Earthquake Reconnaissance and Effects on Structures

(Part 4/4)

Materials in this presentation are reproduced/compiled directly from available on-line resources. These include:

- U.S. Geological Survey Earthquake Hazards Program;
- U.S. Geological Survey Photographic Library;
- National Information Service for Earthquake Engineering;
- NISEE - The Earthquake Engineering Online Archive;
- NOAA National Geophysical Data Center;
- Geotechnical Extreme Events Reconnaissance, GEER;
- The Virtual Museum of the City of San Francisco;
- Federal Emergency Management Agency (FEMA) Library;
- Idriss, I.M. and Boulanger, R.W., 2008. ”Soil Liquefaction During Earthquakes”, EERI, MNO-12;
- The Canadian Association for Earthquake Engineering;
- Risk Management Solutions, Inc.; and

A complete list of References is included at the end of this presentation.
An office building with a partially destroyed first floor. The majority of partial or complete collapses were in the older, reinforced concrete buildings built before 1975. However, significant non-structural damage was also observed for buildings of relatively recent steel or composite construction.

Material reproduced/compiled from: NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/hazard/earthqk.shtml)
1995 Hanshin-Awaji (Kobe) Japan Earthquake

January 17, 1995 – 5:46 AM local time, Magnitude 6.9

- The Hanshin-Awaji Earthquake happened exactly one year to the day after the Northridge Earthquake.

- 5,502 people confirmed killed, 36,896 injured and extensive damage in the Kobe area and on Awaji-shima.

- Over 90 percent of the casualties occurred along the southern coast of Honshu between Kobe and Nishinomiya.

- At least 28 people were killed by a landslide at Nishinomiya.

- About 310,000 people were evacuated to temporary shelters.

- Over 200,000 buildings were damaged or destroyed.

- Numerous fires, gas and water main breaks and power outages occurred in the epicentral area.

- Right-lateral surface faulting was observed for 9 kilometers with horizontal displacement of 1.2 to 1.5 meters in the northern part of Awaji-shima.

- Liquefaction also occurred in the epicentral area.
1995 Hanshin-Awaji (Kobe) Japan Earthquake

Collapse of a span of the Nishihomiya Bridge on the new Harbor Expressway.
1995 Hanshin-Awaji (Kobe) Japan Earthquake

Damages in cities and suburbs

- One in five of the buildings in the worst-hit area were completely destroyed (or rendered uninhabitable).
- About 22% of the offices in the central business district were rendered unusable, and over half of the houses in that area were deemed unfit to live in.
- High rise buildings that were built after the modern 1981 building code suffered little; however, those that were not constructed to these standards suffered serious structural damage.
- Most of the older traditional houses had heavy tiled roofs which weighed around 2 tons, intended to resist the frequent typhoons that plagued Kobe, but they were only held up by a light wood support frame. When the wood supports gave way, the roof crushed the unreinforced walls and floors in a "pancake" collapse.

A residential garage collapsed in Kobe. In general, heavy tile roofs were inadequately supported, and many collapsed.

Photo Credit: NOAA National Geophysical Data Center
(http://www.ngdc.noaa.gov/hazard/earthqk.shtml)

1995 Hanshin-Awaji (Kobe) Japan Earthquake

Damages in cities and suburbs

• Newer homes have reinforced walls and lighter roofs to avoid this, but are more susceptible to typhoons.
• The extent of the damage was much greater than in the similar-magnitude Northridge earthquake in Los Angeles, which occurred exactly one year earlier.
• The difference was in part due to the type of ground beneath Kobe and the construction of its buildings (e.g. many unreinforced masonry buildings collapsed).
• The immediate population bases of the two areas (Kobe area and San Fernando Valley of Los Angeles) were roughly the same – about 2 million; however, only 72 people died in the Northridge quake, compared to the more than 6,000 in Kobe.

A completely destroyed apartment complex. Most of the 1.5 million residents of Kobe were asleep at the time of the quake. It is estimated that if the earthquake had occurred during the work day instead of at 5:46 A.M., the death toll would have been more than 50,000.

Photo Credit: NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/hazard/earthqk.shtml)
1995 Hanshin-Awaji (Kobe) Japan Earthquake

An office building in Kobe. Many buildings were out of plumb, or leaning. This was usually caused by partial collapse of a floor on one side of the building, or by permanent offset of the structural system.

Collapsed walkway between two buildings. The lower walkway remains intact and the glass in the windows remains unbroken.

Material reproduced/compiled from: NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/hazard/earthqk.shtml)
This collapsed building is typical of many residential dwellings that collapsed, leading to the majority of deaths.

There were two types of residential construction:

- Shinkabe, the oldest type, consists of a post-and-beam vertical load-carrying system. Mud-infilled, two-way bamboo latticed exterior and interior walls provide lateral resistance.
- In Okabae, a more recent style, thin, timber lath and stucco, replaces the bamboo lattice and mud. Both types of construction are highly vulnerable to earthquakes.

Many second floor residences had shops with open windows on the first floor. This made them vulnerable to collapse of the ground floor. Widespread dry rot and wood decay accelerated the failure of load-bearing elements.
1995 Hanshin-Awaji (Kobe) Japan Earthquake

Hanshin Expressway - Pier #142, the last of the failed section, showing splice failures and a change of superstructure to steel box girders at pier #143 (from Kawashima).

Material reproduced/compiled from: http://nisee.berkeley.edu/jpg/6317_3071_0981/IMG0031.jpg
1995 Hanshin-Awaji (Kobe) Japan Earthquake

The fifth floor totally collapsed on this high rise in the commercial section of Kobe.

Many buildings had either a collapsed first or fifth floor. Such floor failures often occurred in buildings that appeared from the outside to have floors of equal strength and identical construction.

A completely destroyed concrete frame office building. Such collapses blocked streets, making it difficult for firefighters to extinguish flames.

Only a minimal number of firefighters were on duty at 5:46 A.M. when the earthquake occurred.

Three hours after the earthquake there were at least 150 significant, simultaneous fires in the city.

The only water available at this time came from tanker trucks.

Material reproduced/compiled from: NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/hazard/earthqk.shtml)
1995 Hanshin-Awaji (Kobe) Japan Earthquake

Air view of damaged quay walls and port facilities on Rokko Island. Quay walls have been pushed outward by 2m to 3m with depressed areas called graben 3m to 4m deep forming behind the walls. Local lateral spreading of soils occurred along quay walls in many parts of the extensive port facilities.

Damage to the pier and waterfront. Widespread ground failure was observed throughout the strongly shaken region along the margin of Osaka Bay. Liquefaction caused subsidence in the range of 50 to 300 cm in some areas; large volumes of silt were ejected.

1995 Hanshin-Awaji (Kobe) Japan Earthquake

• As a result, the event instigated many new research programs in all aspects of earthquake engineering, seismology, and disaster management both in Japan and around the world.

• The earthquake illustrated the importance of hazard mitigation for complex urban environments dependent upon a sophisticated array of transportation, communication, and infrastructure systems.

• It also illustrated how the degree of damage clearly differs depending upon a combination of hazard, exposure, and vulnerability and the need for more probabilistic approaches to risk assessment.

Collapsed Hanshin expressway

Photo Credit: http://www.ce.washington.edu/~liquefaction/html/quakes/kobe/kobe.html

1995 Hanshin-Awaji (Kobe) Japan Earthquake

- It was also the first real test of Japan’s post-1981 building code. The structures built to this newer code generally performed well. Code changes enacted in the early 1980s prohibited the use of non-ductile reinforced concrete structures in favor of ductile reinforced concrete structures.

- These newer structures provided greater flexibility, allowing structures to withstand the strong ground shaking levels experienced in Kobe.

Damaged building in Kobe

Photo Credit:
http://web.ics.purdue.edu/~braile/edumod/eqphotos/eqphotos2.htm
1995 Hanshin-Awaji (Kobe) Japan Earthquake

- Design standards to prevent soft story failures were reviewed and revised. Moreover, the detailing, material strength, and hardware requirements, as well as the foundation and shear wall design for wooden buildings have also been significantly improved.

- To enhance overall construction quality, interim construction inspections are now required for all new buildings, in addition to the construction completion inspections that were enforced prior to 1998.

- And, as of late 1995, all pre-1981 buildings in public use must have a seismic evaluation and retrofits are required if needed.

Badly damaged houses in Nada-Wara, the worst effected area from the Hanshin earthquake in Kobe.


In 1985, Professor Robert V. Whitman from the Massachusetts Institute of Technology convened a workshop on behalf of the National Research Council (NRC) in which thirty-six experts and observers thoroughly reviewed the state-of-knowledge and the state-of-the-art for assessing liquefaction hazard. That workshop produced a report (NRC, 1985) that has become a widely used standard and reference for liquefaction hazard assessment. No general review or update of the simplified procedures has occurred since that time.

Port and wharf facilities are often located in areas susceptible to liquefaction, and many have been damaged by liquefaction in past earthquakes. Most ports and wharves have major retaining structures, or quay walls, to allow large ships to moor adjacent to flat cargo handling areas. When the soil behind and/or beneath such a wall liquefies, the pressure it exerts on the wall can increase greatly - enough to cause the wall to slide and/or tilt toward the water.

As illustrated here, liquefaction caused major damage to port facilities in Kobe, Japan in the 1995 earthquake.

1996 NCEER Workshop

- The purpose of the 1996 workshop, sponsored by the National Center for Earthquake Engineering Research (NCEER), was to convene a group of experts to review recent developments and gain consensus on further corrections and augmentations to the liquefaction assessment procedure.

- Emphasis was placed on new developments since the NRC review. To keep the workshop focused and the content tractable, the scope was limited to procedures for evaluating liquefaction resistance of soils under level to gently sloping ground.

- In this context, liquefaction refers to the phenomena of seismic generation of large pore-water pressures and consequent severe softening of granular soils. Post-liquefaction phenomena, such as soil deformation and ground failure, although equally or more important than triggering, were beyond the scope of the workshop.

- The workshop prepared a summary report, which is still the referenced procedure in current design codes (e.g. ASCE/SEI 7, Section 11.8).
1999 Izmit & Düzce, Turkey Earthquakes

Collapsed building in Düzce. Note the failed beam/column connections in the foreground, the unbroken pane of glass in the window frame on the ground, and the building that still stands in the background. The street has been cleared of rubble.

Material reproduced/compiled from: NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/hazard/earthqk.shtml)
1999 Izmit & Düzce, Turkey Earthquakes

August 17, 1999 – 3:01 AM local time, Magnitude 7.6

- The epicenter of the Izmit earthquake was about seven miles southeast of the city of Izmit, Turkey.
- The earthquake originated at a depth of about 10.5 miles and caused right-lateral strike-slip movement on the fault.
- Preliminary field reports confirm this type of motion on the fault, and initial field observations indicate that the earthquake produced at least 37 miles of surface rupture and right-lateral offsets as large as almost nine feet.
- At least 17,118 people killed, nearly 50,000 injured, thousands missing, about 500,000 people homeless and estimated 3 to 6.5 billion U.S. dollars damage in Istanbul, Kocaeli and Sakarya Provinces.

There were probably four or five buildings of five or six story height in this area of Yuzbasilar. Looking at the debris, they seem to have been fully occupied at the time of the quake. Most deaths occurred in these situations.

Photo Credit: NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/hazard/earthqk.shtml)
Izmit Earthquake – Four identical buildings at Halidere. Only one of the structures failed. The failure was probably due to unconsolidated slope soils.

Izmit Earthquake – The ground floor of this brick infill building was occupied. Note how the concrete in two of the columns has disintegrated. The rest of the columns were able to carry the redistributed load.

Material reproduced/compiled from: NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/hazard/earthqk.shtml)
1999 Izmit & Düzce, Turkey Earthquakes

November 12, 1999 – 6:57 PM local time, Magnitude 7.2

- Duzce lies on the eastern fringe of the region hit by the August 17 quake. Some areas experienced a one-two punch from the 1999 earthquakes. The death toll from the November quake was reported to be 260 people. More than 1,282 were injured and at least 102 buildings were destroyed.

Many partial collapses of structures occurred due to a soft lower story collapse on only one side of the building.
1999 Izmit & Düzce, Turkey Earthquakes

Düzce Earthquake - A close up of the support columns of a five-story building. The support columns had steel reinforcing that was smooth but appeared adequate in thickness, spacing, and number. The horizontal stirrups had evidently unwrapped during earthquake shaking, permitting the columns to fail in compression.

Düzce Earthquake - The northern wing of the Duzce hospital, after the November earthquake. This part of the hospital incurred significant damage in the August earthquake. The structure was judged to be unsafe. The November earthquake resulted in further collapse. This type of collapse is called pancaking and results from inadequate support of heavy overlying floors.

On the day of the earthquake, 500 patients were evacuated, and a nurse was killed.

Material reproduced/compiled from: NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/hazard/earthqk.shtml)
1999 Izmit & Düzce, Turkey Earthquakes

It is generally acknowledged by site-visit teams from many countries, including experts in Turkey, that the prime factor that led to poor structural performance was the inadequate and sometimes nonexistent regulatory enforcement of both design and construction. (http://www.caee.uottawa.ca/Publications/LessonFromPreviousEQs/PDFFiles/Kocaeli1.pdf)

Collapsed reinforced concrete frame with hollow-brick infill buildings that were under construction. The one on the left was a 4-story building. The building on the right was a 7-story structure in which the columns supporting the floors failed and the structure pancaked.

Material reproduced/compiled from: NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/hazard/earthqk.shtml)
Fault scarp on street with four meters of vertical offset. Note the height of the basketball hoop. Note apparently undamaged structures on the left on the raised portion of the fault.

Material reproduced/compiled from: NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/hazard/earthqk.shtml)
1999 Taiwan Earthquake

September 21, 1999 – 1:47 AM local time, Magnitude 7.6

- At least 2,297 people killed, 8,700 injured, 600,000 people left homeless and about 82,000 housing units damaged by the earthquake and larger aftershocks.
- Damage estimated at 14 billion U.S. dollars. Half of a village was lost by subsidence into the Ta-an Hsi and landslides blocked the Ching-shui Hsi, creating a large lake.
- Two other lakes were created by substantial ground deformation near the epicenter.
- Surface faulting occurred along 75 km of the Chelungpu Fault.

Oblique view of the damaged ShihKang Dam near Fengyuan.

The fault goes directly under the damaged portion of the dam.

The dam was 50 km from the epicenter.

The severe damage to the dam cut off the water supply from the reservoir.

Photo Credit: NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/hazard/earthqk.shtml)

Material reproduced/compiled from: http://ngdc.noaa.gov/hazardimages/event/show/50
About one out of every five-corner buildings was severely damaged by the earthquake. This could be attributed to a combination of "soft story" and "torsional" effects. It is common that buildings along major streets have stores set up on the first floor. There are only slender columns at the front of the building at the ground floor. Local engineers referred to this type of building as "soft leg shrimp." The corner buildings have columns on two adjacent sides and walls on the other two sides. Thus, torsional effects would put significant additional shear on these columns.

Material reproduced/compiled from: NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/hazard/earthqk.shtml)
1999 Taiwan Earthquake

Partially collapsed 15-story high-rise building. Building was constructed of reinforced concrete with infill brick partitions. There was beam column joint failure at the façade and the first floor collapsed in the right section of the building.

Material reproduced/compiled from: NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/hazard/earthqk.shtml)
1999 Taiwan Earthquake

Fengyuan Cemetery after the earthquake. Ancestors had to be reburied after the bodies were expelled from their graves by the earth shaking. This is a common phenomenon in large earthquakes. Note fault offset on the drainage ditch in the foreground.

One of the spectacular vertical offsets along the fault has formed a new waterfall in the Tachia River northeast of Fengyuan. The new waterfall has an 8-meter vertical fault offset.

Material reproduced/compiled from: NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/hazard/earthqk.shtml)
Earthquake Reconnaissance and Effects on Structures

2001 Nisqually Earthquake

Brick wall failure at the roof level

2001 Nisqually Earthquake

August 172, 1999 – 3:01 AM local time, Magnitude 7.6

- The preliminary mechanism for this earthquake is tensional (normal) faulting in the subducting (downgoing) Juan de Fuca Plate, caused by bending of the plate.
- This earthquake is located in the same general area as a magnitude 7.1 earthquake on April 13, 1949.
- About 400 people were injured and major damage in the Seattle-Tacoma- Olympia area.
2004 Sumatra-Andaman Islands Earthquake

A village near the coast of Sumatra lays in ruin after the Tsunami that struck South East Asia.

2004 Sumatra-Andaman Islands Earthquake

December 26, 2004 – 7:58 AM at epicenter, Magnitude 9.1

- The devastating earthquake occurred as thrust-faulting on the interface of the India plate and the Burma plate. In a period of minutes, the faulting released elastic strains that had accumulated for centuries from ongoing subduction of the India plate beneath the overriding Burma plate.

- In total, 227,898 people were killed or were missing and presumed dead and about 1.7 million people were displaced by the earthquake and subsequent tsunami in 14 countries in South Asia and East Africa. (In January 2005, the death toll was 286,000. In April 2005, Indonesia reduced its estimate for the number missing by over 50,000.)

Banda Aceh, Indonesia is a city with a population of about 300,000 inhabitants before the tsunami. It was subjected to damaging forces of not only the tsunami but also the earthquake. Coastal areas were entirely swept away by tsunami waves, leaving piles of timber as the remains of building infrastructure. A large number of non-engineered reinforced concrete buildings suffered structural damage, especially in their first floor columns. Multi-story engineered reinforced concrete government buildings suffered seismic damage due to poor seismic design and detailing practices.

2004 Sumatra-Andaman Islands Earthquake

December 26, 2004 – 7:58 AM at epicenter, Magnitude 9.1

- The tsunami caused more casualties than any other in recorded history and was recorded nearly world-wide on tide gauges in the Indian, Pacific and Atlantic Oceans. Seiches were observed in India and the United States.
- Subsidence and landslides were observed in Sumatra.
- A mud volcano near Baratang, Andaman Islands became active on December 28 and gas emissions were reported in Arakan, Myanmar.

Nai Thon Beach on the island of Phuket, suffered extensive structural and non-structural damage to reinforced concrete frame buildings. The water height was in excess of 10 m, especially in areas between the shore and the nearby hilly terrains, which led to water run-ups.

In Thailand, there were many low to mid-rise reinforced concrete frame building which appeared to have been well engineered. These frame buildings survived the tsunami pressure without structural damage, though they suffered damage to non-structural elements, especially the first story masonry walls.

Numerous reconnaissance groups reported there was no seismic damage observed in Thailand.
Non-engineered and engineered reinforced concrete frame buildings formed the majority of building stock in Banda Aceh, Indonesia.

There was no new lesson learned from the earthquake, but many of the seismic deficiencies of buildings, known to cause poor structural performance, were clearly visible throughout the city.

Most of the reinforced concrete frame buildings, which appeared to have been engineered, had strong and relatively deep beams supported by smaller size columns.

Therefore, hinging of columns was widespread throughout the area while the majority of the beams remained elastic until the collapse of the structure, triggering overall stability failures of frames.

M9.0 Sumatra - Andaman Islands Earthquake of 26 December 2004
2010 Haiti Earthquake

Damage in Port-au-Prince, Haiti

Material reproduced/compiled from: NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/hazard/earthqk.shtml)
2010 Haiti Earthquake

January 12, 2010 – 4:53 PM local time, Magnitude 7.0

- The January 12, 2010, Haiti earthquake occurred in the boundary region separating the Caribbean plate and the North America plate. This plate boundary is dominated by left-lateral strike slip motion and compression, and accommodates about 20 mm/y slip, with the Caribbean plate moving eastward with respect to the North America plate.
- The earthquake epicenter was located immediately west of the city of Port-au-Prince, and the damage induced by this event was extreme.
- According to official estimates, 316,000 people killed, 300,000 injured, 1.3 million displaced, 97,294 houses destroyed and 188,383 damaged in the Port-au-Prince area and in much of southern Haiti. Other estimates suggest substantially lower numbers of casualties, perhaps as low as fewer than 100,000.

Haitians rummage through a school in the slum of Cité Soleil, near Port-au-Prince, collapsed by a violent earthquake that struck the area on 12 January.
Earthquake Reconnaissance and Effects on Structures

2010 Haiti Earthquake

Estimated Population Exposed to Earthquake Shaking

<table>
<thead>
<tr>
<th>ESTIMATED POPULATION EXPOSURE (x1000)</th>
<th>I</th>
<th>II-III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
<th>VIII</th>
<th>IX</th>
<th>X+</th>
</tr>
</thead>
<tbody>
<tr>
<td>7,090k*</td>
<td>6,303k</td>
<td>777k</td>
<td>749k</td>
<td>1,884k</td>
<td>710k</td>
<td>137k</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**PERCEIVED SHAKING**
- Not felt
- Weak
- Light
- Moderate
- Strong
- Very Strong
- Severe
- Violent
- Extreme

**POTENTIAL DAMAGE**
- Resistant Structures: none
- Vulnerable Structures: none

Estimated exposure only includes population within the map area.

Population Exposure per ~1 sq. km from Landsat

Selected City Exposure

<table>
<thead>
<tr>
<th>MMI City</th>
<th>Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petit Goave</td>
<td>10k</td>
</tr>
<tr>
<td>Leogane</td>
<td>12k</td>
</tr>
<tr>
<td>Grand Goave</td>
<td>5k</td>
</tr>
<tr>
<td>Carrefour</td>
<td>442k</td>
</tr>
<tr>
<td>Gressier</td>
<td>4k</td>
</tr>
<tr>
<td>Miragoane</td>
<td>6k</td>
</tr>
<tr>
<td>Port-au-Prince</td>
<td>1,235k</td>
</tr>
<tr>
<td>Delmas 73</td>
<td>338k</td>
</tr>
<tr>
<td>Verrettes</td>
<td>49k</td>
</tr>
<tr>
<td>Santo Domingo</td>
<td>2,202k</td>
</tr>
</tbody>
</table>

Bold cities appear on map.

2010 Haiti Earthquake

Damage to the City Hall in Port-au-Prince, Haiti

2010 Haiti Earthquake


Ruins of downtown Port-au-Prince following the earthquake.

Destroyed building in Port-au-Prince, Haiti
2010 Haiti Earthquake

Lateral spreading adjacent to the collapsed North wharf at the main port in Port-au-Prince

Submerged 15-m gauge container crane (foreground) and mobile crane (background).

2010 Chile Earthquake

2010 Chile Earthquake

February 27, 2010 – 3:34 AM local time, Magnitude 8.8

- At least 523 people killed, 24 missing, about 12,000 injured, 800,000 displaced and at least 370,000 houses, 4,013 schools, 79 hospitals and 4,200 boats damaged or destroyed by the earthquake and tsunami in the Valparaiso-Concepcion-Temuco area.

- At least 1.8 million people affected in Araucania, Bio-Bio, Maule, O'Higgins, Region Metropolitana and Valparaiso.

- The total economic loss in Chile was estimated at 30 billion US dollars.

- Electricity, telecommunications and water supplies were disrupted and the airports at Concepcion and Santiago had minor damage.

- The tsunami damaged or destroyed many buildings and roads at Concepcion, Constitucion, Dichato and Pichilemu and also damaged boats and a dock in the San Diego area, USA.

2010 Chile Earthquake

An apartment block leans over after an earthquake in Santiago, Chile.

Damaged hotel in Talca, Chile.
Uplifted island with lighthouse, north of Lebu Harbor inlet. Areas with whitish colors were uplifted during earthquake.

Uplifted tidal organisms northeast of Lebu Harbor, looking west; distinct bands of white organic material and brown kelp are at comparable elevations (respectively) throughout this area. Top of kelp band about 2 m above tidal level when photo was taken.

Material reproduced/compiled from:
2010 Chile Earthquake

Collapsed apartment complex in Concepcion some 100 km (62 miles) south of the epicenter

Tanks buoyed above the ground surface when the higher unit weight soil liquefied due to excess pore pressure generation. This occurred near San Fernando.

Material reproduced/compiled from:
Paso San Martin bridge suffered repairable structural damage, characterized by shear key failure as shown. Longitudinal and transverse deck movement was also documented, leading to joint damage between the deck segments.
2010 Chile Earthquake

Typical construction type and observed damage within the city of Talca

Material reproduced/compiled from:

Significant structural damage, including partial collapse of a floor, of a modern highrise building in downtown Concepción
Bridge pier settlement, likely the result of liquefaction settlement-related down drag or the partial loss of bearing capacity in the drilled shaft foundations.
Earthquake Reconnaissance and Effects on Structures

2010 Sierra El Mayor (Baja), Mexico Earthquake

April 4, 2010 – 3:40 PM local time, Magnitude 7.2

- The magnitude 7.2 Sierra El Mayor earthquake of Sunday April 4th 2010, occurred in northern Baja California, approximately 40 miles south of the Mexico-USA border at shallow depth along the principal plate boundary between the North American and Pacific plates.

- This is an area with a high level of historical seismicity, and also it has recently been seismically active, though this is the largest event to strike in this area since 1892.

This residence, situated about 60 m from a free face at the Rio Hardy, suffered severe damage from lateral spreading displacements.

This two story structure in the village of Oaxaca settled approximately 1m, probably due to a liquefaction-induced punching-type bearing capacity failure.

Liquefaction damage to agricultural irrigation canals.
Streets of Christchurch are submerged as the result of substantial liquefaction. A unique aspect of the Christchurch earthquake is the severity and spatial extent of liquefaction occurring in native soils.

Material reproduced/compiled from: NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/hazard/earthqk.shtml)
2011 Christchurch, New Zealand Earthquake

February 22, 2011 – 12:51 PM local time, Magnitude 6.1

- At least 181 people killed, 1,500 injured and about 100,000 buildings destroyed or damaged (VIII) in the Christchurch-Lyttleton area.

- The earthquake was centered 2 kilometers (1.2 mi) west of the town of Lyttelton, and 10 kilometers (6 mi) south-east of the center of Christchurch, New Zealand's second-most populous city.

- This earthquake followed nearly six months after the magnitude 7.1 Canterbury earthquake of 4 September 2010, which caused significant damage to Christchurch and the central Canterbury region.

- The earthquake caused widespread damage across Christchurch, especially in the central city and eastern suburbs, with damage exacerbated by buildings and infrastructure already being weakened by the 4 September 2010 earthquake and its aftershocks.

2011 Christchurch, New Zealand Earthquake

February 22, 2011 – 12:51 PM local time, Magnitude 6.1

• The scientific and engineering significance of this earthquake goes well beyond the effects of this event alone, because the same region was impacted by the magnitude 7.1 Darfield earthquake six months earlier.

• Accordingly, there is much that can be learned from comparing the different levels of soil liquefaction, differing magnitudes and seismic source distances, and variable performance of buildings, lifelines, and engineered systems during these two earthquakes, along with the many strong aftershocks.

• It is rare to have the opportunity to document the effects of one significant earthquake on a modern city with good building codes.

• It is extremely rare to have the opportunity to learn how the same ground and infrastructure responded to two significant earthquakes.

A van that unluckily drove into a hole caused by the terrible liquefaction on Beach Road, North New Brighton during the Christchurch earthquake.
Photo Credit: NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/hazard/earthqk.shtml)

Material reproduced/compiled from:
2011 Christchurch, New Zealand Earthquake

Cathedral of the Blessed Sacrament

Damage to the Christchurch Cathedral

Material reproduced/compiled from: NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/hazard/earthqk.shtml)
Example of severe liquefaction near the intersection of Shortland St and Rowses Rd in the eastern suburb of Aranui. Note the high water marks on the car door window.
The four-storey PGC House on Cambridge Terrace, headquarters of Pyne Gould Corporation, collapsed, and thirty of the building's two hundred workers were still believed to be trapped within as night fell. On Wednesday morning, 22 hours after the quake, a survivor was pulled from the rubble. The reinforced concrete building had been constructed in 1963–1964.

The six-story Canterbury Television (CTV) building collapsed leaving only its lift shaft standing, which caught fire. The building housed the TV station, a medical clinic and an English language school. Initially more than 100 people were believed to have died in the building, the total reached 115.
The tsunami swept away the gas station causing a fire which burned down the whole town of Otsuchi, Japan.

Material reproduced/compiled from: NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/hazard/earthqk.shtml)
2011 Tohoku, Japan Earthquake

March 11, 2011 – 2:46 PM local time, Magnitude 9.0

- At least 15,703 people killed, 4,647 missing, 5,314 injured, 130,927 displaced and at least 332,395 buildings, 2,126 roads, 56 bridges and 26 railways destroyed or damaged by the earthquake and tsunami along the entire east coast of Honshu from Chiba to Aomori.

- The majority of casualties and damage occurred in Iwate, Miyagi and Fukushima from a Pacific-wide tsunami with a maximum runup height of 37.88 m at Miyako.

- The total economic loss in Japan was estimated at 309 billion US dollars. Electricity, gas and water supplies, telecommunications and railway service disrupted and several reactors severely damaged at a nuclear power plant near Okuma.

- Several fires occurred in Chiba and Miyagi.

- At least 1,800 houses destroyed when a dam failed in Fukushima.

- Maximum acceleration of 2.93 g recorded at Tsukidate.

- Horizontal displacement and subsidence observed.

- Landslides occurred in Miyagi. Liquefaction observed at Chiba, Odaiba, Tokyo and Urayasu.

Minamisanriku in some cases 15 m high tsunami debris can be seen on the fourth floor level and rooftops of buildings. No landslides or other geotechnical aspects other than tsunami damage.

Material reproduced/compiled from:
http://www.geerassociation.org/GEER_Post%20EQ%20Reports/Tohoku_Japan_2011/QR1_GEER_Quick_Report_April_5_2011.pdf
Sidewalk settles relative to a building on piles (above left), whereas a three-story building settles more than the adjacent sidewalk surface (above right, and right) in Urayasu.
2011 Tohoku, Japan Earthquake

Fujinuma Dam Failure: Fujinuma Dam had a maximum height of about 18.5 meters and had a maximum reservoir volume of approximately 1.5 million cubic meters. The Dam was constructed between 1937 to 1949. The reservoir was reportedly nearly full when the earthquake occurred. The dam crest reportedly was overtopped approximately 20-25 minutes after the earthquake with a larger discharge developing later.

Image developed by a LiDAR scan of the main dam. The scan was taken from the reservoir area upstream of the dam and looking across the reservoir area at the breach. The image clearly shows the uniform top surface of the overtopped dark brown embankment remaining across the dam site to the left of the breach, together with details of the breach geometry.

Material reproduced/compiled from:
http://www.geerassociation.org/GEER_Post%20EQ%20Reports/Tohoku_Japan_2011/QR1_GEER_Quick_Report_April_5_2011.pdf
The Fukushima Daiichi, Fukushima Daini, Onagawa Nuclear Power Plant and Tōkai nuclear power stations, consisting of a total eleven reactors, were automatically shut down following the earthquake.

Cooling is needed to remove decay heat after a reactor has been shut down, and to maintain spent fuel pools. The backup cooling process is powered by emergency diesel generators at the plants and at Rokkasho nuclear reprocessing plant.

At Fukushima Daiichi (pictured above) and Daini, tsunami waves overtopped seawalls and destroyed diesel backup power systems, leading to severe problems at Fukushima Daiichi, including three large explosions and radioactive leakage.

Over 200,000 people were evacuated.
References

- U.S. Geological Survey Photographic Library (http://libraryphoto.cr.usgs.gov/index.html);
- U.S. Geological Survey Earthquake Hazards Program (http://earthquake.usgs.gov);
- National Information Service for Earthquake Engineering (http://nisee.berkeley.edu/long_beach/long_beach.htm);
- The Virtual Museum of the City of San Francisco (http://www.sf museum.org/1906/06.html);
- NISEE - The Earthquake Engineering Online Archive (http://nisee2.berkeley.edu);
- Federal Emergency Management Agency (FEMA) Library: FEMA 454 (http://www.fema.gov/library/viewRecord.do?id=2418);
- NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/hazard/earthqk.shtml);
- Geotechnical Extreme Events Reconnaissance, GEER (http://www.geerassociation.org/);
- The Canadian Association for Earthquake Engineering (http://www.caee.uottawa.ca/Publications/PDF%20files/CAEE%20Sumatra%20Report.pdf);
- Risk Management Solutions, Inc. (http://www.rms.com/publications/KobeRetro.pdf); and