Learning from Earthquakes

The M_w 7.2 El Mayor Cucapah (Baja California) Earthquake of April 4, 2010

The Earthquake Engineering Research Institute (EERI) coordinated reconnaissance teams in the damaged areas. The California Seismic Safety Commission, Degenkolb, Exponent Failure, GeoHazards International, Hilti North America, JP Singh and Associates, Kleinfelder, Parsons, PSOMAS, Simon Wong Engineers, Tobolski/Watkins, and the University of California San Diego participated in these efforts. The EERI teams worked closely with GEER (Geo-Engineering Extreme Events Reconnaissance). The surface faulting mapping was led by researchers at Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE) in México and at San Diego State University. Geotechnical reconnaissance and mapping was led by researchers at UCLA, the U.S. Geological Survey, and the California Geological Survey.

Support for the reconnaissance was provided by local authorities in Mexicali, including the Department of Civil Protection; State Center of Control, Command, Communication, and Computing; Baja California State Police; SIDUE (Secretary of Infrastructure and Urban Development of Baja California); and CICESE. A complete list of team members is provided at the end of this report.

The research, publication and distribution of this report were funded by the EERI Learning from Earthquakes project, under grant #CMMI-0758529 from the National Science Foundation. Fault rupture and geotechnical engineering aspects reported here are based on GEER studies supported by NSF under Grant #CMMI-1034831.

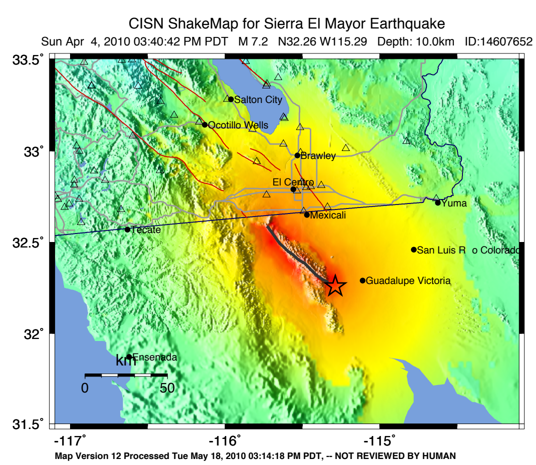
Introduction

On Sunday, April 4, 2010, at 3:40 p.m. local time (22:40:42 UTC), an M_w 7.2 earthquake struck northern Baja California (BC), México, located at 32.259ºN, 115.287ºW at a depth of about 10 km. It was felt throughout Baja California, Southern California, Arizona, and Nevada. The epicenter was approximately 47 km SSE of Mexicali, BC, 51 km SSE of Calexico, California, and 180 km E of San Diego (see Figure 1). This is the largest earthquake in the area since the Laguna Salada quake in 1892.

This brief report describes fault rupture, liquefaction and lateral spread, and the effects of the earthquake on buildings, bridges, water and wastewater systems, nonstructural components, agriculture and the economy. Comprehensive reports on the earthquake by EERI and GEER can be found at http://www.eqclearinghouse.org/20100404-baja/ and http://www.geerassociation.org/Post_EQ_Reports.html, respectively.

Surface Faulting

Surface rupture extends about 100 km from the northern tip of the Gulf of California to the international border and comprises two distinct geomorphologic and structural domains. As shown in Figure 2, the rupture is complex, with breaks along multiple fault strands, including minor re-rupture of the scarps associated with the 1892 Laguna Salada earthquake and several other older events. The southern part of the rupture consists of a zone of distributed fracturing and liquefaction that cuts across the Colorado River delta. Individual fractures vary widely in orientation and have relatively short strike lengths of as small as hundredths of meters. The zone itself may be related to faults that bound the eastern margin of the Sierra El Mayor, but field relationships are unclear, and the zone of more intense fracturing diverges significantly from the mountain front toward the south.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 1. *Distribution of intensities. Star shows location of epicenter (http://earthquake.usgs.gov/earthquakes/eqinthenews/ 2010/ ci14607652/#maps).*

The northern half of the rupture propagated 55 km through an imbricate stack of east-dipping faults in the Sierra Cucapah. In the southern part, the rupture extends 20 km along the Laguna Salada and Pescadores faults, where it reached a maximum displacement of approximately 250 cm of right-lateral strike slip. The amount of dip slip is variable and changes polarity along the Laguna Salada fault before becoming predominantly east-side-down, with maximum offsets of 150 cm along the Pescadores fault. This rupture terminates in the high elevations of the sierra and jumps nearly 10 km north in a left stepover to the Borrego fault. Additionally, the 1892 segment of the northern Laguna Salada fault re-broke with minor (10-30 cm) dip slip along a segment that is adjacent to the primary Borrego rupture.

Figure 3 shows the maximum measured displacement along the Borrego fault in Borrego Valley, which

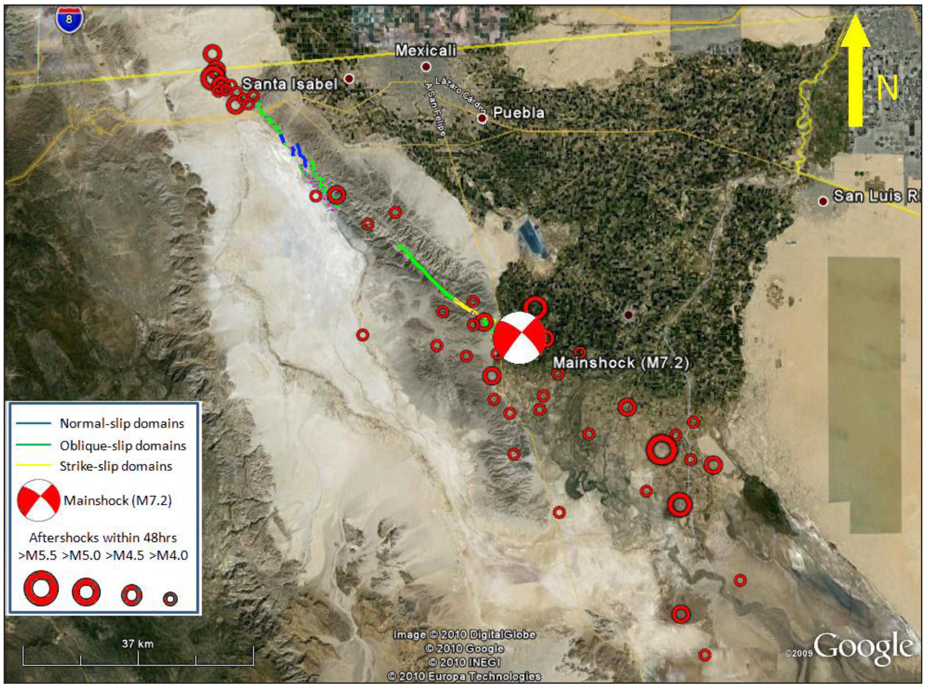


Figure 2. *View of earthquake region showing location of mainshock hypocenter, aftershocks in first 48 hours, and mapped locations of surface rupture (moment tensor and aftershock locations from SCSN web site: http://www.scsn.org/2010sierraelmayor.html).*

was about 3.1 m of strike slip and another 2 m of down-to-the-east dip slip on a nearly vertical fault, yielding oblique slip of nearly 4 m. A low-angle detachment intersects the footwall of the central portion of the Borrego fault at a segment boundary, and rupture bifurcates with a splay that follows the trace of the detachment in a more westerly direction. Over the next 6 km to the north, rupture steps left across a 2-km-wide zone, before finally consolidating on a fault named the Paso Superior and extending an additional 10 km farther north. The Paso Superior fault is well exposed at Highway 2, where it clearly involves a low-angle detachment. Scarps near the fault trace accommodate dip slip, and nearly twice as much strike-slip is spread across a 100-150 m wide zone of cracking and secondary faulting to the east.

Part of the complexity of the rupture can be attributed to interaction with detachment faults that allow the rupture to expand in the near surface. This rupture illustrates the complexity that can develop when a rupture propagates through a network of high- and low-angle faults that accommodate the three-dimensional strain of transtensional plate margin shearing.

Ground Motions

The main event on April 4, 2010, was recorded by 497 strong motion instruments in California (USA) and Baja California (México). The California strong motion instruments are owned and maintained by California Strong Motion Instrumentation Program (CSMIP) and the US Geological Survey, although several smaller networks also operate in the region. The Baja California strong motion instruments, the Red de Acelerografos del Noroeste de México (RANM), are owned and maintained by CICESE.

Strong motion records obtained in California are available at http://www.strongmotioncenter.org and http://gees.usc.edu/ROSRINE/, while records obtained in Baja California are available at http://resnom.cicese.mx/reportes/preliminar/.

The largest peak ground acceleration (PGA) of about 59% g was recorded in El Centro-Array 11, California (RRUP = 21.2 km), and the second largest PGA of about 54% g was recorded in Michoacan de Ocampo MDO station, Baja Califor-

Figure 3. *Panoramic mosaic of the El Mayor-Cucapah earthquake rupture along the Borrego fault in Borrego Valley, Sierra Cucapah, Baja California, México. (photo: Tom Rockwell, photo-stitched by Karl Mueller)*

nia (RRUP = 17.5 km). The ground motion was approximately 2-5% g in the San Diego area and approximately 1% g in the Los Angeles area.

Figure 4a presents the acceleration, velocity, and displacement time histories of the main event recorded at El Centro — Array 11, McCabe School. The PGD and PGV were 53.1 cm and 62.9 cm/sec respectively. Figure 4b presents the acceleration, velocity, and displacement time histories of the main event recorded at MDO station, Baja California. The peak displacement (PGD) and velocity (PGV) for the E-W component were calculated at 32.7 cm and 61.0 cm/sec respectively (Munguia et. al. 2010).

The ground motions recorded at MDO and El Centro 11 stations bear many similarities to recordings from two stations located at almost identical locations on the Imperial Fault during the 1979 Imperial Valley earthquake — the Holtville Post Office (Figure 4c) and El Centro Array 3 (Figure 4d) (Singh 1985).

The main difference is longer durations with long surface wave tails that are a result of a larger magnitude earthquake. Significant long period energy content at an apparent period of 6 to 7 seconds in the Imperial Valley basin is thought to result in part from surface waves generated within the basin (GEER 2010).

The Imperial and Mexicali valleys are soft sediments characterized by values of VS30 of less than 250 m/sec. Displacement and velocity waveforms are rich in long-period motions that are consistent with soft soil deposits and/or basin effects. The seiche effects observed in Fig Lagoon as well as the sloshing of water and sewer tanks and clarifiers in some locations in Imperial Valley were likely amplified by this long-period motion, particularly where sloshing periods coincided with the period of the ground motion. However, due to the lack of

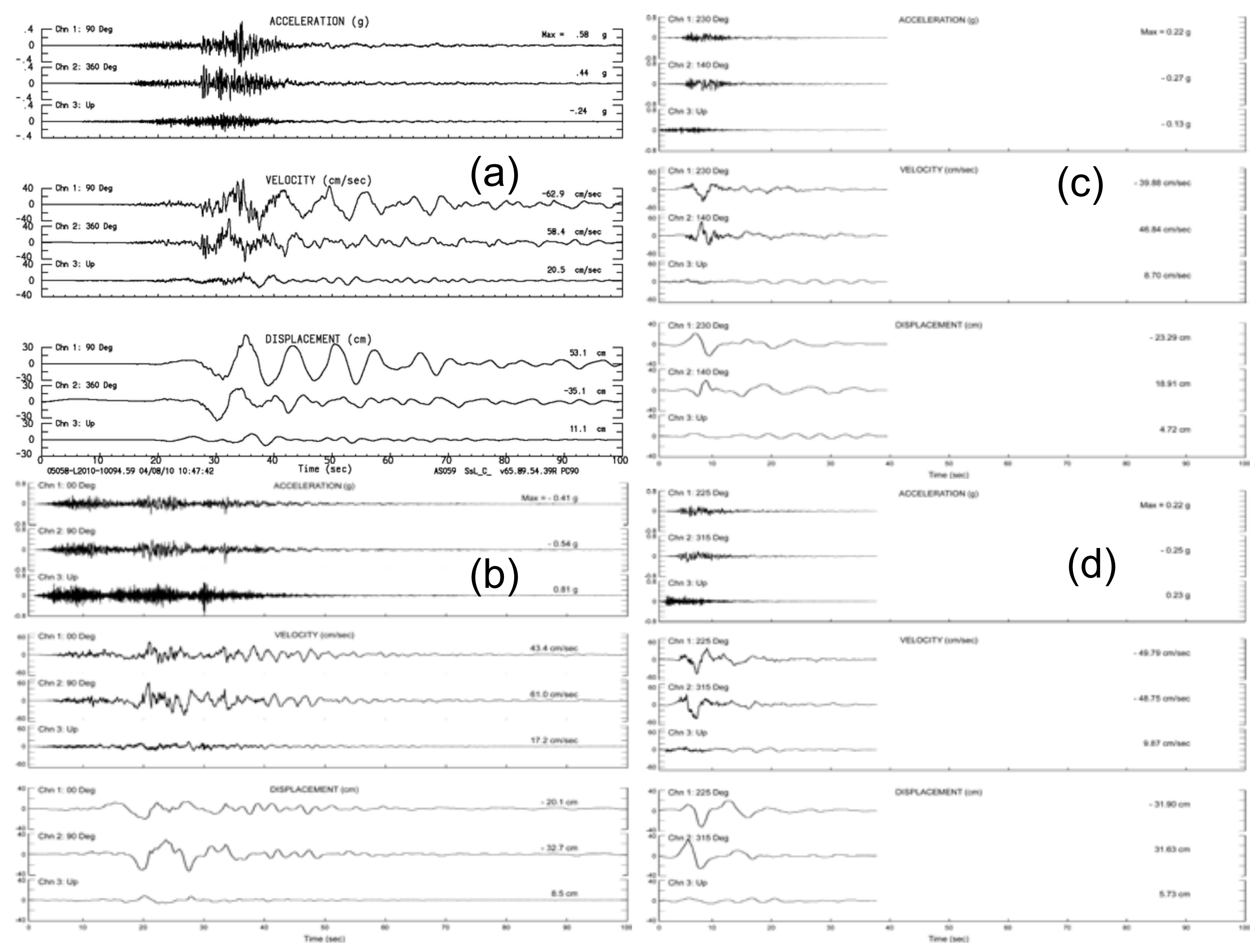


Figure 4. *Ground motions recorded during the 2010 and 1979 earthquakes (a) El Centro Array 11, McCabe School, 2010, California; (b) MDO Station, 2010, Baja California, México; (c) Holtville Post Office, 1979, California; and (d) El Centro Array Station 3, 1979, California.*

Figure 5. *▲ Damage to irrigation canal in Mexicali Valley.*

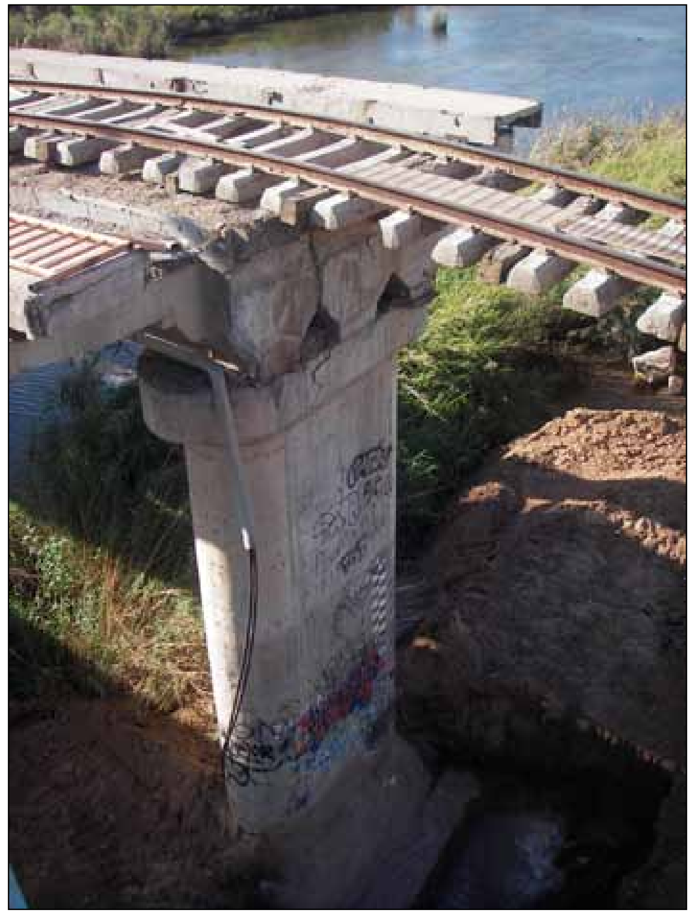


Figure 6. *Unseated span of railway bridge near Guadalupe Victoria.►*

instrumentation throughout the basin, the extent of and variation of this long period response in different locations throughout the valley is not clear.

Perhaps future three dimensional modeling of basin effects as well as the study of the response of long period systems in this earthquake and others could help improve the characterization of these phenomena.

The main event was also recorded at instrumented buildings and bridges in El Centro and San Diego as well as the Los Angeles area. In El Centro, a peak acceleration of about 93% g and a peak displacement of 34 cm were recorded at the roof of the El Centro one-story hospital.

Liquefaction

The geology of the region consists of soft lacustrine and alluvial materials with shallow groundwater in the Mexicali Valley (east of fault rupture), Laguna Salada (west of fault rupture), and Imperial Valley (northeast of faulting). South of the border, liquefaction was widespread, particularly in the largely agricultural Mexicali Valley near the epicenter, where sand boils, lateral spreading, settlement, ground fissures, and flooding were observed. Loose saturated fine sand and non-plastic silts and shallow groundwater contributed to liquefaction. Impacts from liquefaction included topographic warping of the previously flat farmland, and damage to irrigation canals due to settlement, lateral spreading, and ejected sand filling the canals (Figure 5).

Many fields of wheat and hay became submerged due to subsidence and the high ground water table throughout the region. Liquefaction was so widespread throughout the valley that the reconnaissance team could not adequately quantify its extent during the short time it was present. Hence, our observations focused on recording detailed perishable data at a small number of sites of engineering interest.

At parallel bridges that cross the Colorado River approximately 6 km southeast of Guadalupe Victoria, BC, the railway bridge collapsed when a simply supported span was unseated by liquefaction and lateral spreading of surrounding soil (Figure 6); the immediately adjacent and parallel highway bridge did not collapse, but suffered damage due to foundation settlement and strong ground shaking. Ground crack widths were measured along the eastern margin of the flood plain, and the sum of the crack widths was nearly 5 m, indicating significant lateral spreading displacements affecting the bridges.

At a group of buildings and a pedestrian bridge at the Universidad Autónoma de Baja California campus, constructed in the New River flood plain, the buildings and bridge were damaged by liquefaction-induced settlement and some small lateral deformations. The buildings were founded on pile foundations

Figure 7. *Settlement of base slab beneath four-story steel braced frame structure at Universidad Autónoma de Baja California, Facultad de Ciencias Administrativas site.*

that showed no signs of liquefaction-induced settlement, but the floor slab separated from the walls of the building (Figure 7). Liquefaction and lateral spreading also damaged many homes along the Rio Hardy River in the Mexicali Valley to the south of the epicenter.

In the Laguna Salada, a sub-sea-level basin west of Mexicali, the rupture features from the 1892 M_w 7.1 earthquake have been mapped along the eastern side. Earthquake-induced liquefaction from the 2010 quake created sand boils and fissures, bringing water to the surface along the eastern side of the Laguna Salada basin adjacent to the Sierra Cucapah mountain range. Reports from subsequent aftershocks confirmed that additional saline groundwater was brought to the surface, flooding dirt roads along the eastern dry lake basin. The ponding groundwater quickly evaporated and created salt flats.

GEER conducted reconnaissance in the Imperial Valley within one week of the mainshock, concentrating on easily accessed locations along major and minor roads, canals and drains, and the New and Alamo rivers. Liquefaction was most common in the southwest portion of Imperial Valley, though a significant exception was observed northwest of Holtville. Most road closures were associated with crossings of the New River or its tributaries, and were predominantly caused by liquefaction of bridge approach fills and/or the soils underlying the fills. This was the case at Worthington, Drew, and Brockman roads where they cross the New River, and at Brockman Road where it crosses the Greeson Drain. Where Lyons Road crosses the New River, there was liquefaction-induced lateral spreading in natural soils and road fill 100 m east and 200 m west of the bridge, but the bridge structure and approach fills were undamaged.

Most damage to irrigation canals was concentrated on the Westside Main Canal, from its diversion from the All American Canal northeast to Fites Road, approximately 6 km southwest of Brawley. Liquefaction of relatively fine-grained soils was observed at the foundation of the All American Canal aqueduct over the New River. Liquefaction accompanied by lateral spreading on both sides of the Rosita Canal northwest of Holtville disrupted the canal and allowed seepage onto adjacent agricultural fields.

Other notable damage included liquefaction and lateral displacement of the dam embankment and adjoining Drew Road at the west-

Figure 8. (a) ◥ *Liquefaction-related lateral spread of the crest of the Sunbeam Lake Dam (photo: Cindy Pridmore on 4/8/10). (b) ▼ Sinkhole forming on the Sunbeam Lake Dam adjacent to the outlet weir.*

Figure 9. *Breach in Fig Lake levee created by liquefaction-related lateral spread ground failure and settlement.*

ern end of Sunbeam Lake south of Seeley (Figure 8), and liquefaction-induced slump of a levee that allowed overtopping of the levee likely by seiche waves generated in Fig Lagoon (Figure 9). Notable sites that liquefied during the 1979 Imperial Valley earthquake did not show evidence of ground failure in this event, including the Wildlife liquefaction array and the Heber Road site.

Structures

Damage to buildings south of the border was concentrated in the agricultural communities to the south of Mexicali and in older commercial portions of Mexicali. Baja California State Police reported 4,389 residences with major damage (1.3% of the 340,000 buildings) in the Mexicali region, which has a population of over 1 million residents. Most modern homes are concrete frames with clay brick or concrete masonry infill walls; many older homes are built with adobe.

Damage to buildings north of the border was scattered. A population of approximately 90,000 lives in the region of MMI VII-VIII instrumental shaking intensity north of the border. Of the approximately 31,000 buildings in the region, 63 were red tagged (0.2%) out of 431 total buildings that received safety assessments (1.4%). Damage was concentrated in known vulnerable building types such as mobile homes and wood frame dwellings on cripple walls, unreinforced masonry buildings, and multi-unit residential buildings that rely on plaster finishes for earthquake resistance. Several rare older homes constructed with adobe were also moderately damaged.

South of the border: In Mexicali, a five-story concrete shear wall parking structure under construction at the time had floors collapse. It consisted of precast concrete double-tees, spandrels, and columns. A topping slab with dowels was expected to provide out-of-plane anchorage for the perimeter spandrels. The concrete topping had not yet been poured at the outer bays to provide connectivity to the shear walls, and the precast spandrels and columns displaced excessively in the north-south direction; this unseated the double tees from their bearing pads and resulted in collapse of the floors.

At a two-story concrete frame high school in Mexicali, built in 1958, shear cracks developed in the col-

Figure 10*. Short, nonductile concrete column severely damaged in high school building.*

Figure 11. *Soft story apartment with plaster walls in El Centro.*

Figure 12. *Concrete infill with a partial loss of infill brick walls.*

umns 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 exposed concrete inside some of the damaged columns indicated poor concrete quality, i.e., poor consolidation and smooth aggregates (Figure 10). Retrofitted columns performed satisfactorily, but in some cases had damage below jacketed portions. The masonry infills were damaged by a combination of severe diagonal cracks and bed-joint sliding.

The state government decided to delay the return to school for 13,000 students in the 57 schools affected by the earthquake because the climate was too hot for education in tents or mobile classrooms without air conditioning. Officials anticipated reopening schools by the end of May.

At the Universidad Autónoma de Baja California, a two-story building had cracking of the masonry infill, spalling of the stucco-like exterior coating, and spalling of the tile finish. Much damage to exterior finishes was observed in the vicinity of interstory horizontal joints, most likely due to differential horizontal movement.

North of the border: The Cottonwood Circle apartment building in south El Centro has an irregular configuration with a soft and weak story along both axes of the building. It relies on light wood frame walls with plaster finishes to resist earthquake and wind forces (Figure 11). Longitudinal plaster walls on the east side at the north end of the building experienced a residual drift between 1 to 2 inches. The building was reported by neighbors as deteriorating with significant aftershocks, and government officials barricaded it to discourage access to the building's perimeter.

A two-story nonductile concrete frame building in El Centro with unreinforced brick masonry infill walls was severely damaged (Figure 12). Its brick mortar joints had been repaired and one window opening was infilled with concrete masonry units after significant damage in the 1987 Superstition Hills earthquakes (EQE, 1988). The building was also damaged and repaired after the 1940 earthquake (Steinbrugge, NISEE, 1940). Cracks in concrete columns and beam-column joints on three elevations of the building depict a variety of responses of individual components. This building is worth further study regarding the efficacy of prior repairs, particularly since nearby ground motion recordings are available.

Nonstructural Components and Systems

Nonstructural damage was pervasive in the interior of buildings, both in the U.S. (Calexico and El Centro)

Figure 13. *Mexicali campus of UABC: (a) extensive ceiling damage at the Electronics and Computer Laboratory building and (b) damaged CMU infill in the new eastern annex to the Engineering Institute buildings.*

Figure 14. *Typical interior damage to ceilings at the Medical Plaza building in El Centro.*

Figure 15*. Collapse of exterior soffit at Jefferson Elementary School.*

and in México (Mexicali); it caused business closures and significant disruption as well as financial losses. Commonly observed were damaged glazing, ceilings, partition walls, piping systems, HVAC ducts, and other building services equipment. In many instances, building operations were severely hampered or halted due to nonstructural damage alone. One hospital wing in the U.S. and two hospitals in Mexicali were partially evacuated due to nonstructural damage. Schools were widely affected, including a number of elementary schools in Calexico and a university campus in Mexicali.

The Mexicali campus of the Universidad Autónoma de Baja California (UABC) is located approximately 44 km NE of the epicenter of the quake. The university was established in 1957 and has upwards of 16,000 students. In addition to structural damage, extensive nonstructural damage was observed, primarily in the form of ceiling, partition, and contents damage. All but one of 11 buildings on campus were closed, largely due to nonstructural damage. In the rooms of some buildings, over 80% of the ceiling tiles failed (Figure 13a). The buildings were mostly short (typically 2-3 stories) and constructed of masonry block or concrete frame with block infill. Damage to infill walls was also pervasive on the campus (Figure 13b).

The El Centro Regional Medical Center (ECRMC), a community hospital owned by the City of El Centro, has one- and two-story wings, constructed in 1956 and 2003, respectively. A neighboring Medical Plaza building and central plant serve the hospital. Minor nonstructural damage was observed in the main hospital and to its central plant, while the Medical Plaza building (Figure 14) was red tagged largely due to nonstructural damage. Fortunately, no injuries were reported. The ECRMC is an interesting case, as three strong-motion instrumentation stations are located on the complex, one of which recorded a PGA of 0.38g and associated Sa(T=0.3sec) of 1.4g. Despite these rather large accelerations, the hospital performed quite well.

Most modern buildings in Calexico performed well, but in the historic downtown, five blocks were closed following the earthquake due to widespread damage to façades, windows, parapets, plaster, or stucco, and other nonstructural elements. A USGS strong-motion station located at the undamaged

Figure 16. *Fallen light fixtures and ceiling system components.*

Figure 17. *UABC pedestrian bridge strut-connection failure*

Calexico fire station measured a PGA of 0.27g, with the resulting Sa(T=0.3sec) of 0.74g. Buildings in downtown Calexico are predominantly single-story wood with veneer, concrete masonry or brick construction, all with anticipated periods of less than 0.5 seconds.

Jefferson Elementary School in Calexico, constructed in the 1960s, had significant nonstructural damage. Approximately 1200 square feet of exterior plaster ceiling soffits overhanging walkways fell in a progressive fashion (Figure 15). Fortunately, schools were not occupied at the time of the earthquake and no one was injured.

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 16).

Of the 82 public schools in Imperial County, California, many reported minor damage to building contents and nonstructural systems, and took advantage of spring break week to make repairs. Some repairs were complicated by concerns over asbestos.

Bridges

The EERI team observed damage at the pedestrian bridge at UABC, a newly constructed 175-ft. steel arch tied to large diameter concrete piers. At the ends of the superstructure deck, transverse tubular steel struts were designed to provide longitudinal resistance to seismic forces. The end plate of the struts was rigidly connected to the interior face of the piers. All welds of the anchor bolts connecting one strut to the concrete piers had completely fractured. Concrete columns supporting the spiral ramp structure and the anchor bolts were cracked. There was also liquefaction of the soil surrounding the foundation. The fracture may have been caused by excessive longitudinal seismic forces on the strut connections, combined with rotational demands as a result of pier movement in liquefied soil (Figure 17).

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. Sidewalks were also cracked at the piers crossing the centerline of the bridge. Further, hanger rods sloping away from the mid-span at both ends of the bridge, in both planes of hangers, were buckled. These residual deformations are clear indications that the bridge has in fact elongated horizontally between arch pins. It is also apparent that failure of the tie did not result in collapse, and therefore redundant load paths were active.

On Highway 2, about 15 miles west of Mexicali, an overcrossing was damaged. The bridge is a 250-ft. long two-span precast, prestressed (PC/PS) concrete girder bridge on bent cap and round concrete columns supported on drilled shafts. The damage observed included shear key cracking extended into the bent cap, 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.

Figure 18. *Fissure and sand boils in alfalfa field southeast of Cucapah, Baja California, México.*

Figure 19. *El Centro damaged secondary clarifier and well assembly (photo: Jose Angel).*

On Highway 5, many two-span overcrossings had significant approach roadway settlements and partial failures of reinforced embankment soils. These bridges were also recently constructed and have slope paving on the west side, with highly reinforced soils in the east abutment. Most are oriented in the east-west direction. No shear key failures were found, but significant bridge movement and approach settlement were observed in the longitudinal direction due to liquefaction and lateral spread.

The earthquake caused collapse of one span of Puente San Felipito, a railroad bridge over the Colorado River constructed in 1962. It is located approximately 5 miles southeast of Guadalupe Victoria, near the Baja California and Sonora border. The bridge is approximately 650 feet long, spanning the river with multiple spans, including a PC/PS concrete girder supported on concrete piers, with oblong sections supported on piles. Complete unseating of the girders due to both transverse movement of the superstructure and longitudinal pier movement was evident. The superstructure did not have any shear keys or any sizable anchorage to restrain lateral or longitudinal movements relative to the piers.

Water and Wastewater Systems

The quake damaged water and wastewater treatment plants, irrigation canals, and the encasement of the New River. In the Imperial Valley, damage to earthen canals, apparently related to lateral spreading and liquefaction, was widespread but not severe, with the exception of the All American Canal crossing of the New River. No significant damage to drainage systems for farms has been reported. In the Mexicali Valley, there was widespread damage to irrigation canals, fields, and towns due to ground failures and earthquake-related flooding. Portions of the area were inundated with water from liquefaction-induced sand boils, some of it reportedly saline, sulfurous, or otherwise contaminated. Localized sections of roads, fields, and towns were also inundated with water from overflowing canals.

Liquefaction and lateral spreading caused cracking, settlement, and slumping of unreinforced concrete-lined irrigation canals (refer back to Figure 5). The Baja California government initially estimated that 57 km of major canals, 350 km of minor canals, and 380 km of drainage channels were damaged.

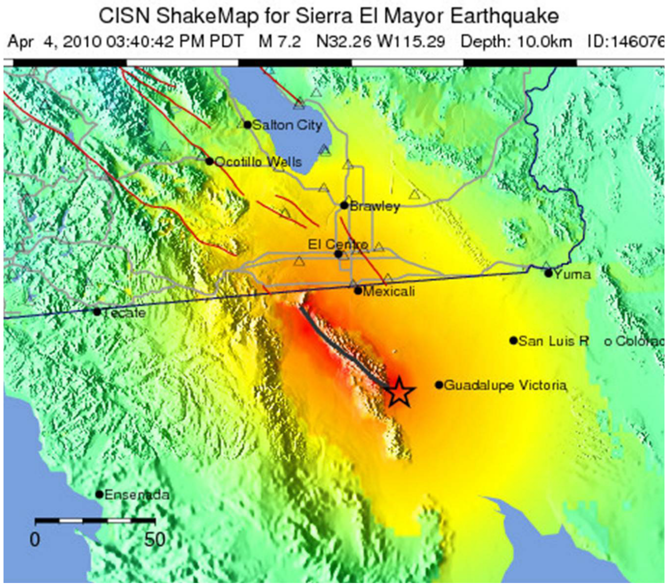
Many crops in the fields at the time of the earthquake, predominantly wheat and alfalfa but also cabbage and newly planted cotton, were wilting due to lack of irrigation and are likely to be lost for this season. In addition, massive sand boils and sand sheets blanketed portions of fields, and large-scale lateral spreading created scarps and fissures that crossed fields (Figure 18). The Baja California government reported that the earthquake also caused permanent regional ground tilting, which will disrupt gravity-controlled irrigation.

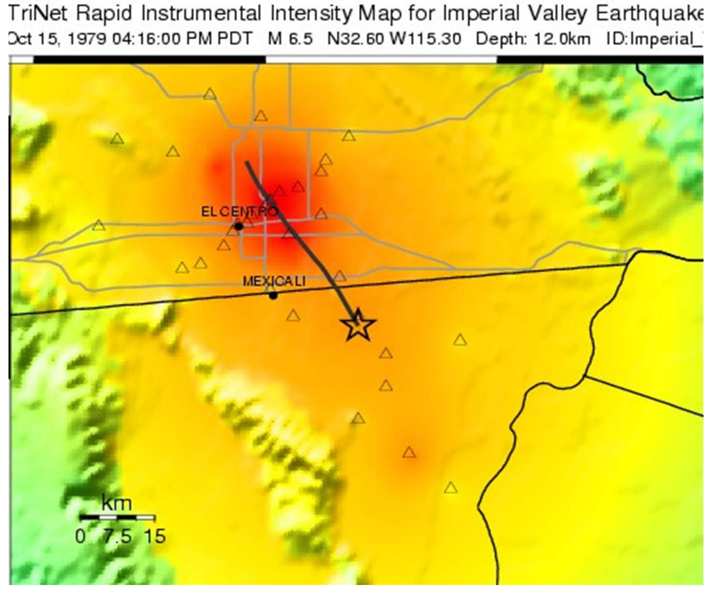
The extensive damage in the agricultural portion of the Mexicali Valley may be an indicator of future earthquake impacts in some agricultural and levee-protected areas in seismically active areas of the U.S.

Damage to water systems in Mexicali may have contributed to the increase in flow of the New River where it crosses into California, but as of May 12, 2010, the extent of direct and indirect damage to farmlands in the Imperial Valley had not been consolidated. On April 14, representatives from the Imperial Irrigation District (IID) discovered that there was leakage between the northern headworks and the spillway adjacent to the All American Canal siphons crossing the New River, downstream from the Calexico wastewater treatment plant.

The siphons are a critical component of the canal, since they allow water to cross the New River to supply the IID with water for the western one-third of its coverage area. The siphons were in operation during the 1979 Imperial Valley earthquake, but were not reported to have been damaged. There was significant damage to earthen canals in the 1979 quake, where the Imperial fault crossed the canal.

Due to the potential loss of water for the communities of Westmoreland, Brawley, and 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 (USACOE) inspect the





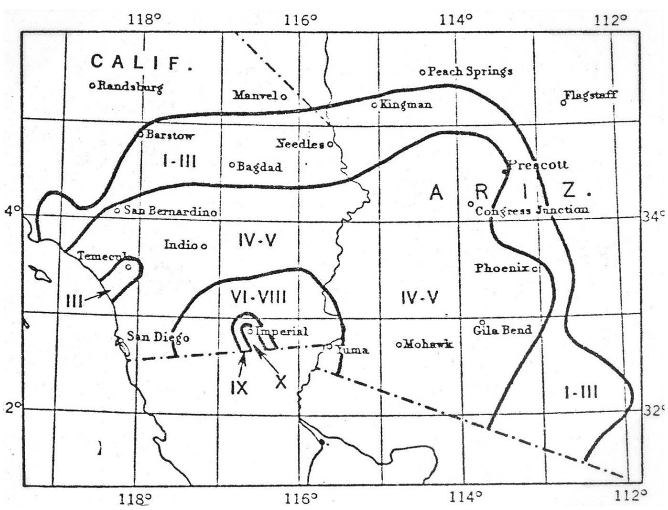


Figure 20. Ground shaking intensity maps from three significant earthquakes in the region: above left 2010; above right 1979; bottom left 1940.

headworks and spillway area on April 14. At the time of this writing, the extent of the damage as well as the scope of the repairs, their cost, and time required to make repairs on the canals are not known.

In Calexico, the wastewater treatment plant had damage to a 36-inch diameter inlet feeder line that crossed the New River 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 9. There was also damage to primary and secondary clarifiers, lagoons, and berms (lateral spreading), and sludge beds. Three water storage tanks were also damaged; they varied in age from 60 to five years old, and in capacity from 1 million to 4 million gallons. The plant production capacity was down 50% after the earthquake. The lack of water treatment capacity for the upcoming summer months is a concern, since water usage is significantly increased beyond spring water usage.

At the El Centro wastewater treatment plant, there was structural damage to one primary clarifier and to two secondary clarifiers. The baffles of the primary clarifier were sheared off of the clarifier and broke. The clarifier also had some relatively superficial small cracks. The center well of the secondary clarifier No. 2 was twisted (Figure 19). The center column of the secondary clarifier No. 3 dropped about 5 inches. There is structural damage to the concrete walkways and inspection bridges of the aeration tanks. Interestingly, the damage to one of the clarifiers was similar to that reported in the 1979 Imperial County M_w 6.5 earthquake.

Economic Losses

As of May 8, 2010, the Baja California State Police estimated US$425 million in direct losses south of the border. As of April 21, CalEMA estimated $91 million north of the border. However, the extent of damage to the water systems, the ensuing floods in Baja California, and the impacts on agricultural irrigation, particularly in Baja California, are not fully estimated at this time. The loss of farming capacity south of the border could cause long-term economic disruption to the region, both north and south of the border. The unemployment rate in Imperial County, California, before the earthquake was 27%, and an additional 250 claims for unemployment due to earthquake damage had been received by April 21, 2010.

Preliminary Conclusions

The border region's five most recent significant earthquakes have many similarities. Both the M6.9 1940 and M6.5 1979 earthquakes struck on the Imperial fault, northeast of Mexicali. Two strong earthquakes (M6.2 and 6.6) struck in 1987 to the northwest in the Superstition Hills. The 2010 earthquake crossed over a series of faults southwest of Mexicali, with a strike similar in orientation to the Imperial fault. ShakeMaps from the 2010 and 1979 earthquakes and an isoseismal map for the 1940 earthquake (north of the border) are provided in Figure 20.

The 1940 earthquake was believed to have caused $5 to 6 million in damage (Ulrich 1940) — $77-$92 million in today's dollars. The 1979 earthquake caused an estimated $30 million (EERI 1980) — $89 million in today's dollars (CPIIndex Measuringworth.com). Nine were killed and 20 seriously injured in 1940 (Ulrich 1940). No deaths and nine serious injuries were reported in 1979 (EERI 1980). In 2010, two deaths and approximately 100 injuries were reported south of the border, and there were 45 injuries requiring hospital visits north of the border.

However, while there are similarities, there is plenty of evidence that future earthquakes may differ in their effects. In 2010, the most severe shaking was focused on lightly populated rural and desert areas. Future earthquakes may shake more densely populated areas, and could cause more casualties, larger damage, and much greater economic losses. Most structures behaved as expected for the level of earthquake intensity, exhibiting some damage but not collapse. Nonetheless, the damage indicates the need for attention in the following areas:

1) improvement and development of low-cost foundation systems for structures on liquefiable soil;
2) seismic design of nonstructural components, particularly in hospitals and schools;
3) better seismic design of water and wastewater systems; and
4) better design of irrigation canals in important agricultural regions with high seismic risk.

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Acknowledgments

Earthquake reconnaissance offers great opportunities to develop and refine current seismic design methodologies. However, this work is challenging and risky in terms of access and guidance to sites of interest in unknown territory. Without local support from individuals and organizations in México, our reconnaissance efforts would not have been possible. The list of those who assisted us is too long to include in this brief report, but can be found on the following web pages: http://www.eqclearinghouse.org/20100404-baja/ and http://www.geerassociation.org/Post_EQ_Reports.html.

The EERI Reconnaissance Report on the 1979 Imperial Valley quake is an excellent source of information and was very instructive for the 2010 reconnaissance team. "The Imperial Valley Earthquakes of 1940," by Franklin Ulrich, was also helpful and provides an interesting glimpse of earthquake reconnaissance documentation prior to EERI's studies.

All photos by team members unless otherwise noted.

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