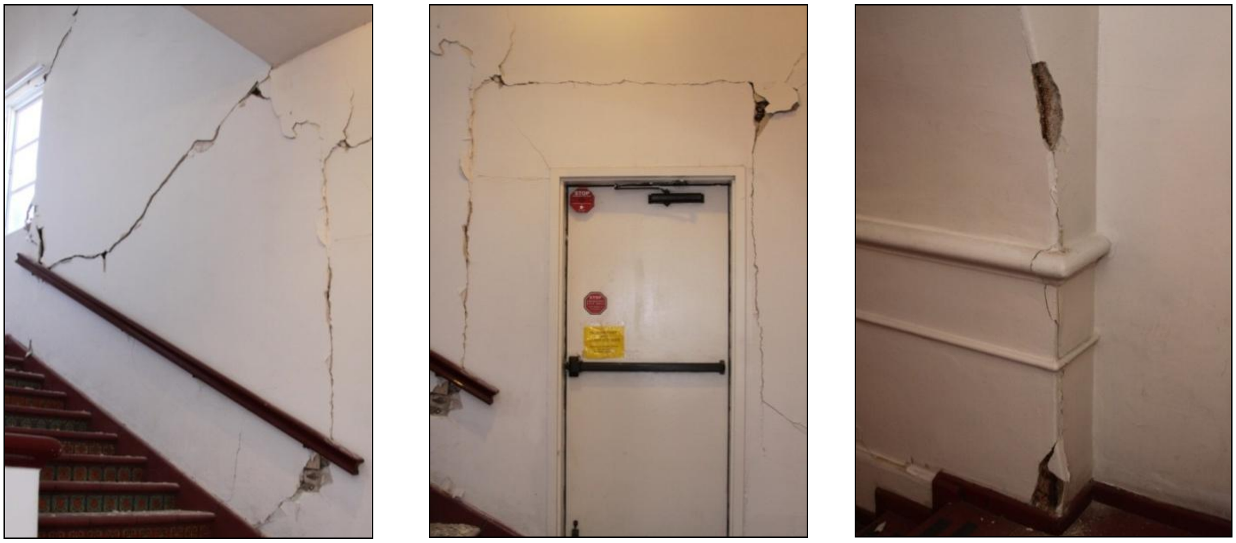


Figure 3.68: *Typical interior damage at the Hotel de Anza in Calexico (images courtesy of professional photographer Joseph Llausas - taken April 6, 2010).*

To the south of the Hotel de Anza, one storefront experienced significant damage to its front overhang (Figure 3.69a). The collapsed overhang at the store entrance of 317 Heffernan Avenue prompted city officials to red tag the business of Gastelum. This overhang was supported by the front columns and by two end connections into the main building. Failure occurred at mid-span of the overhang-building interface because the columns were leaning away from the building, causing the overhang to pull out the nails and consequently collapse (Figure 3.69b).

(a) (b)

Figure 3.69: *Damage observed at Gastelum within the city of Calexico, CA: (a) overview of entrance shown with leaning columns (X shows an end-support); (b) close-up of collapsed overhang (32.6683°N, 115.4950°W).*

Two blocks south of Gastelum's, one column in the front of an abandoned storefront experienced extensive damage (Figure 3.70a). Just to the south of 147 Heffernan Ave, an interior column with poor detailing experienced cover spalling throughout the bottom half along with vertical cracks inline with the load path. This column lacked confinement at its base (Figure 3.70b). The longitudinal reinforcement in the column was approximately 1.27 cm (1/2 inch) square, with only wire ties used for confinement in spacing greater than 15 cm (6 inches). The next adjacent column to the south was retrofitted with a steel jacket and its structural integrity was intact with only minimal concrete cover spalling (Figure 3.70c).

(a) (b) (c)

Figure 3.70: *Damage observed within the Heffernan Business District (Calexico, CA): (a) overview interior column which experienced significant damage; (b) column base close-up showing reinforcement placing; (c) exterior column adjacent to the south with retrofit jacketing (32.6663°N, 115.4948°W).*

Two of the three units in a 2-story apartment complex located at 531 and 539 Paulin Avenue experienced significant structural damage (Figure 3.71). Two of these units were approximately 85 years old and suffered cripple wall failure, the age of the third unit was not known, however it appeared only slightly newer. The construction style of the units is unbraced wood-plaster. Due to the cripple wall failure, the buildings slid eastward towards Paulin Avenue about 5 in (12 cm). A residual shear deformation pattern of the cripple wall was visible at the exterior of the building. Inside the buildings, damage to the plaster and uneven floors was pervasive in the units.

(b)

(a) (c)

Figure 3.71: *Wood-plaster type constructed apartment units at 539 Paulin Ave that suffered cripple wall failure and extensive interior damage: (a) front entrance to apartment complex showing building offset to the east direction (right); (b) close-up of the cripple wall on the southwest corner; (c) approximate 12 cm (5 inches) gap exposed due to the cripple wall failure (32.6705°N, 115.4977°W).*

3.2.2 Fire Station

The fire station in Calexico (Figures 3.72 to 3.75), not more than 2 blocks from the closed off area of Calexico, houses USGS Station 5063. This location is approximately 49.5 km (30.8 mi) from the epicenter of the earthquake. The instrument is anchored on the slab of the structure and measured a peak ground acceleration of 0.272g (Figure 3.75). The station is a one-story reinforced CMU building with a two-story portion and a tower. The building sustained no damage in the earthquake.

Figure 3.72: *The front entrance of the Calexico Fire Station.*

Figure 3.73: *Looking at the rear of the building towards the northwest.*

Figure 3.74: *Looking at the front of the building towards the southeast.*

Figure 3.75: *The USGS seismic sensor on the slab of the fire station in Calexico.*

3.3 EL CENTRO

El Centro, covering 28,539 km^2 (11,019 mi^2), is the largest city in Imperial County. It is located 188 km (117 mi) east of San Diego and 394 km (245 mi) west of Phoenix, Arizona and just 15 minutes from the international industrial complexes in Mexicali, Baja California. El Centro is accessible via Interstate 8, State Highway 86 and State Highway 111. There are two international border crossings nearby for commercial and noncommercial vehicles. The city population in July 2008 was estimated at 40,083.

3.3.1 Downtown

The older section of downtown consists of unreinforced masonry buildings with wood diaphragms, and open store fronts. Observed damage in the historic downtown area was consistent with typical unreinforced masonry structures that have received some level of seismic retrofitting. Specifically, shear and diagonal cross cracking of URM walls and pilasters, partial collapse of URM parapets, cracked and crushed masonry between building joints, and broken store front windows were observed. Early estimates show over $80 million in damage, with over 30 businesses red tagged. Despite the damage, a relatively small number of buildings were red or yellow tagged compared to the old town section of the city of Calexico, where entire city blocks were closed to the public. Figures 3.76 through 3.82 show the damage in the downtown area.

Figure 3.76: *Typical cracking and crushing of masonry and plaster at joints between buildings.*

Figure 3.77: *Damage was also prevalent at the base of the masonry columns at the store fronts, and can be attributed to the increased moment and rotational demands due to the absence of shear walls along the open store fronts.*

Figure 3.78: *Abandoned mortuary building with typical out-of-plane failures of the masonry wall to wood diaphragm. The original wall to ceiling joist connection was insufficient. (32.7919ºN, 115.5560ºW).*

The URM buildings most susceptible to damage were those on corners, or those adjacent to open lots, where they did not have the advantage of an adjacent building to help limit building drifts. This was observed with the Old Town Plaza building on Main Street as seen in the photos below.

Figure 3.79: *The Old Town Plaza on Main Street suffered considerable damage compared to nearby structures of similar age and construction type. The absence of an adjacent building may have contributed to its higher level of damage.*

Figure 3.80: *The out of plane loading on the masonry wall at the second floor level resulted in permanent out of plane shifting of the bricks across a horizontal mortar joint.*

The Central Pharmacy building on the 400 block of Main Street was yellow tagged following the main earthquake on Sunday; however, on the following Friday the tag was revised to a red tag indicating structural damage at the second floor. The visible cracking to the exterior masonry walls did not appear to be typical unreinforced masonry diagonal cracking, although there were some. Instead, there was horizontal cracking that continued around the entire perimeter of the building; one distinct horizontal crack at the roof line, and another distinct horizontal crack at the mid-height of the second floor windows.

Figure 3.81: *The Central Pharmacy building was originally yellow tagged, but was then red tagged five days later.*

Figure 3.82: *The horizontal crack can barely be seen in the photo; however, it occurs at the same elevation throughout all four sides of the building.*

The El Centro Library was also red tagged due to "shearwall cracking, separation of beams and columns, basement column support failure". The team could not gain access to the building to observe this structural damage; however, there was no visible damage to the structure from the outside.

3.3.2 Churches

The Church of Jesus Christ of Latter-day Saints (LDS) meetinghouse in El Centro, California was constructed in the mid 1960s and is a one story masonry and wood framed structure of approximately 1,765 m^2 (19,000 ft^2). The meetinghouse layout consists of a tall, central chapel and cultural hall space with shorter surrounding classrooms and offices. The structure is only two to three blocks east of the El Centro Regional Hospital, where the ground motion sensor (USGS 00412) recorded 0.38g peak ground acceleration.

The 12- to 15-meter (40 to 50 ft) tall steeple shifted and rotated just over 25 mm (1 in) horizontally across a mortar joint just below the roof line; most likely shearing the rebar across the joint (Figure 3.83). This most likely occurred due to the T-shape section of the steeple contributing to a torsional response, combining with the high stresses at the plane where the steeple is tied into the main structure (Figures 3.84 and 3.85).

Figure 3.83: *Damage to the masonry and concrete steeple required partial demolition and removal of the steeple above the roof line.*

The fundamental period of the steeple also appears to be in the range of high spectral acceleration values based on the data from the nearby instrument at the El Centro Regional Hospital (1.50g); therefore, these high spectral accelerations would have contributed to the observed damage. Besides the damage to the steeple, only very minor cosmetic damage could be observed on the structure from the outside.

Figure 3.84: *Steeple shifted and rotated approximately 25 mm (1 inch) horizontally across the horizontal mortar joint.*

Figure 3.85: *Segment of steeple removed by demolition team showing the cross section of the upper segment*

Two interior masonry shear walls that separate the chapel space from the cultural hall space received the most damage, as they are located approximately in the middle of the building and received a significant portion of the transverse lateral loading due to the flexibility of the wood roof diaphragm. The shear wall damage observed consisted of typical diagonal cross cracking of the masonry walls, some vertical cracking in the walls, and some cracking at the joints where perpendicular walls intersected the shear walls (Figures 3.86 and 3.87).

Figure 3.86: *Damage to interior masonry shear wall.*

Figure 3.87: *Damage at interior masonry shear wall and intersecting masonry wall.*

3.3.3 Regional Medical Center and Medical Plaza

The El Centro Regional Medical Center (ECRMC) is a nonprofit, community-based hospital owned by the City of El Centro, California. It serves the City of El Centro as well as outlying areas in the Imperial Valley. The hospital has 165 patient beds. The original one-story facility was completed in 1956 (Figure 3.88, Building A). A two-story annex was added in 2003 (Figure 3.88, Building B). The hospital is serviced by a Central Plant located in the southeast corner (Figure 3.88, Building C). A Medical Plaza located to the northeast houses the information systems, records and administrative offices (Figure 3.88, Building D). Buildings A through C sustained minor nonstructural damage during the main shock. Building D sustained extensive nonstructural damage, significant damage to the façade and possible structural damage. Building D was red-tagged prior to the reconnaissance team's visit and hospital employees were removing property and records from the building while the team was there.

The hospital lost power during the earthquake, but was able to continue running using backup generators. No patients were evacuated. Because the earthquake occurred on a Sunday, Building D was not occupied. No injuries were reported. Facilities personal began repairing damage within 30 minutes of the event. At the time the reconnaissance team visited the hospital, it was still without air conditioning in some areas due to repairs being made to the HVAC systems.

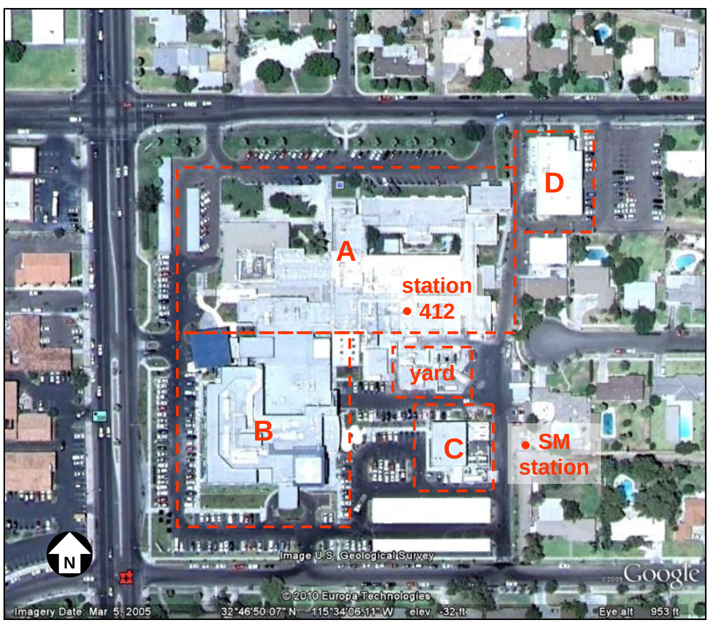


Figure 3.88: *Annotated GoogleEarth image of the El Centro Regional Medical Center.*

In the hospital (Buildings A and B) no structural damage was observed. The majority of the nonstructural systems both in and outside of these buildings appeared unaffected by the earthquake with the exceptions documented below. As an example of the good performance of the service units of the hospital, the cooling towers between buildings A and C are documented. Subsequently, nonstructural damage is documented.

3.3.3.1 Performance of Cooling Tower Yard

Three cooling towers (CT) were located between buildings A and C in an open yard (Figure 3.88; yard [32.7803°N, 115.5680°W]). Each CT was anchored to a concrete foundation using four post-installed anchors (Figures 3.89 and 3.90). The two larger cooling towers were anchored with 16 mm (5/8 in) diameter, 9 cm (3.5 in) to 10 cm (4 in) long (length code E) anchors. The smaller cooling tower was anchored with 12.5 mm (1/2 in) diameter, 10 cm (4 in) to 11.4 cm (4.5 in) long (length code F) anchors. The piping system used flexible connectors (Figure 3.91). There was no visual damage to the CTs and all were fully functional. All anchors were intact with no significant cracks in the concrete (Figure 3.92). Surrounding pipes showed no signs of damage or permanent displacement.

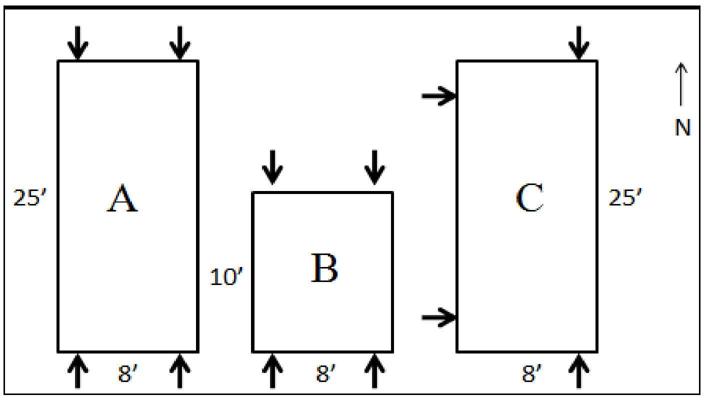


Figure 3.89: *Anchor tie-down points for three cooling towers (plan view): (A) Trane cooling tower west (Model No. RTAA1254XH03B3D1B6KM); (B) Carrier cooling tower (Model No. 30GTN070 621KA); (C) Trane cooling tower east (Model No. RTAA1704XN01A3DOB).*

(a) **(b)**

Figure 3.90: *Photographs of cooling towers: (a) cooling tower pipes; (b) Carrier (left) and Trane (right).*

(a) (b)

Figure 3.91: *Flexible connectors: (a) Trane CT west; (b) Trane CT east.*

Figure 3.92: *Typical CT anchorage.*

3.3.3.2 Nonstructural Damage Observed

Two nonstructural failures were of primary concern for the hospital's immediate operability following the earthquake. The first involved chilled water supply lines located within the older region of the hospital (Building A, Figure 3.88). Two small metal chill lines that connected into larger main chill lines in the mechanical room in Building A ruptured at their connection points (Figure 3.93). The horizontal displacement of the small vertical branch lines was limited by the hole diameter in the ceiling slab through which they passed. The damage caused flooding in the mechanical room and the chiller lines had to be shut down during the repairs. Repair involved rewelding the vertical lines to the larger main lines and occurred within a period of approximately 6 hours following the earthquake.

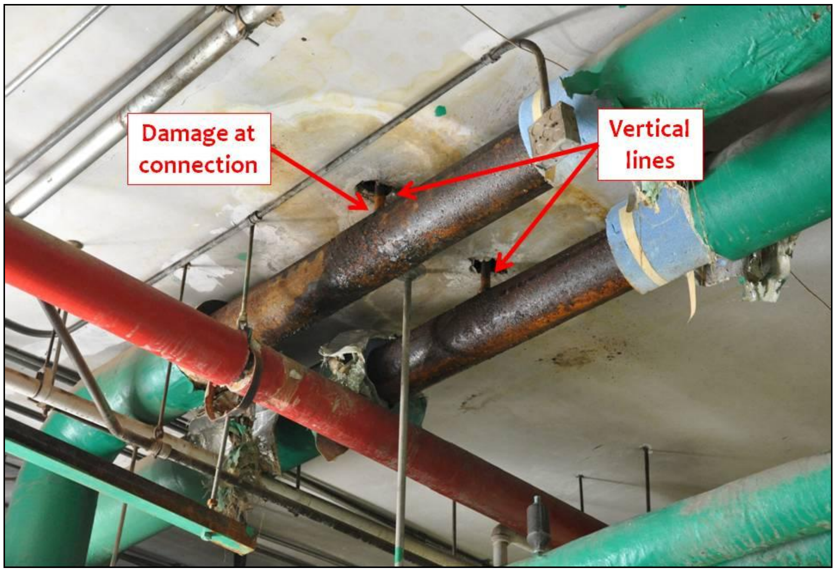


Figure 3.93: *Repaired chill lines in Building A (Figure 3.88) mechanical room.*

The second prominent nonstructural issue occurred in Building B, where copper water feeder lines on a reheater for the HVAC system in the Intensive Care Unit (ICU) ruptured during the earthquake (Figure 3.94). The rupture caused water damage in the ICU and the HVAC system in this area of the hospital had to be shut down during repairs. Repair was ongoing at the time of the team's visit.

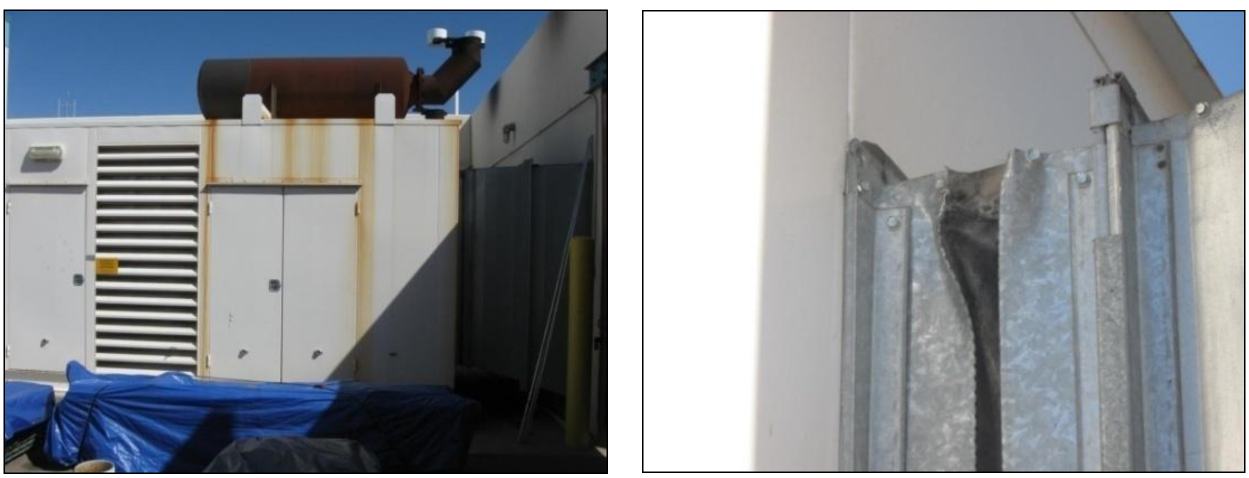
(a) **(b)**

Figure 3.94: *Damage to HVAC re-heater in Building B (Figure 3.88): (a) ceiling tile with water stain; (b) repaired re-heater line (braided copper hose).*

Additionally, minor damage was noted in the open courtyard at the Central Plant (Building C, Figure 3.88), which housed several pieces of large mechanical equipment and was surrounded by pre-cast concrete screen walls (Figure 3.95). Some residual offset of the walls relative to each other was observed in both the north-south and east-west directions. Spalling of the concrete was seen at the top of the wall in the southeast corner (Figure 3.95b). The movement of the east wall in the east-west direction caused what appeared to be cosmetic damage to a light gage metal duct that spanned between the wall and a large piece of anchored equipment inside the courtyard (Figure 3.96). According to the Facilities Manager Mark Obeso, two water softener units located in Building C were also dislodged and damaged during the earthquake.

(a) **(b)**

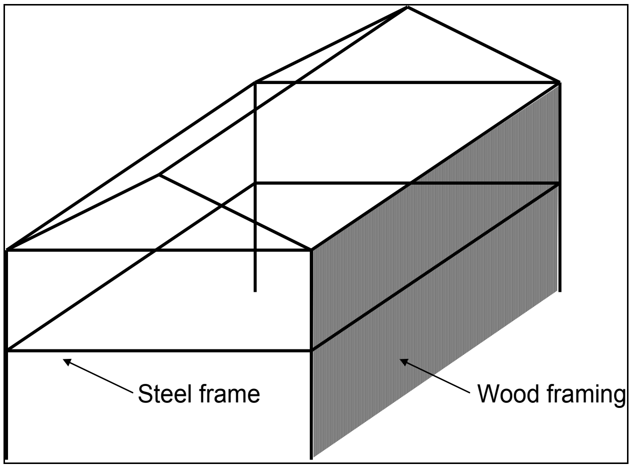
Figure 3.95: *Damage to precast concrete screen walls in southeast corner of Building C in Figure 3.88.*



(a) **(b)**

Figure 3.96: *Equipment in Building C in Figure 3.88: (a) mechanical equipment; (b) damage to duct.*

The Medical Plaza (Building D, Figure 3.88) located to the northeast of the hospital sustained the most significant damage. The two-story building is believed to be a combination of steel frame and wood shearwall construction (Figure 3.97). It had been red-tagged by City officials by the time the team arrived and was in the process of being emptied of its contents by hospital employees. One of the employees indicated that the building “made a lot of noise” when it was windy, which may suggest that it was a flexible structure. Moderate to extensive cracking and spalling was visible on the façade of Building D (Figure 3.98).



(a) (b)

Figure 3.97: *Structural system in Building D: (a) schematic; (b) outside wall at roof (looking up).*

(a) (b)

Figure 3.98: *Medical Plaza (Building D): (a) northwest corner; (b) typical façade cracking (west side).*

The nonstructural damage inside Building D was extensive. Cracking was visible in much of the drywall (Figure 3.99a). Unrestrained file cabinets and shelves located on the second floor of the building tipped over, emptying their contents (Figure 3.99b). Lightweight ceiling tiles fell in several sections of the ceiling (Figure 3.99c). Loss of ceiling tiles was prevalent along the perimeter walls (Figure 3.99d).

(a) (b)

(c) (d)

Figure 3.99: *Nonstructural damage in Building D: (a) drywall cracking; (b) toppled shelves; (c) ceiling tile loss (center of room); (d) ceiling tile loss (perimeter of room).*

3.3.4 APARTMENT BUILDINGS

Two apartment complexes with severe damage and red tags were visited by the reconnaissance team in El Centro and described below. Nearby dozens of other apartment complexes, some with open fronts, suffered much less damage and were occupied shortly after the main earthquake.

The Brighton Manor at the corner of W. Brighton Ave. and S. 5th St. in El Centro is a two-story light wood frame complex of multiple buildings in a cluster with an internal courtyard and connected by walkway canopies. Exterior and interior corridor walls consist of plaster over wood studs. The plaster was severely cracked particularly at the first floor (Figure 3.100). Patio screen walls consisting of unreinforced concrete blocks and wood posts toe-nailed to their supports had partially collapsed (Figure 3.101).

Figure 3.100: *Typical severe plaster cracking along the base and at the wall piers next to first floor windows of the Brighton Manor Apartment Complex in El Centro.*

Figure 3.101: *Partial collapse of patio screen walls and framing at the Brighton Manor Apartment Complex in El Centro.*

The apartment building at 1996 Cottonwood Circle, North Alley, near Ocotillo Dr. in south El Centro has an irregular configuration. The southern portion of the building appears to be an addition to the northern portion. Like the Brighton Manor, the building relies on light wood frame walls with plaster finishes to resist earthquake and wind forces (Figure 3.102). Extensional cracks at the framing where the southern portion of the building connected to the northern portion suggest collector failures at the floor and roof (Figure 3.103). Longitudinal plaster walls on the east side at the north end of the building experienced a residual drift between 25 to 50 mm (1 to 2 in). Irregularities included a soft and weak story along both axes of the building. The condition of the building was reported by neighbors as deteriorating with significant aftershocks and government officials were advised of inadequate barricading to discourage the public's access to the building's perimeter.

Figure 3.102: *1996 Cottonwood Circle apartment building in El Centro with an irregular configuration and near collapse.*

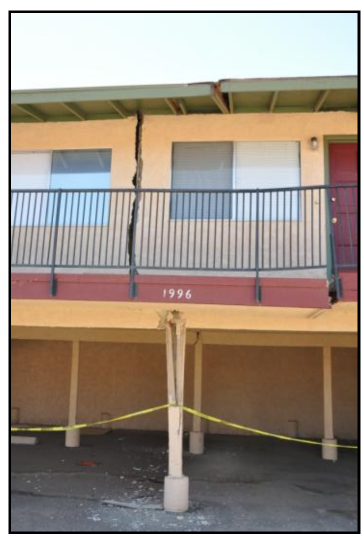


Figure 3.103: *Gap between the south (left) and north (right) portions of the apartment building at 1996 Cottonwood Circle in El Centro.*

3.4 SCHOOL PERFORMANCE IN IMPERIAL COUNTY

Imperial County has 22 public school districts with a total of 82 public school campuses for grades K through 14. All but one public school experienced minor damage to building contents and nonstructural systems. School officials took advantage of Spring Break week after Easter to make repairs to fallen building contents and nonstructural systems so that they could reopen 8 days after the earthquake.

Schools were not occupied at the time of the earthquake and thus no injuries occurred. However, serious injuries could have resulted had the earthquake occurred during school hours. Had the buildings been occupied, drop-cover-and-hold-on responses would have reduced the potential for injuries as there was almost no ceiling detritus observed below the desktops.

The lessons are clear. Field Act-approved public school buildings performed on the whole very well. However, most of the older schools were constructed before rigorous enforcement of earthquake safety standards for nonstructural systems was required by law. Until there are voluntary efforts or mandates to retrofit them, students and teachers continue to be exposed to possible serious injuries due to nonstructural falling hazards.

3.4.1 Jefferson Elementary School

The one exception in Calexico, Jefferson Elementary School, constructed in the 1960s, suffered significant nonstructural damage and will be closed for an extended period of time for repairs. When originally built, the State Architect was not regulating the earthquake safety of nonstructural systems pursuant to the Field Act.

At Jefferson Elementary, approximately 46 m by 2.5 m (150 ft by 8 ft), 115 m^2 (1200 ft^2) of plaster ceiling soffits fell in a progressive fashion. They were suspended on wires below steel canopies that overhung walkways between classrooms (Figure 3.104). Other buildings showed signs of plaster soffit distress, and while the soffits did not collapse, they will likely have to be retrofitted before reopening the school. The soffit collapses in some cases blocked classroom doors from opening and in three locations sheared off door knobs and a hose bib. In some of the classrooms and a multi-purpose room, light fixtures and parts of ceiling systems fell onto desktops and floors (Figure 3.105).

Jefferson Elementary is approximately 1,219 m (4000 ft) from the Calexico Fire Station Ground Motion Recording Station that recorded a peak ground acceleration (PGA) of 0.27g and a peak ground velocity (PGV) of 33 cm/sec (1 ft/sec). Several nearby schools of various ages, both public that are state-regulated and private that are locally-regulated, suffered considerably less damage than Jefferson.

Figure 3.104: *Fallen plaster ceiling soffits below steel canopies at Jefferson Elementary School in Calexico.*

Figure 3.105: *Fallen light fixtures in a Jefferson Elementary public school classroom in Calexico (32.67081ºN, 115.48107ºW).*

3.4.2 McCabe Schools

The McCabe Schools consist of an elementary (Figure 3.106) and adjoining junior high campus (Figure 3.107) in southwest El Centro, California. The elementary school is about seven buildings of varying age. The earliest are of 1950s vintage construction. The structures are all single story and most appear to be light frame wood construction. Additionally there are many portable classrooms in use on the campus. The seven buildings that are the junior high are newer, reportedly built in 2008, but are also light framed wood construction except for the multipurpose room and cafeteria which are masonry buildings.

Figure 3.106: *McCabe Elementary School (32.75173ºN, 115.59557ºW)*

Figure 3.107: *Junior High Campus at McCabe School.*

U.S. Geological Survey recording station 5058 is located on a slab on grade at the back of a building at the elementary school. Ground motions at the McCabe Elementary School were the highest recorded in the U.S. in this earthquake (PGA 0.59g and PGV 55 cm/sec, 1.8 ft/sec). Even with significant shaking, the buildings suffered no structural damage and only minimal nonstructural damage. During a regularly scheduled break the school district was able to complete clean up and repairs to avoid interruption to operation. The 2008 campus at that school recording suffered insignificant losses. The 1950's campus at McCabe experienced minor losses of ceiling systems and minor spalling of cover over tapered columns supporting the roof of a multi-purpose room (32.751820ºN, 115.59534ºW).

3.4.3 Calexico Unified School District

As of April 30, 2010, Calexico Unified School District was delaying the reopening of its 13 schools in the 9,500 student district because of asbestos from walkway coverings that had collapsed or cracked and mercury from light fixtures that fell down during the earthquake. Damage is now estimated at $10 to $15 million for that district compared to its annual budget of $75 million (13 to 20 percent of the annual budget). Jefferson Elementary School in that district will remain closed for the rest of the year (LA Times 4-29-10). The other 12 schools were tentatively hoping to reopen by May 10th (http://www.calexico.k12.ca.us/nsite/).

3.5 URM ISSUES IN CALEXICO AND EL CENTRO

As of 2006, unreinforced masonry (URM) building mitigation rates (e.g., the ratio of unreinforced masonry buildings fully retrofitted plus demolished divided by the number of buildings inventoried) was 20 percent for 55 buildings in El Centro and 11 percent for 19 buildings in Calexico (CSSC 2006-04 Status of the URM Law). However the conditions of these collapse-risk buildings are considerably more complex than these numbers would suggest. Damage to these buildings from prior earthquakes, particularly in 1940 and 1979, required many of them to be repaired and partially retrofitted. In some cases, entire floors were reportedly removed from buildings to reduce their vulnerability. Many buildings had been partially retrofitted prior to these latest earthquakes.

El Centro required mandatory parapet bracing and additional strengthening according to the 1991 Edition of the Uniform Code for Building Conservation Appendix Chapter 1 at the time of remodel. However, evidence of the lack of enforcement of the wall to roof anchorage requirements of the parapet bracing ordinance was observed in two buildings. See Figures 3.108 and 3.109 for an example.

Figure 3.108: *Partial collapse of a Mortuary building wall in downtown El Centro (32.791958ºN, 115.556042ºW).*

Figure 3.109: *Close-ups of the wall anchor connecting the ceiling joists to the brick wall in the Mortuary Building in El Centro. No wall anchors were observed at the roof level.*

Calexico reported that it had sent notices to URM building owners that their buildings were considered by the City to pose a risk of collapse during earthquakes. Calexico also required owners to provide structural reports, and in some cases wall anchors to the floors and roofs in accordance with its 1990 Ordinance based on the City of Los Angeles' Ordinance. While Calexico may have intended to enact a mandatory retroactive strengthening program, efforts by former building officials have reportedly resulted in only partial compliance. Many of the buildings have since experienced façade improvements that typically covered the masonry walls with plaster finishes. One single story masonry building's roof reportedly partially collapsed in an aftershock four days after the main shock on April 8th mid-morning.

3.6 SAFETY ASSESSMENTS IN IMPERIAL COUNTY

Safety assessments of buildings in Imperial County were completed on Friday, April 16, twelve days after the earthquake. 431 inspections resulted in 63 red tags, 78 yellow tags, and 290 green tags in the following jurisdictions: Brawley – 2, Calexico – 381, El Centro – 26, Holtville – 6, Imperial – 9, Westmorland – 7 (source: CalEMA Response Information Management System).

4 PERFORMANCE OF TRANSPORTATION INFRASTRUCTURE

The earthquake seriously affected a few bridges and the road system in the Mexicali Valley. Some observations on performance of transportation infrastructure on both sides of the US-Mexico border follow.

4.1 BRIDGES

4.1.1 Mexicali

The earthquake caused moderate to severe damage to some bridges depending on the proximity to the epicenter and in some cases inherently seismic deficient details. The visits to the damaged sites started from downtown Mexicali westward along Highway 2, then southward along Highway 5 in the regions closer to the epicenter. This highway system seems to be the most heavily impacted by the earthquake. The short period structures (T = 0.3 sec) in these areas were evidently subjected to spectral accelerations as high as 1.0g.

The first observation of a damaged bridge was Universidad Autónoma de Baja California (UABC) Pedestrian bridge over Monte Morelos Avenue (Fig. 4.1). This was a newly constructed 53 m (175 ft) steel arch tied to large diameter concrete piers. There are transverse tubular steel struts at the ends of the superstructure deck, which were designed to provide longitudinal resistance to seismic forces. The end plates of the struts were rigidly connected to the interior faces of the piers. All welds of the anchor bolts connecting one end of a strut to the concrete pier had completely fractured. Concrete columns supporting the spiral ramp structure were cracked. There were also signs of liquefaction of the soil surrounding the foundation. Excessive longitudinal seismic forces on the strut connections combined with rotational demands as a result of pier movement in liquefiable soil may have been the cause of this fracture. (Fig. 4.1.b) It is worth noting that the final position of the piers after the earthquake resulted in large gaps between the inside face and soil on both ends of the bridge (Fig. 4.1.c). Sidewalks were also cracked at the piers crossing the axis of the bridge. Further, hanger rods sloping away from the mid-span at both ends of the bridge in both planes of the hangers were buckled (Fig. 4.1.d). These residual deformations are clear indicators that the bridge elongated longitudinally between arch pins. It is also apparent that failure of the tie did not result in collapse, and therefore redundant load paths were active.

(a)

(b)

(c) (d)

Figure 4.1: *UABC pedestrian bridge over Monte Morelos Avenue, (a) overview of arch span, (b) strut-connection failure, (c) pier movements, (d) buckled hangers.*

On Highway 2, at about 24 km (15 mi) west of Mexicali, an overcrossing was damaged. The bridge is a 76 m (250 ft) long, two-span Precast-Prestressed (PC/PS) concrete girder bridge on bent cap and round concrete columns supported on drilled shafts (Fig. 4.2.a). The damage observed included shear key cracking extended into the bent cap (Fig. 4.2.b), expansion joint damage associated with superstructure translational and rotational movements, crushing and settlement of the slope paving at abutments, spalling and cracking of concrete pedestals for the girder ends at abutments, and permanent distortion of bearings pads.

(a) (b)

Figure 4.2: *Overcrossing over Highway 2 (a) west view of the spans (b) damage to shear keys and bent cap.*

Many of HWY 5 overcrossings suffered moderate damage. These overcrossings are typically 3-span PC/PS concrete bridges, which were recently constructed. They have slope paving on the west side but have high-reinforced embankment fills in the east abutment (Fig. 4.3.a). These bridges do not have any approach slabs or longitudinal restrainers. The high and predominant longitudinal component of ground motions combined with little longitudinal restraint seems to have caused girders to move substantially and exhibit signs of pending unseating (Fig. 4.3.b).

The top portions of reinforced embankment fills in the east approach failed (Fig. 4.3.c). In addition, significant approach roadway settlement was also observed (Fig. 4.3.d). Most of these crossings are oriented in the east-west direction. No shear key failures were found, yet significant bridge movement and approach settlement was observed in the longitudinal direction. Thus, the most damages suffered seem to be consistent with the principal direction of ground motion as normal to the fault rupture.

(a)

(b)

(c)

(d)

Figure 4.3: *(a) Highway 5 overcrossing, (b) pending unseating of girders, (c) failure of reinforced high embankment fill, (d) approach roadway settlement.*

The earthquake caused collapse of one span of Puente San Felipito, which is a railroad bridge over the Colorado River (Fig. 4.4.a). The subject bridge was constructed in 1962. It is located approximately 8 km (5 mi) to the south east of Guadalupe Victoria, near the Baja California and Sonora border. The bridge is approximately 198 m (650 ft) long, spanning the river with multiple spans including a 3-PC/PS concrete girder supported on concrete piers with oblong sections, which are supported on piles. Complete unseating of the girders due to both transverse movement of the superstructure combined with longitudinal pier movement was evident (Fig. 4.4.b). The superstructure did not have any shear keys nor any sizable anchorage to restrain lateral or longitudinal movements relative to the piers. Small permanent drift combined with evidence of liquefaction indicated pier longitudinal movements that could have led to unseating in the longitudinal direction. The girders that collapsed came unseated at the pier on the south edge of the river on the side of the pier away from the river. Though no girders collapsed on the north side, the superstructure was shifted relative to the pier on the north edge of the river. The unseating direction was again on the pier side away from the river. There was no significant gap in the superstructure between these two piers at the river edges, which is further indication that these two piers moved longitudinally toward the river. Permanent displacement of the piers toward the river was caused by liquefaction-induced lateral spreading. Members of the GEER team, which may be found at (http://www.geerassociation.org/ GEER_Post%20EQ%20Reports/ Baja%20California_2010/Baja_Index_2010.html) measured more than 5 m (16.5 ft) of lateral spreading of the east bank of the river along a transect approximately 40 m (131 ft) north of the bridge, and over 1 m (3.3 ft) of lateral spreading on the west bank. Lateral soil deformation along the bridge axis was restrained by the deep foundation elements supporting the bridge as they attracted loads from the spreading soil. Substantial transverse misalignment of the two piers in the river was observed (Fig. 4.4.c). This misalignment raises the possibility that piers in the river moved more as a result of softer and less soil surrounding them than the piers on land. It is interesting that the two piers in the river are misaligned downstream from the rest of the piers. The possibility of movement of the piers over the life of the bridge, rather than as a result of the earthquake, should also be considered.

(a)

(b)

(c)

Figure 4.4: *Puente San Felipito, Railroad Bridge: (a) collapsed span, (b) girder unseating, (c) transverse mis-alignment.*

Directly adjacent to Puente San Felipito was a highway bridge crossing the Colorado River, seen in some of the pictures in Figure 4.4. This bridge is newer than the railway bridge and was built on drilled shafts. The large pier movements seen on the railway bridge were not observed here. However, significant deformations in the deck were observed at the same location as the collapse of the railway bridge span (Fig. 4.5.a). The column cracking at their base, as anticipated in a plastic hinge location, was observed confirming column rotations (Fig. 4.5.b). Cracks were on the riverside of these columns on both banks of the river, indicating tension was mobilized on this side of the pier columns. This is evidence that the foundations moved slightly and permanently toward the river in the direction of lateral spreading. The deck was cracked across the width of the roadway and sidewalk above this bent (Fig. 4.5.c). Figure 4.4.c shows an originally repaired crack in the sidewalk that had re-cracked during the earthquake. This original repair indicates that there may have been some foundation problems with this bridge and the aforementioned adjacent railway bridge prior to the event of April 4, 2010. Spalling of concrete in the curb was seen at the low point of this deformed deck on both sides of the bridge and was clearly quite recent (Fig. 4.5.d).

(a) (b)

(c) (d)

Figure 4.5: *Highway bridge next to Puente Del Ferrocarril: (a) overview of deck deformations, (b)column tension cracking in the plastic region , (c) repaired, re-cracked sidewalk, (d) spalling in curb.*

4.1.2 Calexico

The bridge on CA-98 is located at milepost 22 along CA 98 over an irrigation canal. The GPS coordinates are 32.67852ºN, 115.67324ºW (Figure 4.6). According to the information provided by Caltrans, the bridge was constructed in 1955 and has a total length of 46 m (151 ft). The bridge deck is mildly skewed and has three spans supported on two intermediate bents and an abutment at each end. Each bent has six octagonal piles, and each abutment has four supporting piles.

Only the west abutment was inspected due to the bank conditions and vegetation close to the east abutment. Cracks were observed in some of the piles. Some cracks appeared to be caused by the earthquake, while others could be pre-existing. Some of the piles appeared to be slightly tilted; according to Caltrans engineers the tilt was introduced in the original construction due to an alignment problem (Figure 4.7). In general, the damage caused by the earthquake was light with some mildly cracked columns (Figure 4.8) and some crushing of the nonstructural unreinforced slurry wall beneath the abutment wall (Figure 4.9).

During the visit on the morning of April 7th (three days after the earthquake), the bridge was open to traffic.

Figure 4.6: *View of the bridge on CA-98 at milepost 22.*

Figure 4.7: *Tilted exterior columns – a pre-existing condition.*

Figure 4.8: *Cracked exterior column.*

Figure 4.9: *Crushing of nonstructural slurry wall beneath abutment wall.*

4.2 ROAD SYSTEMS

4.2.1 Imperial County

On the US side, there was very little evidence of road damage. In some areas at canal crossings and bridges, there was a minor amount of differential settlement, which either had been quickly repaired or did not need repair. The access road to Calexico's WWTP was damaged as shown in Figure 5.12. An apparent lateral spread near a lake significantly damaged the westbound lanes of Interstate 8. The lanes were returned to service within 24 hours.

4.2.2 Mexicali

There was significant damage to roads in Mexico either due to lateral spreading or displacement from the actual fault (Figure 4.10). Further information can be found in the GEER report (http://www.geerassociation.org/GEER_Post%20EQ%20Reports/Baja%20California_2010/Baja10_Ch05.html).

Figure 4.10: *Damage to roads due to liquefaction and lateral spread.*

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5 PERFORMANCE OF WATER AND WASTEWATER SYSTEMS

The El Mayor Cucapah earthquake has presented an unusual problem for the recovery and livelihoods of those affected by the earthquake since water and wastewater treatment plants, irrigation canals and locally the encasement of the New River were damaged. In Calexico, damage to the City's primary water clarifier and water tanks have seriously reduced its ability to produce potable water from 10 million gpd to around 5 million gpd. The City used its reverse 911 system to notify residents of the need to conserve water and has posted information about the need to conserve water on its website as well. The situation in Calexico for the production of potable water is expected to worsen during the hotter portion of the year when demand for water is greater.

Damage to water systems in Mexicali may have contributed to the increase in flow of the New River where it crosses into California from Mexicali to Calexico; however this water is not potable. As of April 23, 2010, the extent of direct and indirect damage to farmlands in the Imperial Valley has not been consolidated. In the Mexicali Valley approximately 140,000 acres (567 square kilometers) of farm lands were damaged or lost water service due to damage to the irrigation canal system. The following observations are intended to help memorialize the conditions at selected sites after the earthquake and to suggest potential impacts of damage to sewer lines, water lines and canals and liquefaction.

As of April 23, 2010, no significant earthquake-related damage to water and wastewater systems was identified by or reported to the California Seismic Safety Commission (CSSC) in San Diego County, California, Yuma County, Arizona or Sonora, Mexico. The following observations are restricted to southern Imperial County, California and Baja California, primarily around Mexicali, Mexico, and were provided by the CSSC or by individuals who supplied the CSSC with information. Mr. Jose Angel, the Region 7 Assistant Executive Officer of the State of California's Regional Water Quality Control Board in Palm Desert, contributed information and select imagery for sites in Imperial County and Baja California.

Water and wastewater systems were heavily damaged in Imperial County. Irrigation, process and drinking water for the majority of the Imperial Valley comes from the Colorado River via the All American Canal. This is because the area has a desert climate and ground water quality is generally unfit for irrigation, industrial use or drinking. The regional water district in the area is the Imperial Irrigation District (IID) and is the largest regional irrigation district in the United States. It serves most of Imperial County including 1,821 km^2 (450,000 acres) of irrigated farmlands.

Figure 5.1 shows the location of the Calexico Wastewater Treatment Plant, the Calexico Water Treatment Plant and the siphons and northern headworks and spillway that were damaged on the All American Canal.

Figure 5.1: *Location map for the Calexico wastewater and water treatment plants and the damaged headworks and spillway next to the All American Canal siphons crossing the New River, Imperial County, California.*

5.1 WATER TREATMENT PLANTS

5.1.1 Calexico

The Calexico Water Treatment Plant (Figure 5.2), which is located approximately 650 m north of the Mexican border and east of downtown Calexico, provides all water to the city of Calexico. The plant operates with three on-site tanks of 4, 3, and 1 million gallon (MG) capacity and two clarifiers (one back-up and one in continuous operation). The maximum daily use of the plant is on the order of 10 million gallons. The facility outputs a maximum annual total of 2.2 billion gallons of water. The tanks are 9.1 m (30 ft) high and extend between 1.8-2.4 m (6-8 ft) below ground level. All tanks were nearly full during the earthquake (between 30-60 cm or 1-2 ft below the top). More information on water tanks is provided in Section 5.3.

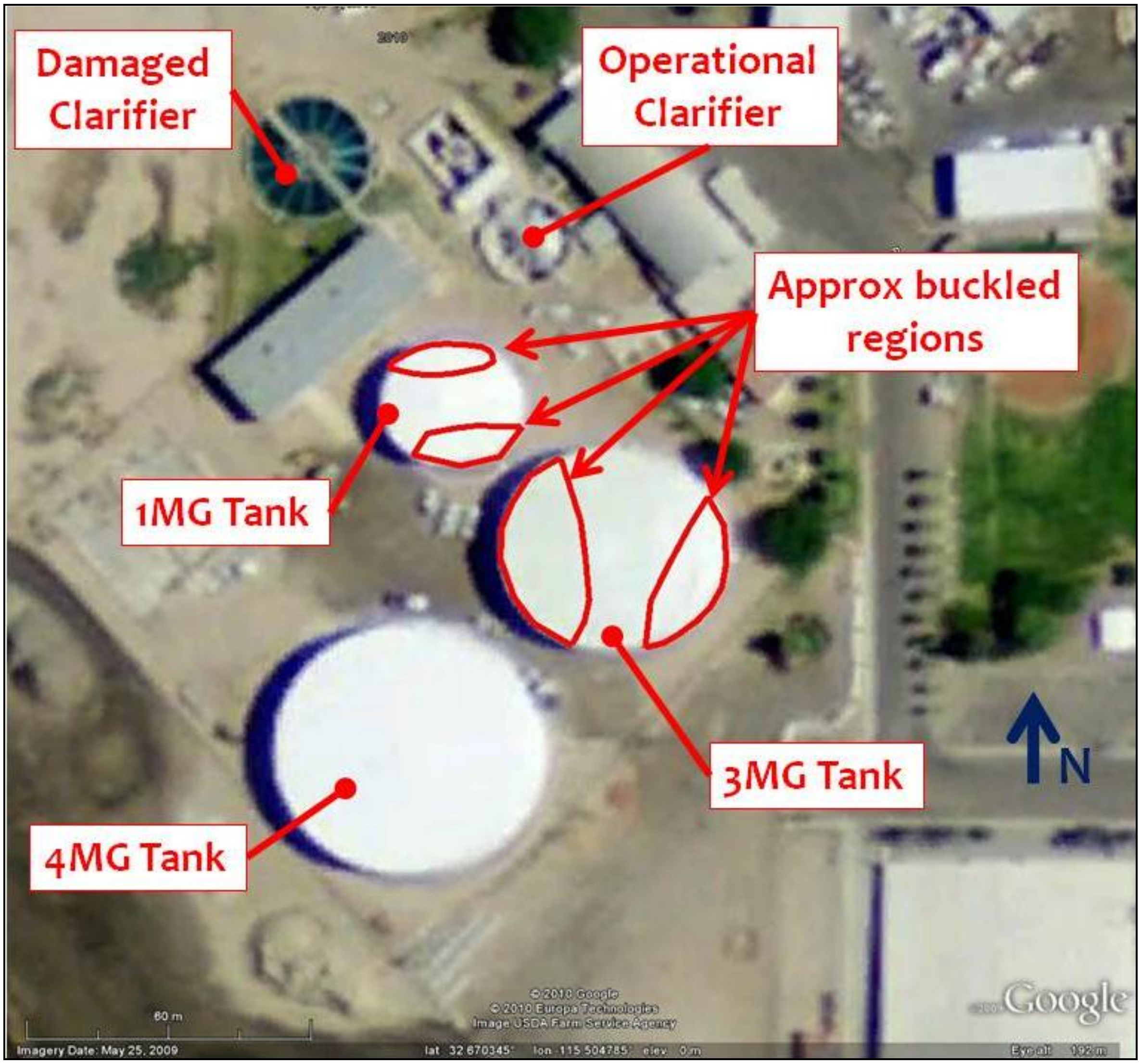

Figure 5.2: *Annotated GoogleEarth image of the Calexico water treatment plant (32.6703°N, 115.5050°W).*

Sloshing water heavily damaged the City of Calexico's water treatment plant. The main circular clarifier was damaged by sloshing (Figure 5.3), which took down the effluent weirs, the main settling chamber and the sludge scrapers on the tank bottom. However, the treatment plant capacity was reduced from 10 mgd to 5 mgd mainly due to damage to the primary clarifier and to the water tanks. This is critical because their summer demands approach 10 mgd.

Damage to the northern clarifier was severe. The steel walkway ruptured at multiple points and the clarifier scraper structure and its central motor unit were damaged (Figure 5.4). The perimeter concrete wall of the clarifier tank was damaged at the walkway support on the north end (Figure 5.5). The walkway anchorages were severely deformed in bending and shear (Figure 5.6). The working clarifier is shown in Figure 5.7 for comparison. The northern clarifier was full of water when the earthquake occurred while the southern clarifier was empty, which accounts for the difference in performance. The clarifier as well as two large tanks (3MG and 1MG) will likely need to be demolished and replaced.

Figure 5.3: *Damaged water clarifier at the Calexico Water Treatment Plant.*

(a) (b)

Figure 5.4: *Damage to clarifier: (a) view of failed walkway (looking east); (b) buckled scraper central ring (looking west. (32.6709°N, 115.5053°W).*

(a) (b)

Figure 5.5: *Damage to clarifier: (a) tank wall and walkway (looking north); (b) tank wall (looking south) (32.6709°N, 115.5053°W).*

(a) (b)

Figure 5.6: *Damage to walkway anchorage: (a) north end; (b) south end.*

Figure 5.7: *Operational clarifier at the Calexico Water Treatment Plant (32.6708°N, 115.5048°W).*

Work was underway less than a week after the earthquake to repair the clarifier components to get the capacity returned before the critical summer months.

5.1.1.1 All American Canal Siphon Northern Headworks and Spillway, Northwest of Calexico, California

At the time of this writing the Imperial Irrigation District (IID) indicated that they had 160 sites that had suffered some damage; however, the IID did not offer the CSSC a copy of their findings. On April 14th, representatives from the IID told the CSSC that a leak was found between the northern headworks and the spillway adjacent to the All American Canal siphons crossing the New River upstream from the Calexico wastewater treatment plant (see Figure 5.1 for location of siphons and Figures 5.8 and 5.9 for the location of the damaged pier between headworks and the spillway, and the damaged pier between the headworks and the spillway). The CSSC field team observed the siphons from a distance during their tour of the sewer treatment plant on April 7th but did not observe the siphons or the headworks up close. The siphons are a critical component of the All American Canal since they allow water to cross over the New River, supplying the IID with water for the western one-third of their coverage area.

Figure 5.8: *Location of damaged pier between northern headworks and spillway at the New River siphons on the All American Canal (source: Michael Kemp, Imperial Irrigation District).*

Figure 5.9: *Damaged pier at the headworks of the All American Canal siphons crossing of the New River northwest of Calexico (source: Michael Kemp, Imperial Irrigation District).*

Due to the potential loss of water for the communities of Westmoreland, Brawley, Seeley, and farmlands west of the siphons as well as the potential for flooding properties near the siphons, the IID had representatives from the Los Angeles office of the United States Army Corps of Engineers (USACE) inspect the headworks and spillway area on April 14th, 2010. The USACE indicated that at the time of their inspection, the damage did not pose an immediate threat of flooding. The canal was leaking water at the location of the damaged pier at the time of the USACE inspection. At the time of this writing the extent of the damage as well as the scope of the repairs, the cost and time to make repairs on the All American Canal at the northern end of the headworks was not known.

5.1.2 El Centro

The City of El Centro's water treatment plant suffered similar damage to two of their clarifiers. One was at their old plant and another was at their recently completed plant addition. Since the old plant is operating in conjunction with the new one, there is adequate capacity with these two clarifiers out of service.

5.2 WASTEWATER TREATMENT PLANTS

5.2.1 Calexico

The City of Calexico also had extensive damage, much of which was similar to their water treatment plant. Two of their secondary clarifiers were heavily damaged by sloshing significantly impacting capacity. In addition they had extensive damage related to liquefaction and lateral spreading. One of their lined aeration ponds had subsidence in the embankment causing the liner to tear and the pond to leak (Figure 5.10). Waves also tore some of the floating aerators from their moorings.

Figure 5.10: *Leakage of pond.*

Lateral spreading along the New River also caused the riverside sludge bed wall to tilt towards the river causing gaps between the various sludge drying beds. Liquid sludge will not be able to be applied to the beds until these leaks are repaired.

The main influent trunk sewer to the treatment plant was also severely damaged. The 1 m (36-in) sewer crosses the New River on two concrete supports on driven piles. Subsidence caused the pipe to drop and break on both sides of the river (Figure 5.11). After 6 days, the City installed a temporary bypass to this break using portable pumps (Figure 5.11) and HDPE pipe strapped to the existing crossing.

Figure 5.11: *Breakage of pipe on both sides of river (32.6726ºN, 115.5149ºW).*

The main access road to the treatment plant was also damaged by lateral spreading perhaps causing damage to the second main influent pipeline to the treatment plant (Figure 5.12).

Figure 5.12: *Damage to road by lateral spread (32.6677ºN, 115.5097ºW).*

On April 7, 2010, staff from the Alfred E. Alquist (California) Seismic Safety Commission (CSSC) were given a tour of water and wastewater treatment facilities in Calexico, California. The tour was lead by Mr. Arturo Estrada, the chief plant operator. The damage to the waste-water treatment plant (WWTP) generally consisted of damage to a 1 m (36 in) diameter inlet feeder line that crossed the New River from Calexico to the plant. The pipe was discharging between 200,000 to 300,000 gallons per day of wastewater into the New River before being bypassed on April 9th. Damage to the wastewater treatment plant included damage to primary and secondary clarifiers, lagoons, and berms, possibly due to lateral spreading and sludge beds. Figure 5.13 shows the general layout of damage at the Calexico Wastewater Treatment Plant; Figure 5.14 shows the broken 1 m (36 in) diameter inlet main discharging sewage; Figure 5.15 shows the damaged primary clarifier being repaired. As of April 22, 2010, the Calexico Wastewater Treatment Plant flow was 2.7 million gallons per day.

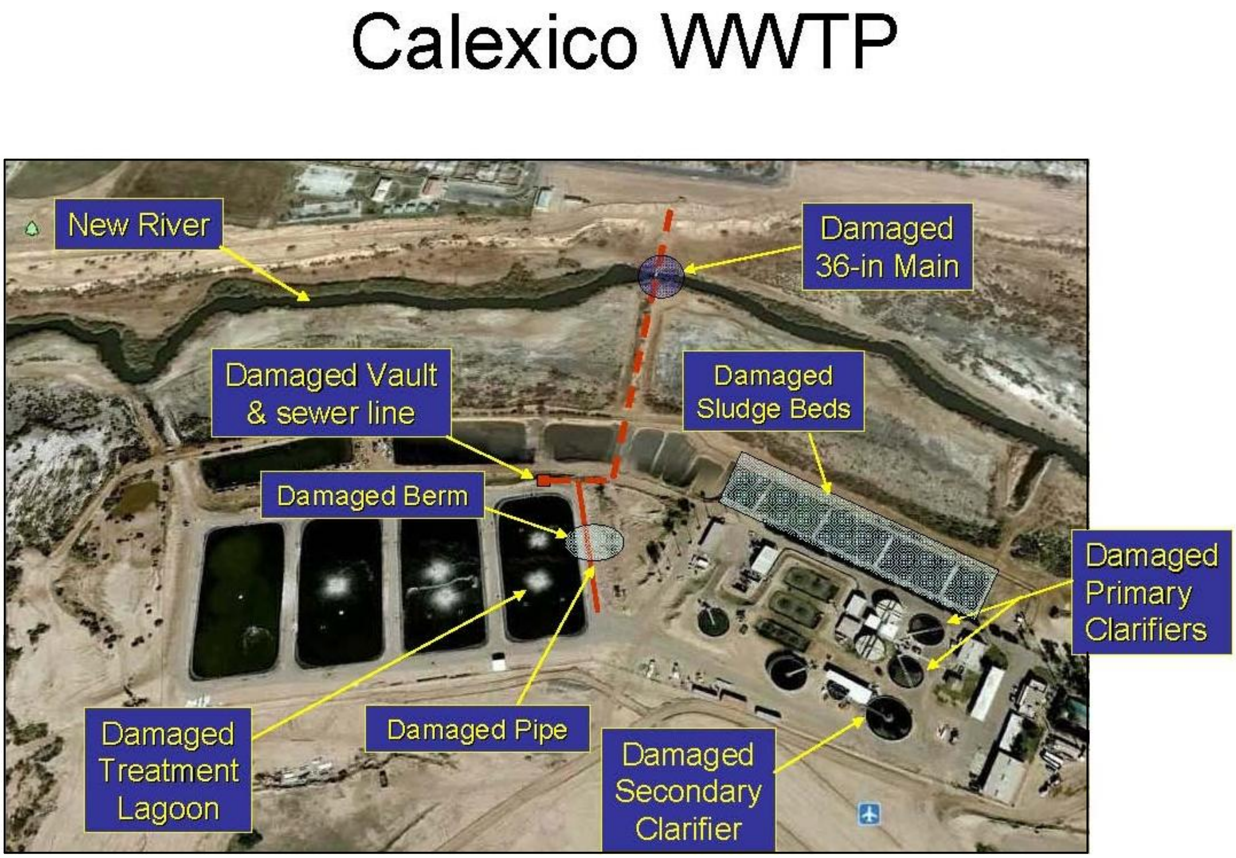

Figure 5.13: *Damage location map Calexico Wastewater Treatment Plant (32.6703ºN, 115.5135ºW).*

Figure 5.14: *Damaged 1 m (36 in) diameter inlet mainline from Calexico to the Calexico Wastewater Treatment Plant (32.6726ºN, 115.5149ºW).*

Figure 5.15: *Damaged primary clarifier at Calexico Wastewater Treatment Plant.*

Mr. Jose Angel, the Assistant Executive Officer for Region 7 of the State of California, Regional Water Quality Control Board indicated that groundwater had been flowing into a secondary clarifier. This made sense since groundwater was estimated to be relatively close to existing grade and the area adjacent to the wastewater treatment plant was subject to moderate levels of lateral spreading and liquefaction (Figure 5.16).

Figure 5.16: *Lateral spreading and liquefaction near western side of Calexico Wastewater Treatment Plant.*

The City of Calexico has submitted a report regarding the wastewater treatment plant to the Regional Water Quality Control Board in Palm Desert (Region 7) and representatives from the Regional Water Quality Control Board have visited the plant. As of April 23, 2010, the CSSC had not obtained or seen the Preliminary Damage Assessment (PDA) for the Plant.

5.2.2 El Centro

The average daily flow from the plant is 4.1 mgd. Treated wastewater from the WWTP is discharged to a drain tributary to the Alamo River. There is structural damage to 1 primary clarifier and to 2 secondary clarifiers (see Figure 5.17 for damage location map). The baffles of the primary clarifier were sheared off of the clarifier and broke. The clarifier also has some relatively superficial small cracks. The center well of the secondary clarifier No. 2 was twisted (Figure 5.18). The center column of the secondary clarifier No. 3 dropped about 13 cm (5 in). There is structural damage to the concrete walkways and inspection bridges of the aeration tanks. There may be more serious structural damage to the aeration tanks compartments (e.g., walls), but the aeration tanks will have to be emptied to assess the extent of damage, if any.

Figure 5.17: *El Centro WWTP damage location map.*

Figure 5.18: *El Centro WWTP damaged secondary clarifier and well assembly.*

5.2.3 Heber Community Services District WWTP

The average daily flow is 0.2 mgd. Treated wastewater from the WWTP is discharged to a tributary to the New River. There is very little damage. There are some relative small cracks on the concrete of the oxidation ditch. One of the clarifiers probably titled a few degrees from the horizontal plane.

5.2.4 City of Holtville WWTP

The average daily flow is 0.8 mgd. Treated wastewater from the WWTP is discharged to the Alamo River. There are no signs of structural damage, but plant personnel noticed some “wet spots” (about 3 of them) on the terrain between the trickling filter and the secondary clarifiers. They excavated one of the “wet spots” and found shallow groundwater that they are pumping into a clarifier every 10-15 minutes at about 30 gpm.

No damage was reported after Regional Water Quality Control Board staff visited the following WWTPs on April 23, 2010: City of Brawley WWTP, City of Calipatria WWTP, Date Gardens MHP WWTP, McCabe School District WWTP, El Centro Navy Air Station WWTP, and Niland Community Services District WWTP.

5.2.5 Mexicali, Baja California, Mexico

The Regional Water Quality Control Board has been working with water and wastewater officials in Baja California with CILA, the Comisión Internacional de Límites y Aguas (the International Boundary and Water Commission between Mexico and the United States). The following notes are from CILA and presented to the Regional Water Quality Control Board. The information was obtained by CILA on April 6, 2010.

5.2.5.1 Zaragoza WWTP

The average daily flow is 25 mgd. Minor damage was observed at the lagoons. Flow from the lagoons is discharged into a tributary of the New River. The New River then flows into California at Calexico. Damage to one of the berms was due to erosion by seiches in the lagoon.

5.2.5.2 Las Arenitas WWTP

Information on the average daily flow was not forwarded. The discharge from the plant flows towards the Colorado River Delta in Baja California Norte. Only minor damage has been observed to its lagoons but the damage did not affect the performance of the plant.

5.3 WATER STORAGE TANKS

5.3.1 Calexico

The City of Calexico had significant roof damage to their three storage tanks at the water treatment plant. Two tanks with capacities of 1 MG and 3 MG were constructed in the 1950s. A third 4 MG tank was constructed in the 1990s. All had damage to the roof girder systems with tearing of the roof steel and partial collapse of the roof (Figures 5.19 and 5.20).

There was slight evidence of tank movement, but no evidence of elephant foot failures.

Figure 5.19: *Damage to roof girder systems.*

Figure 5.20: *Partial collapse of roof.*

A video survey was conducted on all three tanks and repair plans are underway for the replacement of the roofing systems.

5.3.2 El Centro

One of El Centro's main steel water storage tanks was also damaged in a similar manner by sloshing. Water force tore girder welds causing the roof to tear and partially collapse (Figures 5.21 and 5.22).

Figure 5.21: *Partial collapse of roof.*

Figure 5.22: *External view of partial collapse of roof.*

6 AGRICULTURAL AREAS

A map of the shaking intensity at a number of localities mentioned in this report is included as Figure 6.1. Agricultural fields and irrigation infrastructure sustained damage over a large region of southern Imperial County, California, and the Mexicali Valley, Baja California. The area with the greatest damage is south of Mexicali approximately 40 km (25 mi). The satellite image in Figure 6.2 shows the reconnaissance route of the Exponent team, which visited portions of the Mexicali Valley in the Colorado River delta south and southeast of the Cerro Prieto geothermal field. This agricultural area experienced widespread damage to irrigation canals, fields, and towns due to ground failures and earthquake-related flooding.

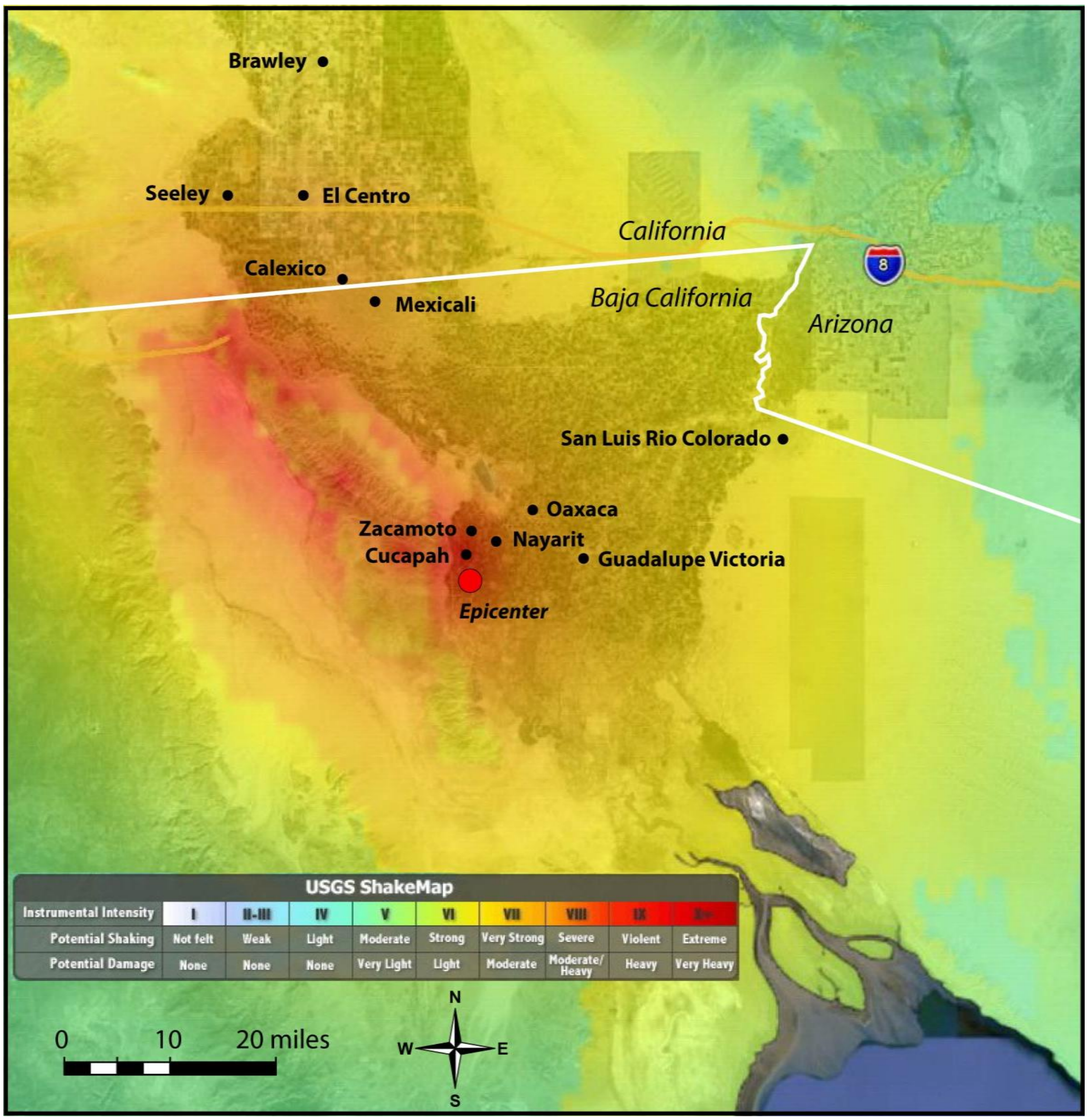

Figure 6.1: *Map of the area most affected by the April 4, 2010, M_w 7.2 earthquake. White line is the Mexico - U.S. border. Red dot is the epicenter of the earthquake. Shake map and epicenter from USGS; base map from Google Earth.*

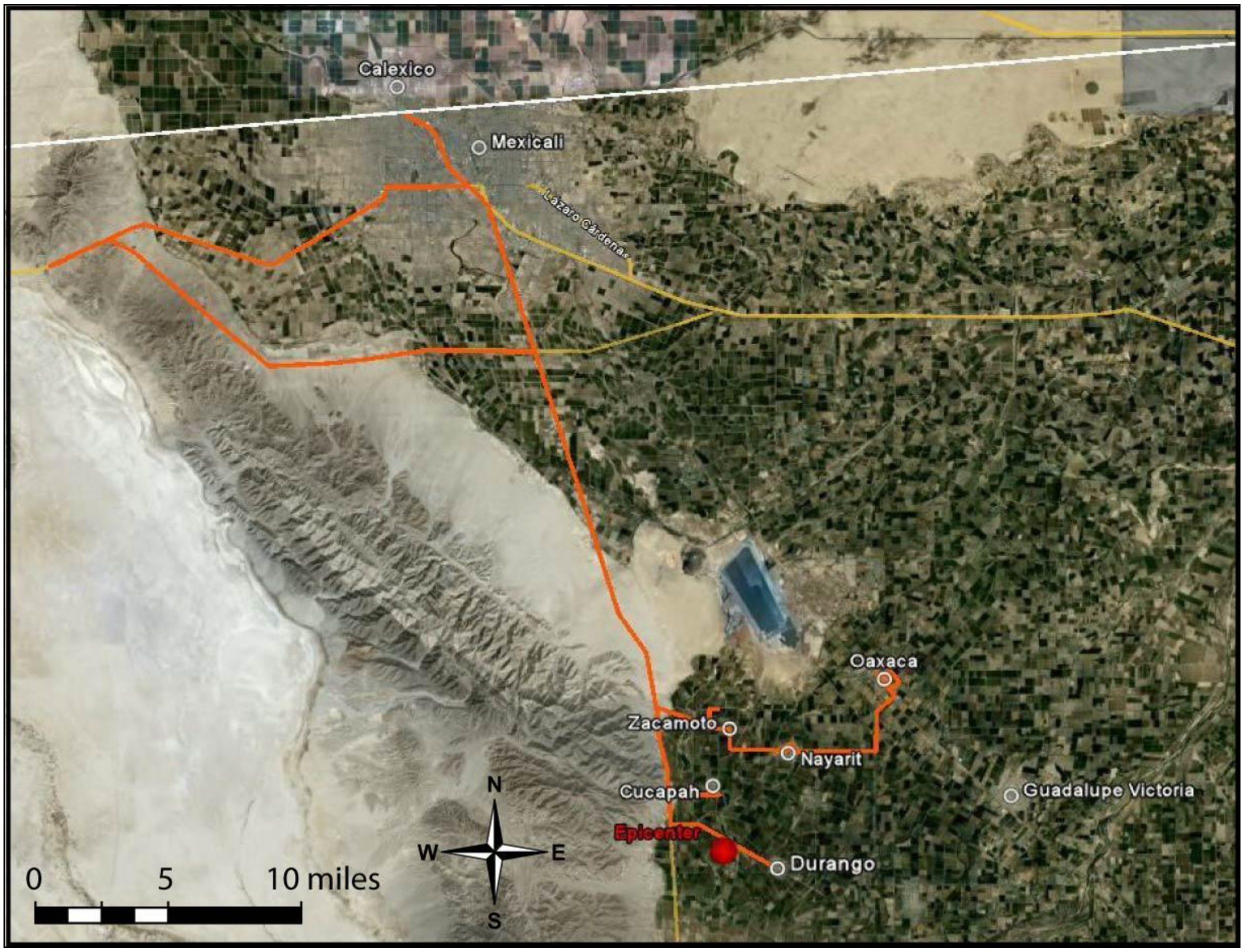

Figure 6.2: *Map of the northern Mexicali Valley. White line is the Mexico - U.S. border. Orange line is the track that the Exponent team covered during reconnaissance in the Mexicali Valley. Red dot is the epicenter of the April 4, 2010, M_w 7.2 earthquake. Base map from Google Earth.*

Portions of the area were inundated with water from liquefaction-induced sand boils, some of it reportedly saline, sulfurous, and/or contaminated. Some of the sand-boil deposits dried with a white mineral crust that appeared to have high gypsum content. Localized sections of roads, fields, and towns were also inundated with water from overflowing canals (Baja California government officials reported that canals overflowed the day after the earthquake as a result of increased flow in the Colorado River due to post-earthquake releases from one of the dams near the U.S./Mexico border). Standing water remained in some roadside ditches and fields (Figure 6.3) as of April 16, 2010.

Figure 6.3: *Flooded roadside ditch and partially flooded wheat field west of Durango, Baja California, Mexico.*

Liquefaction and lateral spreading caused cracking, settlement, and slumping of unreinforced-concrete-lined irrigation canals (Figures 6.4, 6.5, and 6.6), including the Nuevo Delta, Reforma and Revolución Canals (Figure 6.7). Some of the canals failed when portions of their sidewalls shifted laterally into adjacent unlined stream channels or drainage ditches (Figures 6.8 and 6.9). The Baja California government estimated that 57 km (35 mi) of major canals, 350 km (217 mi) of minor canals and 380 km (236 mi) of drainage channels were damaged.

Figure 6.4: *Irrigation canal west of Cucapah, Baja California, Mexico.*

Figure 6.5: *Irrigation canal west of Nayarit, Baja California, Mexico.*

Figure 6.6: *Irrigation canal west of Cucapah, Baja California, Mexico.*

Figure 6.7: *Stream bank on eastern edge of Nayarit, Baja California, Mexico.*

Figure 6.8: *Irrigation canal northwest of Zacamoto, Baja California, Mexico.*

Figure 6.9: *Irrigation canal northwest of Zacamoto, Baja California, Mexico.*

Most crops in the fields at the time of the earthquake, predominantly wheat and alfalfa but also cabbage and newly planted cotton, were beginning to wilt due to lack of irrigation and are likely to be lost this season. In addition, massive sand boils (see Figures 6.10, 6.11 and 6.12) and sand sheets blanketed portions of fields, and large-scale lateral spreading created scarps and fissures that crossed fields (Figures 6.13 and 6.14). The Baja California government reported that the earthquake also caused regional topographic tilting. The resulting disrupted topography will require earthwork and leveling before gravity-controlled irrigation can resume.

Figure 6.10: *Sand boils in alfalfa field southeast of Cucapah, Baja California, Mexico.*

Figure 6.11: *Sand boils in newly seeded cotton field west-northwest of Zacamoto, Baja California, Mexico.*

Figure 6.12: *Sand boils and cotton seedlings west-northwest of Zacamoto, Baja California, Mexico.*

Figure 6.13: *Pre- and post-earthquake aerial images of southern portion of town of Cucapah and adjacent fields. Arrows indicate location of field shown in Figures 6.10 and 6.14. First image undated. Second image dated April 14, 2010. Source: Baja California Servicio de Información Agroalimentaria y Pesquera, http://w3.siap.gob.mx/mexicali/map.phtml.*

Figure 6.14: *Fissure and sand boils in alfalfa field southeast of Cucapah, Baja California, Mexico*

The Baja California government estimated that 567 km^2 (140,000 acres) of fields needed to be repaired. Many hours per acre will be required to perform the earthwork, and laser-leveling equipment is in short supply. The extent of acreage damaged overwhelms repair capabilities.

With the current year's crops apparently lost due to damage to irrigation facilities, local economies are seriously impacted. (CNN reported that the state of Baja California is Mexico's third-largest producer of wheat). If repairs to irrigation canals and fields cannot be completed quickly, additional growing seasons will also be lost.

Farmworkers are out of work, as are suppliers and distributors who serve the farmers and the consumers of their produce. The immediate direct impact to rural communities will grow into an indirect impact to Mexicali and other cities as farmworkers' incomes drop. Farmworkers and other impacted residents may look for work in the U.S.

As in the fields, sand boils and sand sheets also blanketed portions of roads, yards, and parks in towns (Figure 6.15) including Nayarit, Oaxaca, and Zacamoto, and scarps and fissures damaged roads, utilities, and buildings (Figure 6.16).

Figure 6.15: *Sand boils and mobile homes west-northwest of Durango, Baja California, Mexico.*

Figure 6.16: *Ground fissure beneath building in Nayarit, Baja California, Mexico.*

The Baja California government was evaluating whether the occurrence of extensive ground cracking and sand boil activity in some towns will necessitate permanent relocation of some of the area's residents for safety reasons. In the meantime, tents have been provided to some residents, and arrangements are being made to acquire portable trailers that were purchased by the U.S. in the aftermath of Hurricane Katrina, but were never used.

The extensive damage in the agricultural portion of the Mexicali Valley may be a predictor of future earthquake impacts in some agricultural and levee-protected areas in seismically active areas of the U.S.

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7 ECONOMIC IMPACT

Initial estimates for total economic losses are expected to be less than US$1 billion for Baja California, Mexico and Imperial County, U.S., with insured losses less than US$300 million (EQECAT 4-6-10). Similarly, economists in Mexico estimate the economic damage to be greater than US$1 billion and insured losses more than US$300 million (AON Benfield Webwire 5-4-10) By April 21, 2010, the state of California's Emergency Management Agency in cooperation with the Imperial County Office of Emergency Services and local governments produced initial damage estimates of direct property losses of $91 million in that Imperial County (West News, CALEMA, 4-21-10). The unemployment rate in Imperial County before the earthquake was 27 percent and has been exacerbated with an additional 250 claims for unemployment due to earthquake damage (West News, CalEMA, 4-21-10). Governor Schwarzenegger has requested that the President declare a Federal Disaster and preliminary damage estimates by FEMA are being considered. The Federal Small Business Administration declared a disaster on April 21, enabling the issuance of low-interest loans.

However, the extent of damage to the water systems, the ensuing floods in Baja, and the impacts on irrigation and agriculture related to the loss of water transportation through canals particularly in Baja are not fully estimated nor publicly reported at this time. South of the border, 567 km^2 (140,000 acres) of crops including wheat (405 km^2, 100,000 acres), alfalfa (109 km^2, 27,000 acres), cotton (20 km^2, 5,000 acres) and 32 km^2 (8,000 acres) of other crops (including cabbage) could be lost due primarily to failures of water canals that transport water through the arid country from the Colorado River by way of the damaged All American Canal (LaCronica.com; 4-12-2010).

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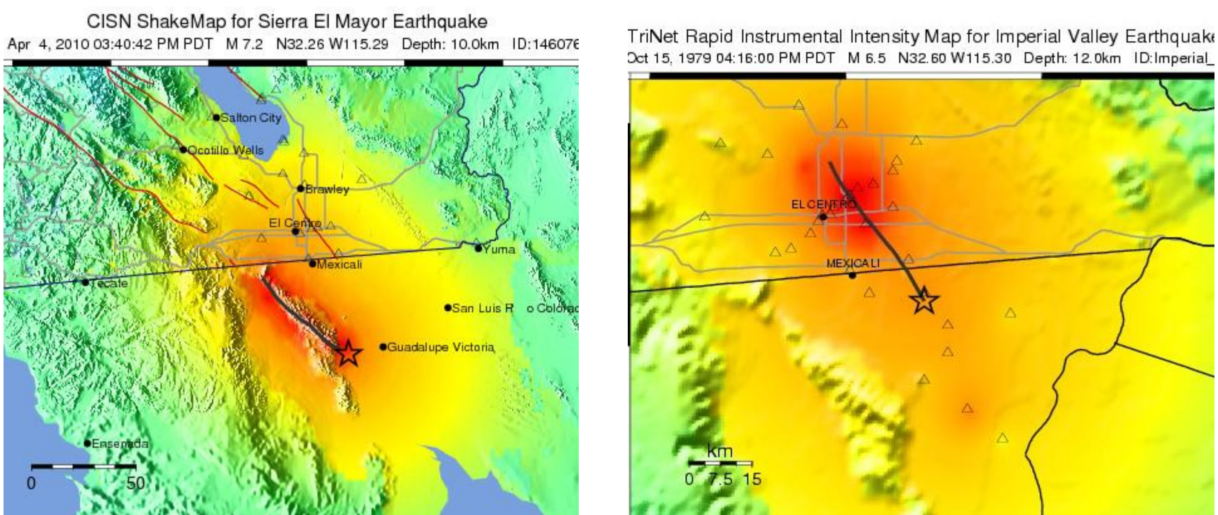
8 COMPARISON OF REGION'S 2010, 1979 AND 1940 EARTHQUAKES

The effects of the border region's three latest significant earthquakes bear many similarities. Both the M 6.9 1940 and M 6.5 1979 earthquakes occurred on the Imperial fault, to the east and north of Mexicali. The 2010 earthquake occurred by crossing over a series of faults, with a strike similar in orientation to the Imperial fault, but to the south and west of Mexicali.

The often-cited El Centro strong-motion record from the 1940 earthquake was recorded in downtown El Centro. Efforts by the USGS and CGS to install instruments in this region and record ground motions have helped revolutionize earthquake engineering worldwide.

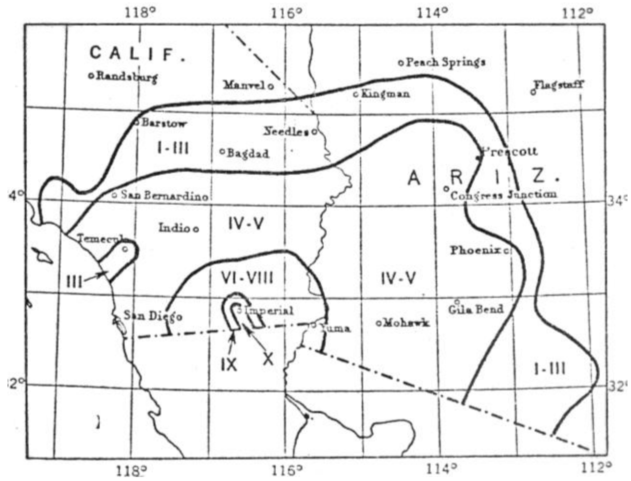
In 1979, the instrumented Imperial County Services building nearly collapsed, providing the world's first comprehensive recording of the response of a severely damaged building. Locations of strong-motion instruments have changed somewhat since then. After the 1940 earthquake, the USGS installed an instrument array perpendicular to the Imperial fault. Remnants of that array recorded ground motions during the 2010 earthquake.

ShakeMaps from the 2010 and 1979 earthquakes and an isoseismal map for the 1940 earthquake for north of the border are provided in Figures 9.1 and 9.2 for comparison.



(a) (b)

Figure 9.1: *Ground shaking intensity map for the region: (a) 2010 event; (b) 1979 event.*



Isoseismals of the Imperial Valley earthquake of May 18, 1940.

Figure 9.2: *Ground shaking intensity maps from the region's 1940 event.*

The 1940 earthquake was believed to cause $5 to 6 million in damage (BSSA, Ulrich, 1940) which is $77 to $92 million in today's dollars. The 1979 earthquake caused an estimated $30 million (EERI, 1980), which is $89 million in today's dollars (CPI Index, Measuringworth.com). The 2010 earthquake is estimated at less than $1 billion.

All three earthquakes significantly damaged irrigation canals, buildings of unreinforced masonry, wood and reinforced concrete, roadways, bridges, and liquid tanks. Mexicali, the largest city in the region, did not report a great amount of damage in 1940 (BSSA), 1979 (EERI 1980) or in 2010. A major hotel in Mexicali was destroyed in a fire caused by the earthquake in 1940. Portions of El Centro suffered severe damage in each of the earthquakes, albeit not generally to the same buildings. Similarly while liquid tanks were damaged in each of the earthquakes the differences in the regions of greatest shaking and the limited life spans of the tanks minimized the opportunity to observe performance to specific sites that experienced damage from more than one earthquake. The cities of Imperial and Brawley were more significantly damaged in the two earlier earthquakes and were generally situated beyond the region of noted damage in 2010.

Nine were killed and 20 seriously injured in 1940. No deaths and 9 serious injuries occurred in 1979 (www.seismic.ca.gov). Two deaths and approximately 100 injuries south of the border as well as 45 injuries requiring hospital visits north of the border were reported in 2010.

The 1980 EERI Reconnaissance Report titled *Imperial County, California, Earthquake, October 15, 1979* was coordinated by Gregg Brandow and is an excellent source of information that assisted the 2010 reconnaissance team greatly. The *Bulletin of the Seismological Society of America* report titled "The Imperial Valley Earthquakes of 1940" by Franklin Ulrich provides an interesting glimpse of earthquake reconnaissance documentation a generation ago.

While there are clear similarities, comparisons between these three earthquakes provide plenty of evidence that future earthquakes are not likely to repeat effects caused by prior earthquakes. The most severe shaking from these three earthquakes impacted lightly populated rural lands. Future earthquakes, particularly those that cause severe shaking in more densely populated areas than these, could result in far greater losses.

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