The Kumamoto, Japan Earthquake of 2016: Summary of Observations and Key Lessons

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The fault rupturing the surface on a road in Mashiki Town

The Kumamoto Earthquake Investigation: A Preliminary Report

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April 29, 2016

Introduction:
Overall report content

- The investigation
- Where else can this happen?
- Earthquake geology
- Overview of the effects
- Schools
- Airport
- Hospital
- Strong motion

Knowledge Base:
130+ Natural Disasters Investigated

Earthquakes and Tsunami

1971 San Fernando, CA (M6.5)
1972 Managua, Nicaragua (M6.3)
1973 Point Mugu, CA (M5.9)
1973 Managua, Nicaragua (M5.8)
1975 Ferndale, CA (M5.5)
1975 Lice, Turkey (M6.8)
1976 Friuli, Italy (M6.5)
1977 Vrancia, Romania (M7.4)
1978 Izu Peninsula, Japan (M6.7)
1978 Miyagi-Ken-oki, Japan (M7.4)
1978 Santa Barbara, CA (M5.1)
1979 Bishop, CA (M5.8)
1979 Gilroy, CA (M5.5)
1979 Imperial Valley, CA (M6.6)
1980 Livermore, CA (M5.5 and 5.8)
1980 Eureka, CA (M7.0)
1980 Mammoth Mt., CA (M6.5, 6.5, 6.7)
1981 Brawley, CA (M5.6)
1983 Coalinga, CA (M6.7)
1983 Borah Mt., Idaho (M6.9)
1984 Morgan Hill, CA (M6.2)
1985 Santiago, Chile (M7.8 and 7.2)
1985 Mexico City, Mexico (M8.1 and 7.5)
1986 Painesville, Ohio (M5.0)
1986 Adak Island, Alaska (M7.7 and 6.5)
1986 North Palm Springs, CA (M6.0)
1986 Chalfant Valley, CA (M6.0 and 5.5)
1986 San Salvador, El Salvador (M5.4)
1986 Northern Taiwan (M6.8)
1987 Cerro Prieto, Mexico (M5.4)
1987 Bay of Plenty, New Zealand (M6.2)
1987 Whittier, CA (M5.9)
1987 Superstition Hills, CA (M6.3)
1988 Gorman, CA (M5.2)
1988 Alum Rock, CA (M5.1)
1988 Saguenay, Quebec (M6.0)
1988 Armenia, USSR (M6.9)
1989 Acapulco, Mexico (M6.8)
1989 Loma Prieta, CA (M7.1)
1989 Newcastle, Australia (M5.5)
1990 Upland, California (M5.5)
1990 Bishop's Castle, Wales (M5.4)
1990 Manjil, Iran (M7.7)
1990 Central Luzon, Philippines (M7.7)
1991 Valle de la Estrella, Costa Rica (M7.4)
1991 Sierra Madre, CA (M5.8)
1992 Erzincan, Turkey (M6.8)
1992 Roermond, Netherlands (M5.8)
1992 Desert Hot Springs, CA (M6.1)
1992 Cape Mendocino, CA (M7.0, 6.0, & 6.5)
1992 Landers-Big Bear, CA (M7.6 and 6.7)
1992 Cairo, Egypt (M5.9)
1993 Scotts Mill, OR (M5.3)
1993 Nansei-oki Hokkaido, Japan, (M7.8)
1993 Agana, Guam (M8.2)
1993 Klamath Falls, OR (M5.7)
1994 Northridge, CA (M6.6)
1994 Tohoko-oki, Hokkaido, Japan (M8.1)
1995 Great Hanshin (Kobe), Japan (M7.2)
1995 Pereira, Colombia (M6.5)
1995 Sakhalin Islands, Russia (M7.2)
1995 Antofagasta, Chile (M7.4)
1995 Manzanillo, Mexico (M7.6)
1996 Duvall (Seattle,), WA (M5.3)
1997 Calico, CA (M5.0)
1997 Umbria, Italy (M5.5)
1990 Adana-Ceyhan, Turkey (M6.2)
1999 Armenia, Colombia (M5.0)
1999 Puerto Escondido, Mexico (M7.5)
1999 Western Washington (M5.8)
1999 Izmit, Turkey (M7.4)
1999 Duzce, Turkey (M7.2)
1999 Central Taiwan (M7.6)
1999 Athens, Greece (M5.9)
1999 Algeria (M5.5)
1999 Hector Mine, California (M7.1)
2000 Napa, CA (M5.2)
2000 Tottori, Japan (M6.7)
2001 Gujarat, India (M7.6)
2001 Seattle, WA (M6.8)
2002 San Simeon (Paso Robles), CA (M6.5)
2007 West Sumatra, Indonesia (M6.3)
2007 Niigata (Kashiwazaki), Japan (M6.8)
2008 Wells, Nevada (M6.3)
2008 Sichuan, China (M8.0)
2009 L' Aquila, Italy (M6.3)
2010 Haiti (M6.9)
2010 Chile (M8.8)
2010 Baja California, Mexico & CA (M7.2)
2011 Christchurch, New Zealand (M6.3)
2011 Tohoku (Sendai), Japan (M9.0)
2011 Mineral, Virginia (M5.9)
2011 Van, Turkey (M7.2)
2014 Napa, CA (M6.0)
2016 Kumamoto, Japan (M7.0)

Hurricanes, Floods and Typhoons

1989 Hugo (Caribbean, Puerto Rico, South Carolina)
1992 Andrew (Florida, Louisiana)
1992 Iniki (Kauai, Hawaii)
1995 Luis (Northeast Caribbean)
1995 Marilyn (Northeast Caribbean)
1995 Opal (Florida panhandle)
1995 Angela (Philippine Islands)
1996 Fran (North and South Carolina)
1997 Paka (Guam)
1997 Red River (North Dakota)
1998 Georges (NW Caribbean, Puerto Rico, Gulf Coast)
1999 Floyd (Eastern US)
1999 Lothar (Western Europe)
1999 Martin (Western Europe)
2005 Katrina (Gulf Coast, Mississippi, Louisiana, New Orleans)
2011 Tropical Storm Nock-ten (Thailand)
2013 Sandy (New York, New Jersey)

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Where else could this happen?

A residential area at the foot of the hills in the Town of Mashiki. All of the damaged houses are wood-frame construction.

A heavily damaged residential area of Mashiki. All of the houses in the photo are wood frame; most are relatively new.

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Where else could this happen?

Along the Futagawa fault through a hilly residential area of Mashiki. Here the fault has offset a retaining wall by about 4 feet (1.2m). Houses right on top of the fault were typically completely destroyed. Nearby wood frame houses, not directly on the fault, had various degrees of structural damage – from light to extreme, including many collapses.

On the left is a practically undamaged house, which is not far away from the severely damaged house on the right. The difference in performance is primarily due to lack of bracing in the garage in the house on the right. Note the unbroken window on the second floor.

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Where else could this happen?

Another house with too many openings (windows) and not enough walls on the ground floor. Note the relatively undamaged houses behind and on the right of the collapsed house.

Other severely damaged houses in Mashiki. Most of the damage that occurred was due to inadequate strength in the lower floor walls, including too many windows. That additional strength can be easily provided by adding bracing with a few more well-nailed plywood sheets.

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Where else could this happen?

Much of the damage to houses in the hills was also due to ground failures around the house foundations. This was caused by minor local land sliding and/or the slumping of inadequately compacted fills around the houses. These types of fills are necessary to create level pads for the house foundations, and is the common practice along the West Coast of the U.S. and Canada. The extent of such failures in Mashiki was surprising. The likely cause of this unusually high damage is the very strong shaking in the immediate vicinity of the fault.

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Where else could this happen?

Damage to a house in the hills above Mashiki primarily caused by local ground failure, either due to minor landsliding or inadequate compaction of fill in the construction of a level building site. The building is leaning to the right; the main ground movement was to the left and downhill.

One of several undamaged public housing apartment buildings in Mashiki in the hills just above most of the houses shown in this report. The reinforced concrete structures are built with shear walls and have relatively little glazing when compared to most modern apartment buildings along the West Coast of North America. The inhabitants reported, however, that the contents of their apartments suffered extensive damage, as would be expected in such a strong earthquake in the vicinity of the causative fault.

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Schools

The author (in hardhat) with the Tsumori Elementary School principal and staff

The Tsumori Elementary School in Mashiki, the town most affected by the destructive Kumamoto earthquake. The bridge leading to the school was a major concern for the principal of the school, as it provides access to the school for many of the students. We did not find any significant damage.

Schools

The Tsumori Elementary School gym. One quick look at the building, and adequate familiarity with school earthquake strengthening programs in Japan and around the world, was sufficient for me to realize that this school had been strengthened for earthquakes after it was originally built (well before the more recent earthquake code standards). The steel X-braces (behind the second floor windows and inside the gym) are used often in Japan and elsewhere for strengthening.

Another obvious strengthening detail - note that the two story solid concrete wall has been added to strengthen the original school. It replaced the windows that were there in the original design. This "shear wall," which adds strength, is a common retrofit detail and works well for this type of concrete-frame construction.

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Schools

A view of the school from a neighboring house. Contrast the performance of the virtually undamaged school with that of the collapsed house just across the street.

Views of collapsed buildings around the school. The bottom photograph is from inside a classroom, looking at a collapsed small commercial building across the river (also shown in the left photo above).

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Schools

Interior of the virtually undamaged gym. A few lightweight ceiling tiles fell because of inadequate attachment to the structural roof (and ceiling). The debris can be seen in the lower right corner. Note that all of the windows are intact.

Additional photos of the practically undamaged interior and exterior of the elementary school.

Schools

Another essentially undamaged older school in the earthquake area. Again, note the additional "shear walls" that were added, blocking some of the pre-existing windows. Because of the declining student population, the school is no longer used for teaching. Fortunately, the buildings are now available as emergency shelters for those that lost their homes in the earthquake. Other than life safety for students, one of the primary additional reasons for focusing on strengthening schools is their potential use as emergency shelters following disasters.

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Kumamoto Airport

Kumamoto Airport, as seen on Google Maps. Our team conducted a rapid visual evaluation of the effects of the M7.0 earthquake, with emphasis on the terminals and some of the infrastructure to the south of the runway (in the central area of the photo).

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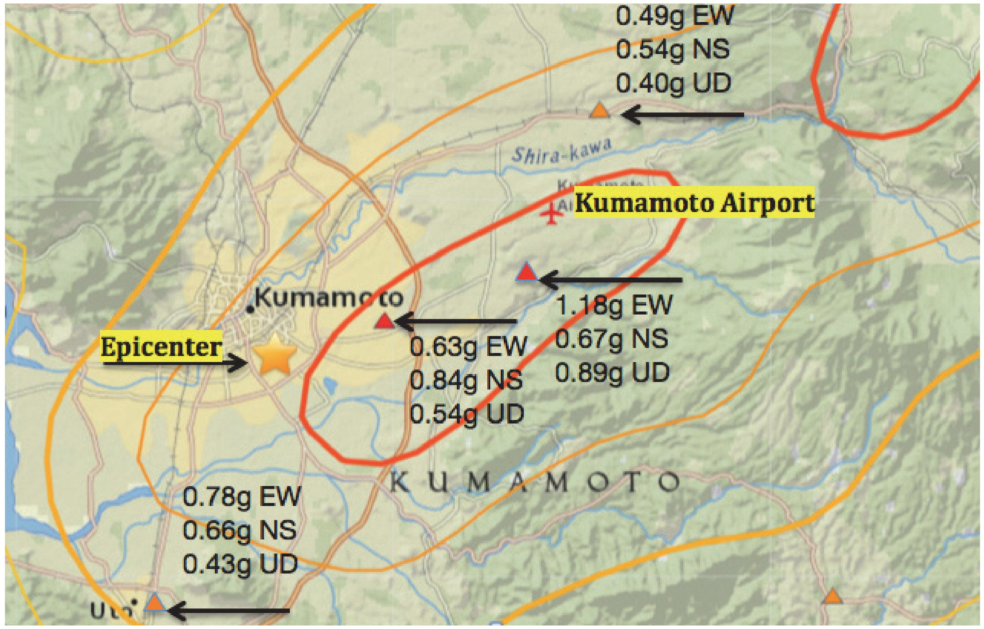
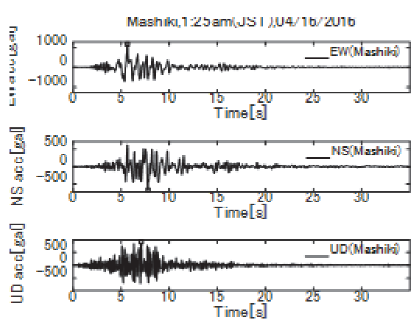
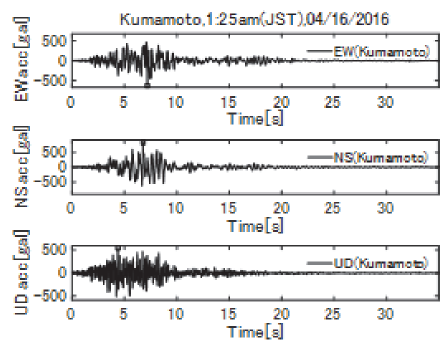
Kumamoto Airport



Summary of the ground motions recorded nearest to the Kumamoto Airport. The PGAs for the three components of each record are shown. The map also shows the intensities of the earthquake estimated by the USGS. The area within the red contour is MMI IX; the area within the wider orange contour is MMI VIII. The airport is in MMI IX.





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The recorded time histories at Mashiki, left, and Kumamoto, right. Courtesy EERI.

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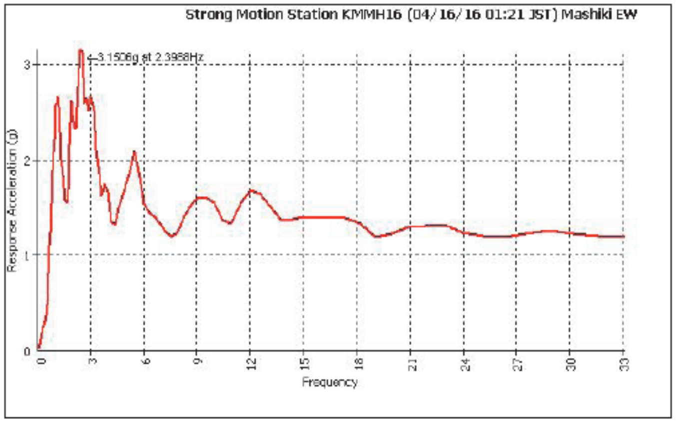
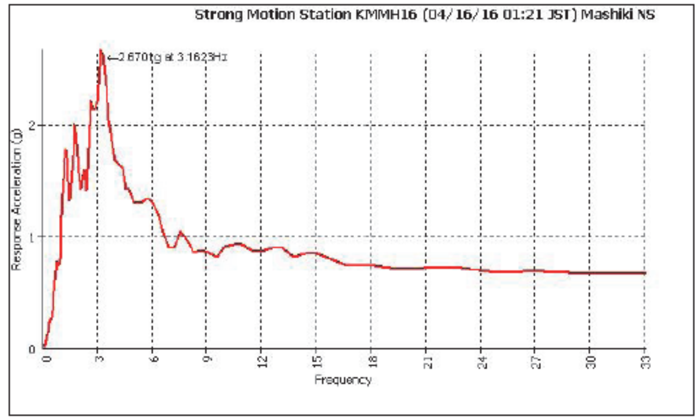
Kumamoto Airport





The 5% damping response spectra for the Mashiki EW and NS records.

Exterior views of the newer steel framed Domestic Terminal building. The control tower is to the left. There was no obvious significant structural damage.

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Kumamoto Airport

A notable success at the new terminal was the performance of the glazing. We found no damage to these large glass panels. Given the strength of the shaking at the airport, the design details for the glazing should be studied in further detail. Details such as these are difficult for engineers to analyze. Further, they are difficult to test on shake tables. Post-earthquake experience data, such as what we collected at the Kumamoto Airport, are valuable for future designs as well as for the development of adequate and not overly conservative building code requirements for architectural and equipment details.

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Kumamoto Airport

The rigid suspended ceilings throughout the new terminal performed well. We did not notice any significant damage. There was minor damage at interfaces with columns and walls. In the past, damage to flexible suspended ceilings at airports has been a major cause of service interruptions.

The most life-threatening damage that we observed at the new terminal was the falling of inadequately anchored or braced light fixtures. Note the missing fixture in the right photo. Many of these fixtures had fallen. The ceilings around the failed fixtures are undamaged.

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The late 1960s reinforced concrete International Terminal was closed at the time of our investigation due to reported structural damage. We could not observe the damage from the outside, but given the vintage of the structure and the outdated and inadequate code to which it was designed, plus the strength of the ground shaking, serious structural damage should have been expected unless the structure had been strengthened more recently. This type of structure is a classic example of a high-risk structure that requires strengthening for life-safety and for the reduction of business interruptions.

The airport has several steel framed warehouses, hangars, and other service buildings. None appeared to have significant structural damage, including older steel structures that were designed and built to outdated codes. Over time, and in many earthquakes these types of structures, have proven to be much lower risk than comparable concrete frame, precast or tilt-up, and shear wall structures.

Kumamoto Airport

Damage to an older building at the airport training facility, where inadequate attachments for the heavy precast concrete cladding failed. I have observed this type of failure many times in earthquakes in Japan and elsewhere around the world. Typically, older buildings with these types of facades, as well as older precast concrete buildings, are much higher risks than comparable age steel framed and massive concrete shear wall buildings. Several other similar buildings at the airport had comparable, but less dramatic, damage.

At first glance, this aviation fuel storage facility at the airport appeared to have suffered damage to one of its two tanks. It turned out that the blue plastic tarps covering the effects of the earthquake were providing temporary cover replacing the damaged asphalt waterproofing around the tank base. The damage was inconsequential. Generally, equipment such as this had adequate anchorages and performed well.

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Nishikumamoto Hospital

The hospital, as seen on Google Maps, consists of several buildings including an Assisted Living Facility. The main hospital building is in the lower left corner, and is also shown below.

The main building of the hospital was built in 2012 and showed no visible structural damage. The only significant damage inside the building was minor spalling at seismic (expansion) joints. There was also minor settlement of the ground and of excavation backfills around the buildings.

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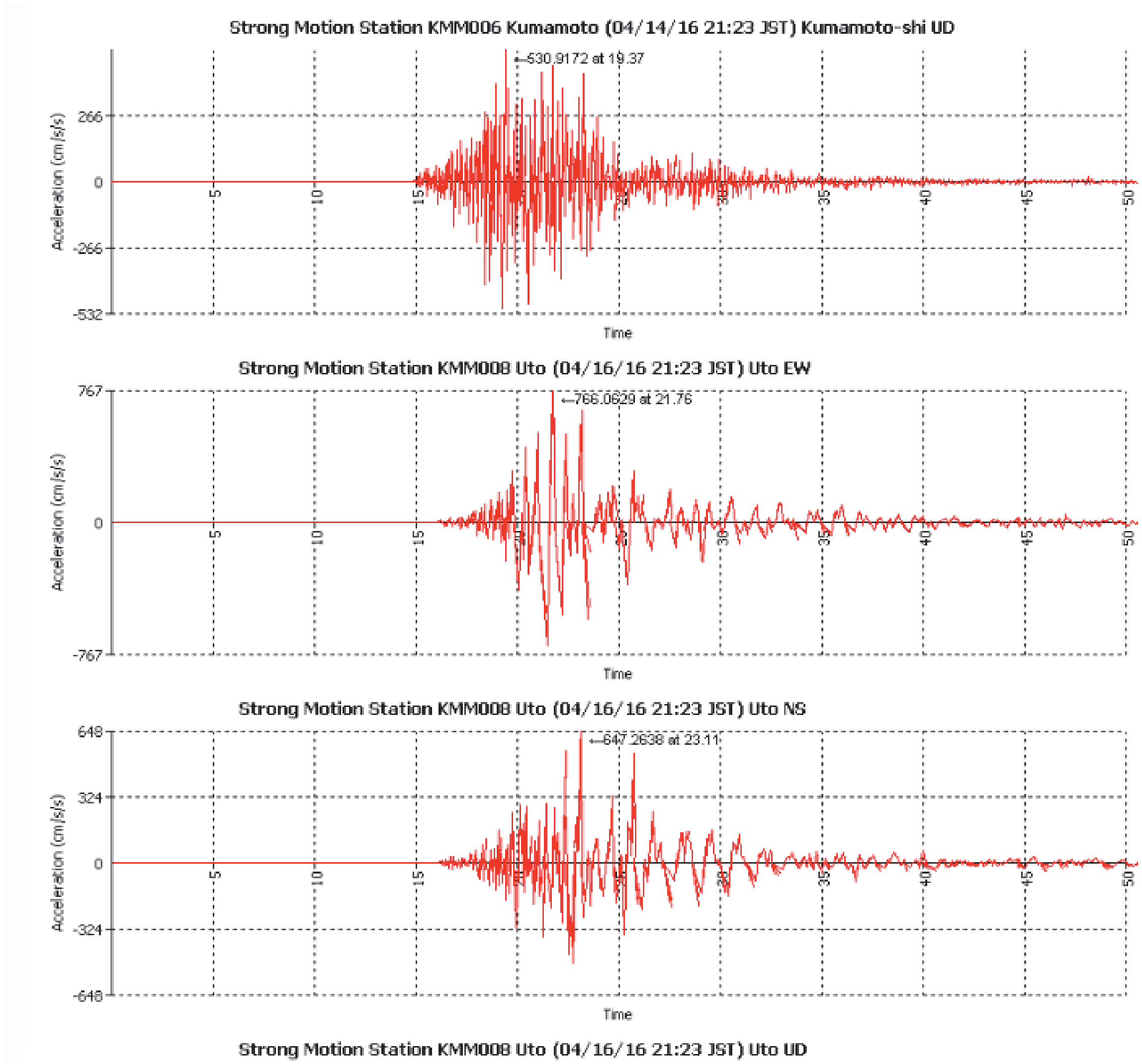
Nishikumamoto Hospital



The strong motion records from the Uto City Hall site that is about 2 miles (3km) from the hospital.

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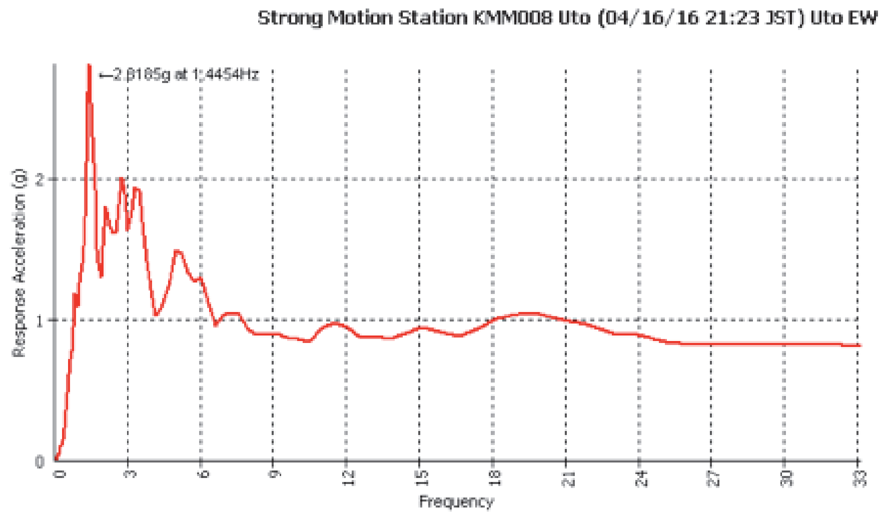
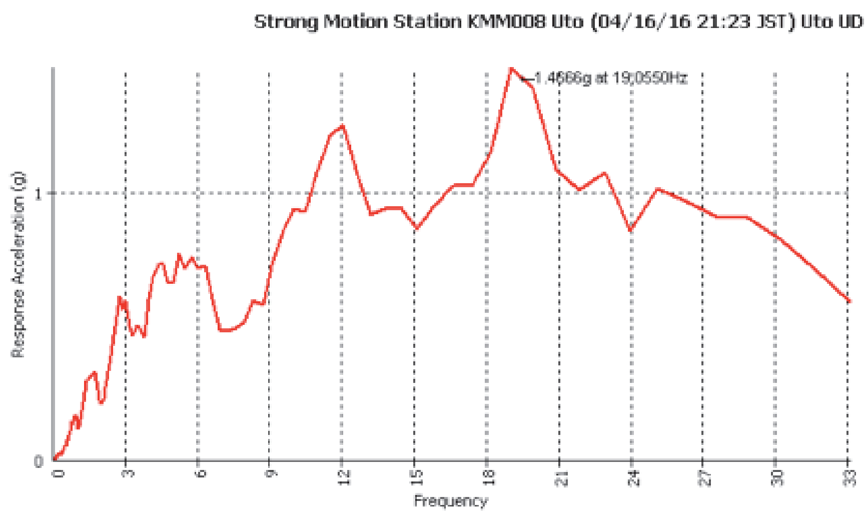
Nishikumamoto Hospital





The response spectra for the EW and UP components of the Uto City Hall time histories. The site is about 2 miles (3km) from the hospital. (Courtesy of Woody Epstein)

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Nishikumamoto Hospital

Two heavily damaged reinforced concrete buildings are in the general region and roughly equidistant from the hospital. Both buildings are much older and were designed to outdated building codes. The top building is Uto City Hall. The visible façade damage is due to the failure of precast concrete non-structural façade panels, shown in more detail on the right. The main concrete frame is heavily damaged and near collapse. The recorded ground motions, shown in the previous illustrations, were taken on the City Hall. The three-story building (lower left) had a soft-story ground floor that collapsed. The lower right photo shows collapsed silos at the nearby Kumamoto Ryoko Concrete Co. Two of five silos collapsed. The three newer silos in the back designed to more recent criteria have no significant damage.

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Nishikumamoto Hospital

A partial view of one of the two-story hospital buildings (left) and the undamaged steel framed and braced parapet on the roof of the 6-story main building.

The most obvious and inconsequential damage to the hospital was minor settlement around the periphery of buildings. The photo in the upper left shows some settlement at the main entrance to the hospital. The other three photos are of interiors of the main building, including the lobby (lower right). Note that the undamaged ceilings are rigid, unlike flexible suspended ceilings that are typically easily damaged.

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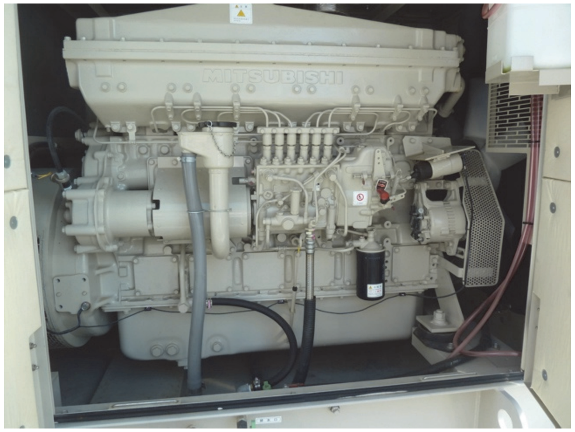
Nishikumamoto Hospital



The emergency diesel, located on the roof of the six-story main building, started up upon loss of off-site power. The diesel, plus a second generator in another building, provided adequate power to the hospital following the earthquake until off-site power was restored.

Some of the equipment on the roof of the six-story main building, none of which was damaged in the earthquake. Our investigation revealed good design details for the anchorages and braces of the equipment, piping, and other systems.

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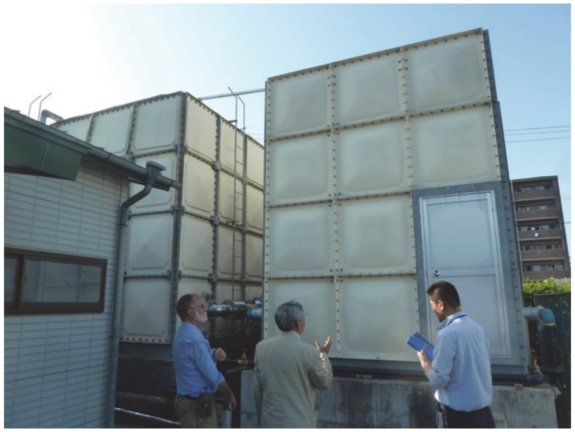
Nishikumamoto Hospital

Two anchored potable water tanks lost content when the rigid piping that interconnected them failed due to differential tank movement during the earthquake. The repaired lines are shown on the left. A flexible pipe connection between them would have prevented the only significant equipment and systems damage at the hospital.


Other anchored equipment at ground level had no damage, including the two potable water tanks on the left and a diesel generator on the right.

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Nishikumamoto Hospital

Out of concern for further aftershocks, the hospital staff placed art and other wall-mounted objects on the floor (left). Heavy furniture that can overturn, such as the tall cabinet on the right, were also lowered to the floor so that they would not tip over in aftershocks. I have visited many hospitals, and other public buildings along the Pacific West Coast and throughout the world after earthquakes – this thoughtful precaution was a first for me. Japan has experience with what to do after earthquakes………