16 Aug 2008, 8:45am - 12:30pm

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Recommended Citation

Kayen, Robert, "Recent Damaging Earthquakes in Japan, 2003-2008" (2008). *International Conference on Case Histories in Geotechnical Engineering*. 21.
https://scholarsmine.mst.edu/icchge/6icchge/session03/21

RECENT DAMAGING EARTHQUAKES IN JAPAN, 2003-2008

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ABSTRACT

During the last six years, from 2003-2008, Japan has been struck by three significant and damaging earthquakes: The most recent M6.6 Niigata Chuetsu Oki earthquake of July 16, 2007 off the coast of Kashiwazaki City, Japan; The M6.6 Niigata Chuetsu earthquake of October 23, 2004, located in Niigata Prefecture in the central Uonuma Hills; and the M8.0 Tokachi Oki Earthquake of September 26, 2003 effecting southeastern Hokkaido Prefecture. These earthquakes stand out among many in a very active period of seismicity in Japan. Within the upper 100 km of the crust during this period, Japan experienced 472 earthquakes of magnitude 6, or greater. Both Niigata events affected the south-central region of Tohoku Japan, and the Tokachi-Oki earthquake affected a broad region of the continental shelf and slope southeast of the Island of Hokkaido. This report is synthesized from the work of scores of Japanese and US researchers who led and participated in post-earthquake reconnaissance of these earthquakes: their noteworthy and valuable contributions are listed in an extended acknowledgements section at the end of the paper.

During the Niigata Chuetsu Oki event of 2007, damage to the Kashiwazaki-Kariwa nuclear power plant, structures, infrastructure, and ground were primarily the product of two factors: (1) high intensity motions from this moderate-sized shallow event, and (2) soft, poor performing, or liquefiable soils in the coastal region of southwestern Niigata Prefecture. Structural and geotechnical damage along the slopes of dunes was ubiquitous in the Kashiwazaki-Kariwa region. The 2004 Niigata Chuetsu Earthquake was the most significant to affect Japan since the 1995 Kobe earthquake. Forty people were killed, almost 3,000 were injured, and many hundreds of landslides destroyed entire upland villages. Landslides were of all types; some dammed streams, temporarily creating lakes threatening to overtop their new embankments and cause flash floods and mudslides. The numerous landslides resulted, in part, from heavy rain associated with Typhoon Tokage. The earthquake forced more than 100,000 people into temporary shelters, and as many as 10,000 displaced from their upland homes for several years. Total damages was estimated by Japanese authorities at US$40 billion, making this the second most costly disaster in history, after the 1995 Kobe earth-quake. The 2003 Tokachi-Oki earthquake was the third event of magnitude 8.0+ to strike the southeastern portion of Hokkaido in the last 50 years. The event produced tsunami run-ups along the shoreline of southern Hokkaido that reached maximum heights of 4 meters. Accelerations recorded by seismic networks of Hokkaido indicated a high intensity motion region from Hiroo area to Kushiro City, with a PGA values in the range of 0.35 to 0.6g. Despite high acceleration levels, the observed ground failure, liquefaction, structural, port, and lifeline damages were remarkably light.

INTRODUCTION

During the past five years Japan has been struck by three significant and damaging earthquakes: The most recent M6.6 Niigata Chuetsu Oki (offshore) earthquake of July 16, 2007 off the coast of Kashiwazaki City, Japan; the M6.6 Niigata Chuetsu earthquake of October 23, 2004, as located in Niigata Prefecture in the central Uonuma Hills; and the M8.0 Tokachi Oki (offshore) Earthquake of September 26, 2003 effecting southeastern Hokkaido Prefecture. These earthquakes stand out among many in a very active period of seismicity in Japan between January 1, 2003 and the present. In the upper 100 km of the crust during this period, Japan experienced 472 earthquakes of magnitude 6 or greater (Figure 1). Both Niigata events affected the south-central region of Niigata Prefecture, and the Tokachi-Oki earthquake affected a broad region of the continental shelf and slope southeast of Hokkaido.

These three earthquakes, though the most significant, were not the only damaging events of the past five years. In 2005, northwestern Kyushu was shaken by the magnitude 7.0 Fukuoka-ken Seiho-oki earthquake (Fukuoka western offshore) in Fukuoka Prefecture, March 20, 2005. Shaking lasted for approximately 50 seconds. The quake occurred on the offshore projection of the Kego fault in the Genkai Sea, The earthquake resulted in one person was killed, and over one thousand injured.

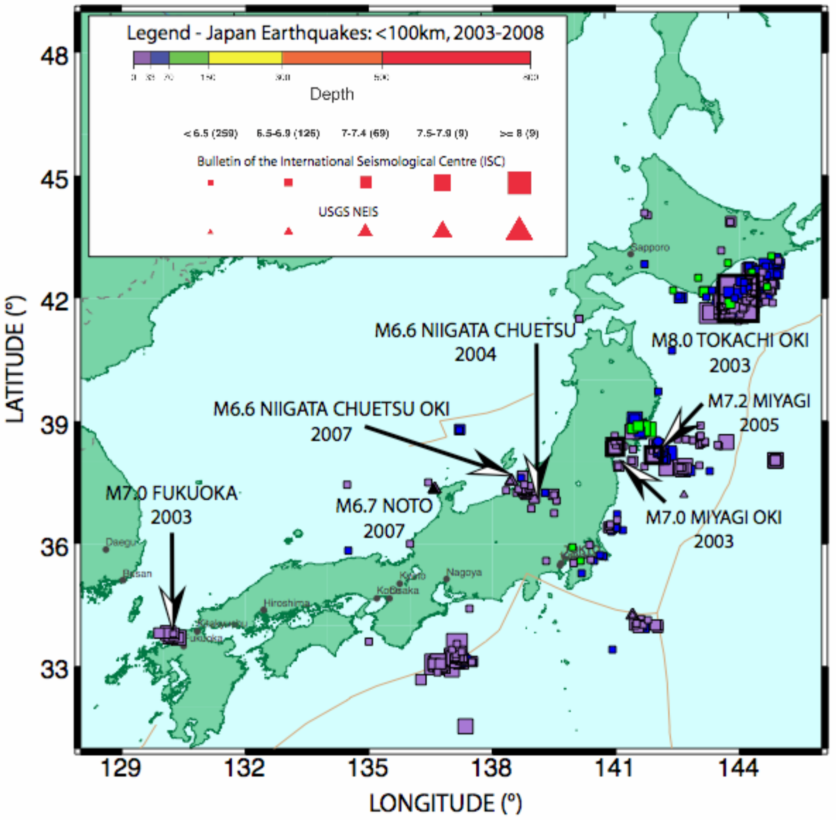


Figure 1: Damaging earthquakes in Japan, 2003-2008. Seven primary events are plotted against 472 events in the upper 100km of crust, of magnitude 6 or greater, that struck Japan in that timeframe. Events where centered in the Tokachi region of Hokkaido Prefecture; The southern central region of Niigata Prefecture; The Sendai Bay region of Miyagi and Iwate Prefectures; along the subduction zone offshore Wakayama and Ise; and an unusual large event in northwestern Kyushu near Fukuoka.

Old homes made of soil-stucco and bamboo lathe (tsuchi-kabe method) and covered with heavy ceramic Kawara roof tiles accounted for almost all of the damage. On Genkai-jima, an island offshore Fukuoka, landslides and structural collapses of homes forced the evacuation of all the residents.

On 26 May 2003, a deep M7.0 quake occurred along the Pacific plate boundary injuring over 100 people in Iwate and Miyagi prefectures. No death has been reported. Property damage was, again, limited to several hundred old homes. Landslides were observed in Ishinomaki City, Miyagi Prefecture and in Sumita, Iwate Prefecture. Two years later, on August 16, 2005 another Miyagi ken oki event struck Sendai Bay. This time M7.2 struck Miyagi and Iwate Prefectures. Several fatalities occurred at a structural collapse of a pool roof Sendai city, Miyagi prefecture, and over a dozen injuries were reported.

On the Japan sea coast on the Noto peninsula in Ishikawa Prefecture, a M6.7 earthquake struck on March 25, 2007. The earthquake was remarkable for the general lack of damage, liquefaction or landsliding. One death was reported in the city of Wajima and several hundred were injured.

The three damaging events, reported here, are described beginning with the most recent. These events were each the focus of reconnaissance activities of the EERI (Earthquake Engineering Research Institute) and GEER (Geo-Engineering Earthquake Engineering Reconnaissance) activities of the US National Science Foundation. The geo-engineering observations of the earthquake events described below are the product of the reconnaissance activities and its' participants. The contributors to the reports and articles for each of the events are listed in the extended acknowledgements at the end of the paper.

(I) THE JULY 16, 2007 M6.6 NIIGATA-CHUETSU OKI EARTHQUAKE

The M6.6 mainshock of the Niigata Chuetsu Oki (offshore) earthquake occurred at 10:13 a.m local time on July 16, 2007, and was followed by a sequence of strong aftershocks (Figure 2). The event had a shallow focal depth of 8 km and struck in the Japan Sea immediately offshore Kariwa. The quake affected an approximately 100 km-wide area along the coastal areas of southwestern Niigata prefecture and triggered numerous ground failures as far inland as the Uonuma Hills located approximately 50 km inland - the source area of the 2004 Niigata Chuetsu earthquake.

In Niigata prefecture, the JMA seismic intensity was 6+ (IX in MMI) in Kariwa-cho, Kashiwazaki city, Nagaoka city, and also Ohzuna-machi in Nagano prefecture. The downtown Kashiwazaki City K-NET site recorded a PGA of 0.67g. The earthquake resulted in eleven fatalities and nearly two thousand injuries. Close to 1,100 collapses of residential structures occurred almost exclusively in old bamboo and stuccoed post-and-lintel structures with heavy kawara tile roofs. Many of these collapses were associated with displacements on the slopes of sand dune deposits or liquefied ground. Damage occurred in lifeline utilities of gas, water, and electricity and to the world's largest nuclear power plant, the Kashiwazaki-Kariwa facility. The power plant was in the region of highest iso-seismal intensity. Expanded reports on the earthquake can be found at http://pubs.usgs.gov/of/2007/1365/ (Kayen et al., 2007), www.eeri.org , and gees.usc.edu/GEER/

The spatial position and severity of ground failures and structural damage are archived in a Google Earth database at *http://walrus.wr.usgs.gov/infobank/n/nii07jp/html/n-ii-07-jp.sites.kmz*, which contains a comprehensive explanation of each site. The use of Google Earth as an earthquake investigation tool is presented in paper 3.55 of Session 3 of this conference (Kayen et al, 2008a). High-resolution laser-mapped data sets of the most significant structural and geotechnical damage features were collected for preservation using a terrestrial LiDAR (Light Detection and Ranging) system of the USGS.

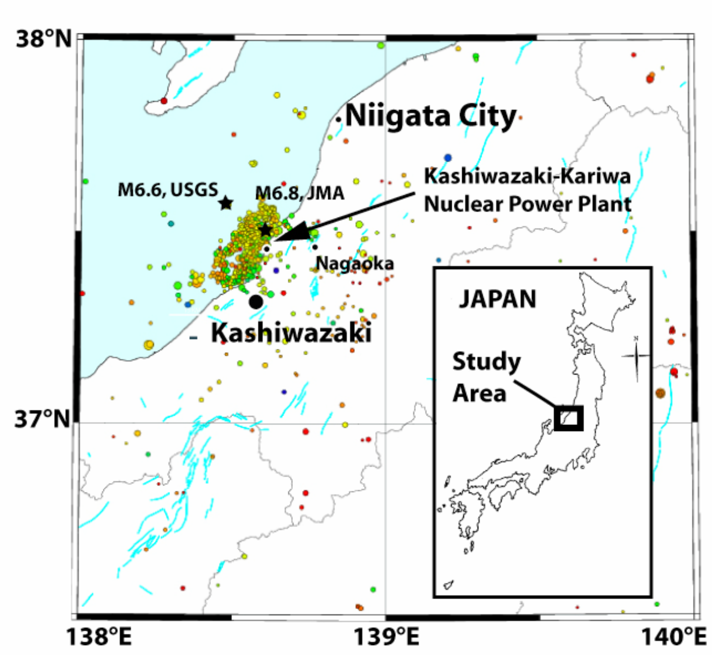


Figure 2: Main shock and aftershock pattern of the 16 July 2007 Niigata Chuetsu Oki, Japan, Earthquake. The estimated moment magnitude of the event is M6.6. The aftershock pattern is useful for defining the principal rupture plane of the event. The worlds largest nuclear power plant, the Kashiwazaki-Kariwa facility of Tokyo Electric Power Company (TEPCO), is sited in the epicentral region and experienced the strongest recorded motions of the earthquake

Seismological Aspects Of The 2007 M6.6 Niigata-Chuetsu Oki Earthquake

Niigata is located in a subduction zone near the boundary between the Amur plate and the Okhotsk plate (two relatively small plates that lie between the larger Eurasia and Pacific plates). The moment magnitude of the mainshock of this event was estimated to be 6.6 using teleseismic data (USGS) and 6.7 using regional data. The Japan Meteorological Agency assigned a magnitude of 6.8 to the mainshock.

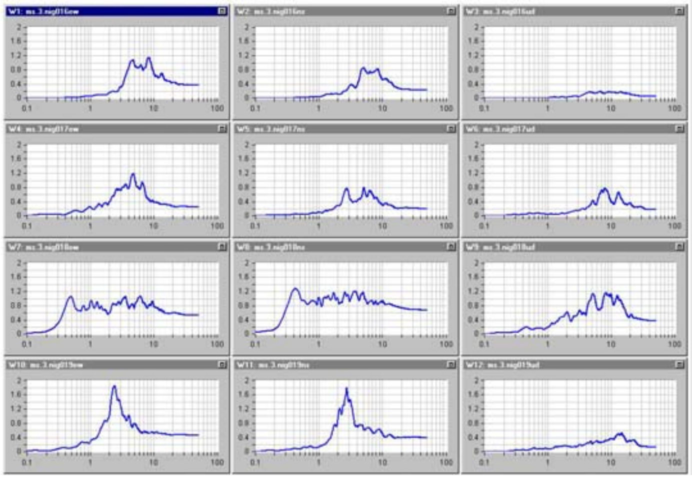


Figure 3: Acceleration response spectra for a damping coefficient of 5%. From top to bottom: NIG016, NIG017, NIG018, NIG019. The left panel is the EW component, the middle panel is the NS component, the right panel is the Z component. The horizontal axes represent frequency, in Hz, and the vertical axes represent absolute acceleration as a fraction of the acceleration of gravity.

The Niigata earthquake was a buried reverse-slip earthquake. The hypocenter had an estimated depth of 8 km (NRI ESDP, 2007). Two potential planes of faulting are unresolved, as aftershock locations fell on both planes. The rupture length is estimated to be 30 km and the down-dip fault width is estimated to be 22 km for both planes. The inferred location of the hypocenter is at the northeast end of both planes and the rupture is inferred to have progressed from the northeast toward the southwest. Slip models for both rupture planes show a single strong asperity in the western end of the rupture. The maximum computed slip is 3.5m.

The Japanese nationwide strong motion network, K-net, recorded the earthquake at 390 stations, with 20 stations within 50 km. The accelerograms obtained at station NIG018 (close to the fault plane and within the area where damage was heavier) have unusually low frequency content that is most likely due to liquefaction below the site. Acceleration response spectra computed for a damping coefficient of 5% are shown in Fig. 3.

The Kashiwazaki-Kariwa Nuclear Power Plant

The worlds largest nuclear power plant, owned by Tokyo Electric Power Corporation (TEPCO) is located 7 km from the epicenter reported by K-NET, 10 to 20 km above the fault plane dipping southeast and 3 km above the northwest dipping plane. and instrumented at 99 locations. The motions at 33 locations with a new sensor system were recorded, but unfortunately the recordings at the other 66 older instrument locations, including two free-field down-hole arrays and most of the structural arrays, were lost with the exception of the peak values. The ground motion data on the old system could not automatically transmit due to communication congestion, and aftershooks triggered the recorders and overwrote the buffer containing the mainshock recordings. The 33 recordings of the new system included 27 from a majority of the reactor and turbine buildings and one 4-depth free-field array at the Service Hall. The data indicates a large range in the foundation motions for the EW component with PGA values ranging over a factor of two (322-to-680 gal). The NS component shows more similar values (267-to-311 gals). The large range in the EW component values is likely due to different soil structure interaction (SSI) effects at different units and spatial variation of the ground motion over short distances probably due to the near-fault rupture mechanism (Fig 4a and 4b). The large range of PGA values on the EW component shows the need for multiple recordings at NPP sites to reliably determine the input ground motions for the structures.

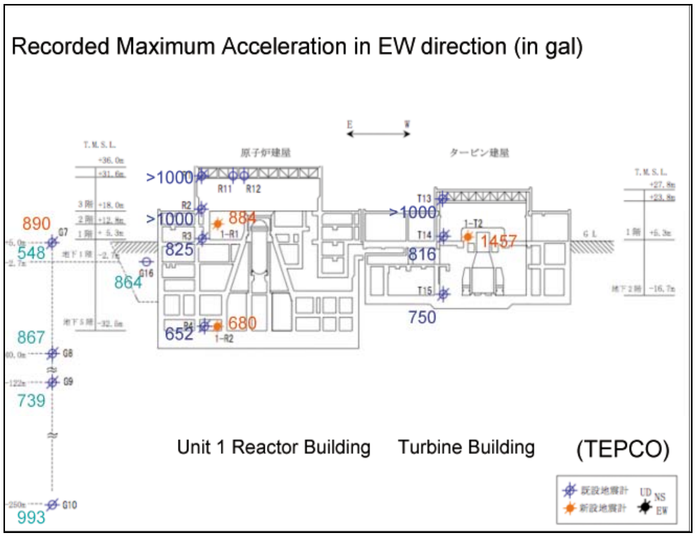


Figure 4a East – West peak accelerations (cm/sec/sec) in and around Unit 1 (From TEPCO, 2007).

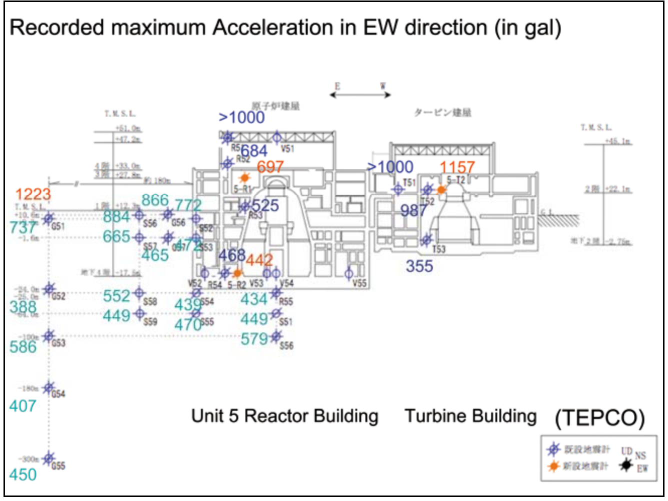


Figure 4b Peak accelerations in and around Unit 5 Reactor (From TEPCO, 2007)

The performance of the facility was mixed: the main structures did not suffer significant damage, but a fire started and radioactive material was released. There was no loss of life and the emergency shutdown system, which had been set to be triggered by accelerations exceeding 120gal, operated successfully. In structures surrounding the primary facilities of the plant, a fire broke out in an electrical transformer. Radiation leaks were caused by spilling of water from used nuclear fuel cooling pools, failure of joints in exhaust pipes, and the falling of drums containing low-radiation nuclear waste.

Figure 5: Damaged road at the nuclear power plant (Kayen et al. 2007).

Structural and road damage that was observed was related to problems with foundation soils, including liquefaction (Figure 5) , embankment failure, settlement and distress of footings, and a landslide. Joints of piping resting on isolated footings and expansion joints in covered pathways failed, and underground pipes supplying fire retardant to reactors broke because of the relative movement between soils and the foundations. In a two-story steel building used for plant administration, drop-ceilings fell and windows broke. Access through doors was impaired by ground settlements of up to 40 cm. The plant was closed after the earthquake and is currently undergoing inspections prior to restarting.

Fig. 6: Kashiwazaki Wastewater Treatment Plan on the south side of Sabaishi River near its outlet to the Sea of Japan (Google Earth map site RK9 RK9 N 37.38748 E 138.56587) Pipe breaks due to separation of two halves of building (Photo taken on 7/21/07).

Liquefaction During The 2007 M6.6 Niigata-Chuetsu Oki Earthquake

Liquefaction was observed from the southern port of Kasashima village south of Kashiwazaki City, to Shiya village north of the Kashiwazaki-Kawira Nuclear Power Plant. Liquefaction evidence was seen in four general settings: riverbank deposits, beach deposits, dune sand, and placed fill. Along the Sabaishi River, liquefaction and lateral spreading features were observed for approximately five kilometers from the river-mouth. River deposits near the sea liquefied and settled severely at the Kashiwazaki wastewater treatment facility (Fig. 6) causing the separation and differential settlement of two plant buildings. Upriver, liquefaction resulted in settlement and lateral spreading of the levee embankment near the Kai-Un Bridge (Fig. 7 and 8), a large water main pipe separation, and a large lateral spread along the river bank immediately east of the municipal incinerator.

Figure 7: Lateral Spread on North side of Kai-Un Bridge area of the Sabaishi River (Google Earth map site RK6, N 37.39343 E 138.58555, 7/19/2007).

The U River, located in the southwestern portion of Kashiwazaki City, was further from the epicentral region and exhibited less liquefaction damage, all within one kilometer of the mouth of the river.

A long, coast-parallel, surficial unit of dune sand extends within and north of the city. This deposit was the source of numerous liquefaction failures, particularly along the edge of the modern flood plain (Figure 9). The sand was typically very soft under foot, and may have been reworked in areas by the ancient, meandering Sabaishi and U Rivers. At one site liquefaction settled ground was observed around the foundation pile cap of a large high-voltage power transmission tower leading from the nuclear power plant. Though the soil pulled away from the cap, the pile cap and tower had no indication of deformation (Figure 10)

Sandy fill deposits used for backfill for the wastewater and storm water drain network performed poorly throughout the epicentral region causing hundreds of separated and uplifted manholes that incapacitated the drains and impeded traffic (Figure 11). Ports and harbors suffered only moderate levels of settlement and liquefaction-related lateral spreading.

Figure 8: Failure of reinforced concrete stack and a large liquefaction-induced lateral spread on the north side of the Sabaishi River (Google Earth map site SP31, N 37.3939° E 138.5840°).

Figure 9: Liquefaction and lateral downslope movement of underlying soil buckled the floor slab of a large warehouse store. (Google Earth map site RK41, N37.41468 E138.60840, 7/22/2007).

Figure 10: Settlement of ground adjacent to the grade beam between footings of a high voltage transmission line tower (Google Earth map site RK40 - N 37.41633 E138.60792, 7/22/2007).

Figure 11: Uplifted manholes from storm-water drains impeded traffic and compromised rainfall drainage throughout Kashiwazaki City and the surrounding villages.

Landslides During The 2007 M6.6 Niigata-Chuetsu Oki Earthquake

Landslides caused by the earthquake consisted of shallow translational slides, debris slumps, and deep-seated rotational slides. In general, landslide activity was focused near the coast, with many steep (50° +) slopes experiencing shallow landsliding of overlying colluvial debris and residual soils (Fig. 12).

Figure 12: Coastal landslides on Highway 352 north of Kashiwazaki-Kariwa Nuclear Power Plant at road closure south of Route 373 (Google Earth map site RK34; N37.48455° E138.62435°; Photo taken 7/22/07).

Shallow coastal landslides were observed to be 0.5 to several meters deep in colluvial and residual soils and ranged from 5 m^3 to several thousand cubic meters in volume. Typical slope surface and failure plane inclinations were between 50° and 70°, failing in translation as debris slides and slumps. Additional landslides also occurred some distance away from the main damaged areas (~10 km northeast of Kashiwazaki and 7 km east of the Kashiwazaki-Kariwa Nuclear Power Plant) in an upland, mountainous region. These slides also generally consisted of shallow translational events. Where transportation lines crossed areas of steep terrain, landslides often blocked or destroyed whole sections of roadways and railways. Three major transportation routes were blocked by landsliding in the region: the coastal road (Route 353) to the north of the Kashiwazaki-Kariwa Nuclear Power Plant (Fig. 12), the railway to the south of Kashiwazaki, at the Oumigawa train station on the Shin-etsu Line (Fig. 13) and Highway 8, north of the intersection with Route 252 located inland from the coast

Figure 13: Landslide at the Oumigawa Train Station on the Shin-etsu Line (Google Earth map site RK20/YT16/SA9; N37.34490° E138.48435°, 7/21/07)

An area of dense landslide activity not investigated by the field reconnaissance team, but identified through helicopter reconnaissance by the Japanese Public Works Research Institute (PWRI) was identified approximately 20 km to the southeast of Kashiwazaki, in the Takayanagi-Machi region. Because this area is located a significant distance away from other observed landslides from the earthquake, it is anomalous to the general pattern of observed seismic-induced geotechnical and structural damage and should be investigated more thoroughly.

Embankment failures were typical in road fills both along the coast, and were also observed at three sites located further inland (Fig. 14). Embankments underwent from 10 cm to in excess of one meter of vertical displacement, extending between 10 and to 60 meters in length. Three embankment failures required full closures of roads, and/or protection with tarps to reduce rainfall infiltration and the associated potential for additional movement. Among these was a 15-meter high, 97.5-meter wide, earth-fill dam located to the east of the region, where cracking through the midpoint of the crest was observed. The water level at the time was well below the crest. At a water supply dam located southwest from the city of Kashiwazaki, cracking of the crest was also observed along with minor concrete cracking and spalling on the upstream side. Here, the reservoir water level was within several meters of the dam crest at the time of observation.

Figure 14: Road embankment failure off Route 8 on the way to Kasashima (Site YT18; N 37.33325 ° E 138.46500°; Photo taken 7/21/07)

Damaged Houses with soil-wall construction During The 2007 M6.6 Niigata-Chuetsu Oki Earthquake

The earthquake caused the collapse of nearly eleven hundred houses in the Niigata prefecture in Japan. Damage to one-to-three story wood buildings was observed along the 30-kilometer long coastal region between Hatsusaki, to the south, and Shiya, to the north. Damage extended inland to western Nagaoka, 12 kilometers west of the coast. The city of Kashiwazaki reported the highest number of collapses in the region. The structures that collapsed were almost exclusively wooden structures and unreinforced masonry fences. Preliminary estimates of collapse rate were between 5 and 7% for buildings and houses in the vicinity of the K-NET instrument in Kashiwazaki. A large fraction of the houses affected were of old-style heavy clay-tile kawara roofs with soil walls (Figure 15). Soft story collapses occurred in buildings with open businesses on the ground floor. The business arcade of Higashi-Honcho Dori was particularly hard hit.

Figure 15: Typical collapse of a heavy kawara-tile roofed home supported by the weak & brittle tsuchi-kabe ("soil wall") construction technique and wooden post and lintel frame.

Bridge Damage During The 2007 M6.6 Niigata-Chuetsu Oki Earthquake

Damage to bridges crossing the Sabaishi River (north of Kashiwazaki) and the U river to (south of Kashiwazaki) was caused by permanent deformation of embankments that run parallel to the rivers and preserved in bridge bearings (Fig. 16). Lateral and vertical deformations of embankments ranging from a few centimeters to about a meter were observed. Embankments cracked at their crests and, in instances, sand boils flowed upward through these cracks indicating liquefaction. Larger ground deformation, and more damage to bridges was observed along the Sabaishi River compared with the U River.

The bridges along the Sabaishi River consist of 15 to 100m-long continuous steel I-girder or reinforced concrete superstructures resting on elastomeric bearings supported by reinforced concrete piers and abutments. The thickness of the bearings ranged from 15 to 30 cm. Bearings deformed where embankment slumping pushed abutments toward the river (Fig. 16). Deformations of bearings ranged from 7 to 17cm. Cracks up to 1-cm wide were observed in reentrant corners of abutments. Spalling of pavement and concrete was observed at expansion joints.

Figure 16: Strained bearing (site SA18, N37.39041° E138.59052°; 7/21/2007)

Vertical offsets at bridge approaches caused by soil settlement ranged from 5 cm to a meter (Fig. 17). Asphalt or gravel fill was placed to permit cars to cross bridges. Utility lines attached to bridges where approaches settled were damaged. Settlement of approaches was observed at bridges crossing the Sabaishi and U rivers and bridges along the Hokoriku Expressway.

Damage to Utilities During The 2007 M6.6 Niigata-Chuetsu Oki Earthquake

According to the Niigata Prefecture Government, approximately $13 billion in damage occurred to the lifeline infrastructure as a result of this earthquake. Several lifelines remained closed a month after the event. Water for the region is provided by reservoirs in the mountains north of Kashiwazaki and two of the three pipes carrying water into the city broke. Pipe breaks were the result of landslides, lateral spreading, liquefaction, and soil settlement. Manholes blocked roadways when pipes rose due to soil liquefaction. Damage to the wastewater treatment plant, including damage to pipes, clarifiers, sludge digesters, and other equipment by soil displacements and differential settlements, prevented removal of sludge from the system.

In addition to the problems at the nuclear power plant, there was damage to the transmission system maintained by Tohoku Electric. Towers, transformers, and other equipment were affected by soil lateral spreading, soil settlement, and ground shaking. There were five-minute to 10-hour power disruptions after the earthquake. Natural gas lines broke as a result of liquefaction and settlement of soils and pressurized tanks exhibited permanent displacements after the event. One month after the earthquake, restoration of service was ongoing.

Figure 17: Settlement of approach fill to bridges along the Sabaishi, here, and U Rivers created critical transportation hazards immediately following the earthquake.

The high volume of calls following the earthquake and the damage to underground optical cable conduits in five locations impaired telephone and internet services. Approximately 5% of the fiber conductors in these cables were cut. Power interruption longer than 10 hours impacted cellular phone services. The phone system was restored three days after the earthquake. A phone emergency service system worked well during the earthquake.

Geoengineering Damage to Transportation Systems During The 2007 M6.6 Niigata-Chuetsu Oki Earthquake

Transportation systems were disrupted by landslides, lateral spreads, embankment slumping and spreading, bridge approach settlement, liquefaction of utility trench fills, and post-earthquake sub-grade construction recovery efforts. In many cases, roadways were blocked by landslide debris, in others, the roadfill and foundation failed requiring extensive repair. Despite the numerous road closures and pavement damage, significant progress was made toward repairing critically damaged roadways during the time of the reconnaissance.

The most striking damage to the transportation network was caused by large landslides destroying sections of roads (Fig. 18). In one location, both lanes of a busy regional highway were moved down slope by about 10 m as a result of a deep-seated slope movement. The road was re-opened less than seven days following the earthquake, which is a testament to the excellent Japanese post-earthquake response, and an illustration of the importance of deploying reconnaissance teams soon after earthquakes to record perishable data. A large lateral spread affected a road near the Kashiwazaki municipal waste incinerator, forming a headscarp with a vertical offset of 2.5 meters that transected the road. The pavement was heavily damaged for a length of over 200 meters in the lateral spread (Figure 8).

Figure 18: The Ozumi Senbon Landslide (Site RK1; E37.41422° N138.71347°)

Embankment failures affected transportation access, closing partial to whole lanes. In most cases, one lane remained open despite longitudinal ground cracks in many pavement sections that required cars to progress slowly and carefully over the damaged roadway. Settlement of soils at bridge approach fills caused vertical offsets at many bridges by as much as one meter. (Fig. 17). Two tunnels were closed: one due to landsliding near the portal area and the other from unknown causes. Pavement damage was widespread and caused by liquefaction of utility trench fills, and/or uplift of buried utilities due to buoyancy in liquefied ground. Such damage typically caused closure of one lane of traffic, and in only a few cases were closure of entire roadways necessary due to utility trench fill liquefaction failures.

Damage to railways was caused by landslides (for example, at the Oumigawa Train Station south of Kashiwazaki), settlement of foundation soils, spreading and slumping of railway embankments, and transient ground shaking. Horizontal track offsets up to 30 cm were observed (Fig.19). Liquefaction and resulting ground failure caused rail damage in many cases, but there were cases where rail offsets occurred without ground failure, presumably due to transient shaking. Some damage occurred to trains carrying passengers at the time of the earthquake - news reports immediately following the earthquake indicated that a stationary train tipped over at Kashiwazaki Station but that no one was injured.

Figure 19: Lateral deformation of train tracks at Arahama Station (Site RK13; N37.40555° E138.60197°, 7/21/07)

Port and Airport Damage During The 2007 M6.6 Niigata-Chuetsu Oki Earthquake

The coastal location of this moderate-sized earthquake resulted in moderate damage to port and coastal infrastructure from the southwest, at the small village of Kasashima, to north of the town of Kariwa. The Kasashima harbor exhibited negligible to very minor evidence of ground deformation and seismic effects to coastal infrastructure (e.g. quay walls, seawalls, breakwaters). Trace remnants of very small, localized ground deformations were observed, and it appears that the ground motions in this area were just strong enough for incipient lateral deformation of the ground and waterfront earth retention structures (Figure 20). The westernmost section of the Port of Kashiwazaki was subjected to the effects of widespread liquefaction, lateral spreading and settlement exceeding 30 cm in many areas and a pronounced graben formed between a port building and the waterfront quay wall. A pile supported structure performed very well, but two pedestrian-accessible roof areas on either side of the main structure were distressed by ground settlement and lateral spreading.

Figure 20: Kashiwazaki Harbor – Liquefaction induced lateral spreading and settlement of soil beneath a harbor-front caisson resulted in rotation toward the harbor and lateral displacement of the soil behind it (Site RK25, N37.36713 E138.53210, 7/20/2007).

Along the waterfront to the southwest of the Sabaishi River and transverse to the riverfront sheet pile wall is a seawall that extends southwest roughly 2.0 km towards the Minatomachi Seaside Park. On the north end of the seawall, the lateral wall movement was roughly 0.6 m and exhibited an increased seaward tilt to the southwest with lateral deformation of approximately 1.5 m to 2.0 m. At the TEPCO Nuclear Power Plant liquefaction, ground settlement and tilting of a building were observed near the shore on the west of Unit 5.

(II) THE NIIGATA KEN CHUETSU EARTHQUAKE OF OCTOBER 23, 2004

The Mw 6.6 earthquake that struck Niigata Prefecture on the evening of October 23, 2004, was the most significant earthquake to affect Japan since the 1995 Kobe earthquake. Forty people were killed, almost 3,000 were injured, and numerous landslides destroyed entire upland villages. Landslides were of all types; some dammed streams, creating new lakes that threatened to overtop their new embankments and result in flash floods and mudslides. Landslides and permanent ground deformations damaged roads, rail lines and other lifelines, resulting in major economic disruption. The numerous landslides resulted, in part, from heavy rain associated with Typhoon Tokage. At Nagaoka City, there had been 100 mm (4 inches) on October 20 and 13 mm (.5 inch) on October 21. The earthquake forced more than 100,000 people into temporary shelters, and as many as 10,000 will be displaced from their upland homes for several years, if not permanently. Total damages are estimated by Japanese authorities at US$40 billion, making this the second most costly disaster in history, after the 1995 Kobe earth-quake.

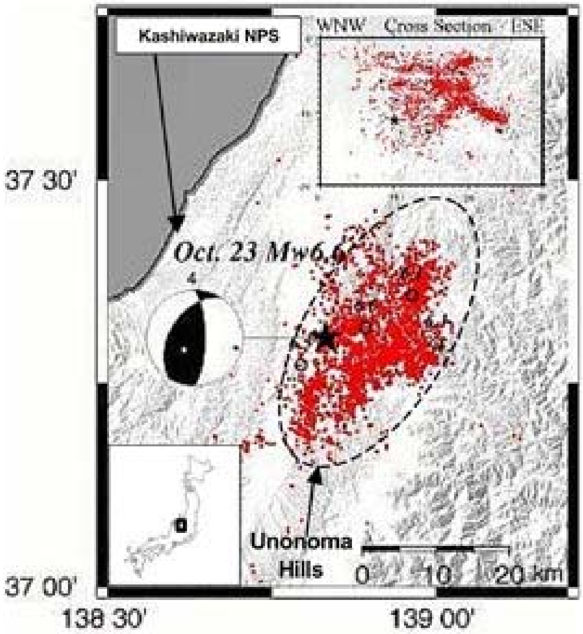


Figure 21: Aftershock pattern and mechanism. The Unonoma Hills are approximately outlined by dashed ellipse, and the Shinanogawa Lowland is the white area to the west (adapted from original figure by Group for Joint Observation, Kyoto and Kyushu Universities).

The epicenter was in northwestern Honshu, about 80 km south of Niigata City (population 500,000), a city well-known for liquefaction damage following the 1964 M7.5 earthquake. The 2004 epicenter was beneath the Uonuma Hills along the Shinanogawa Lowland (Figure 21). Though the 2004 earthquake was felt in Niigata City, no damage or liquefaction was observed there. South (or upriver) of Niigata, toward the epicentral area, there are a number of smaller cities and towns on the plain and some industrial sites; the remainder of the plain is covered by wet rice farmland (i.e. rice paddies). Nagaoka (population 194,000) was the largest city significantly affected by the earthquake. It suffered minimal damage, but had highway and train service disruptions, school closures, and an influx of refugees from surrounding areas. More seriously damaged areas were the city of Ojiya (population 41,000) and surrounding rural areas, most notably the village of Yamakoshi (population 2,222) and the town of Kawaguchi (2000 population 5,748), which sustained JMA intensity 7, the maximum on that scale (approximately equivalent to MMI XI-XII). The Joetsu Shinkansen crosses this region in a north/south direction and terminates in Niigata. One of its trains was derailed by the earthquake.

Seismology And Strong Ground Motions During The 2004 Niigata Ken Chuetsu Earthquake

The mainshock at 17:56:00 Japan time (08:56:00 UT) on October 23 had a moment magnitude Mw 6.6. The epicenter (lat. 37.30, long. 138.84) was located 4 km east of the city of Ojiya (Figures 21 and 23). The main shock was followed by an aftershock sequence with four events of JMA magnitude 6 or larger, and 12 events of magnitude 5 to 5.9 (as of November 28), far more than usual for an event of this magnitude. There was no surface rupture observed with the earthquake, and the mainshock is currently not associated with any mapped fault. The focal mechanism of the main shock shows almost pure reverse faulting on a fault striking 30 degrees east of north, dipping down to the northwest at 54 degrees. The source area is 20-30 km long, with down-dip widths of about 14 to 25 km.

The earthquake occurred near the Sea of Japan in an area of relatively high seismicity. Within 100 km, there have been five other earthquakes greater than $M_{jma}6$ since 1941, including the 1964 Mjma7.5 Niigata earth-quake. All the large earthquakes of the present sequence occurred beneath the mountainous region east of Ojiya, where there are mapped Neogene-Quaternary folds. Across the region, there are many mapped short lineaments (1-10 km) trending north-east-southwest, along with the recognized Muika-Machi-Bonchi-Seien fault (Geological Survey of Japan).

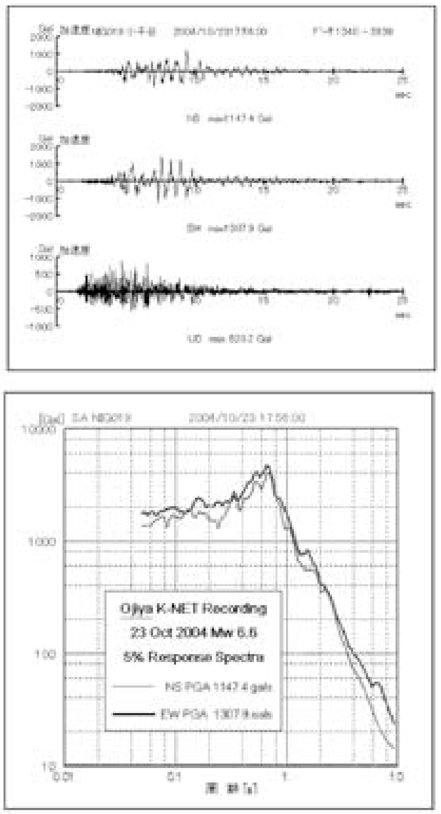


Figure 22: Ojiya K-NET Seismograph NIG019. (top) PGA 1.33 g EW, 1.17 g NS, and 0.83 g UD, and (bottom) 5% damped response spec-tra for two horizontal directions (source: NIED).

The hypocenter was in the central or lower region of the fault, so the rupture propagated updip toward the east and along strike in the north-east and southwest directions, with a duration of about 10-15 sec. The largest amount of slip was in an area about 10 km x 10 km in the region of the hypocenter. Strong hanging wall effects were manifested in the large peak accelerations recorded above and to the west of the fault at locations such as Ojiya, where 1.33g PGA and 128.7 cm/sec PGV were recorded 4 km west of the hypocenter (Figure 22). The largest recorded peak acceleration, 1.75 g (and 53.1 cm/sec PGV), was recorded at Tohkamachi (NIG021), located about 20 km south-southwest of the epicenter. Peak accelerations of 0.48g and 0.89g were recorded at Nagaoka and Nagaoka-Shisho, respectively, located 16 km north of the epicenter. The peak acceleration recorded at Niigata City, at an epicentral distance of 70 km, was 0.11g. For comparison, the Mw 7.5 1964 Niigata earthquake, which caused the extensive liquefaction, was located offshore at an epicentral distance of about 55 km north of the city, and had a peak value of 0.16 g, with a longer duration in Niigata City.

Aftershock hypocenters are distributed over a region that is about 30 x 20 km at depths ranging from 15 km to the surface, which roughly coincides with the area of the main-shock and larger aftershock rupture areas. The locations show a complex pattern of westward and eastward dipping structures that are associated with the mainshock and larger aftershocks.

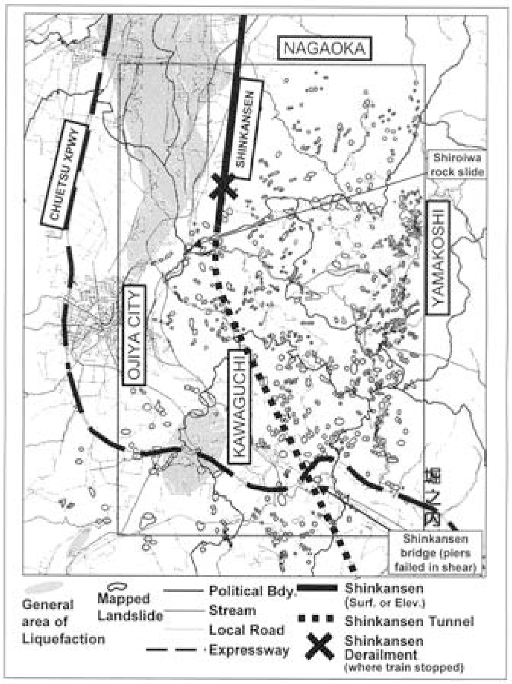


Figure 23: Map of affected area showing main effects of mainshock (adapted from KKC aerial photos).

Geotechnical Aspects Of The 2004 Niigata Ken Chuetsu Earthquake

Landslides, liquefaction, and permanent ground displacements accounted for most of the physical and economic effects of the earthquake. Figure 23 shows the distribution of landslides caused by the earthquake, as well as areas where liquefaction was generally observed. The map also shows other effects discussed below.

Landslides During The 2004 Niigata Ken Chuetsu Earthquake

Niigata Prefecture documents 442 individual landslides in this earthquake, although on the ground the number appeared even larger. Heavy rainfall in the days prior to the earthquake likely had a fundamental impact on the distribution and scale of landsliding. Bedrock throughout the area of major landsliding consists of a folded sequence of very weak and friable claystone and siltstone that is fairly nondurable, with interbedded sandstone and minor conglomerate. For the argillaceous bedrock materials, high antecedent moisture would tend to cause softening and strength reduction, as well as elevated pore or joint water pressures and seepage forces.

Observed modes of slope failure included translational soil slips, deep-seated rotational slumps, debris-flows, slump-flow complexes, and large block slides. In some cases, the failures were clearly controlled by bedrock structure., Observations indicate that some preexisting (ancient) deep-seated landslides were not remobilized during the earthquake.

Figure 24: North-facing valley wall with extensive translational soil sliding into valley bottom, Yamakoshi epicentral area (photo: K. Kelson).

The most widespread type of observed failure consisted of translational slip of the regolith and highly weathered bedrock materials on very steep slopes flanking floodplains and along incised river and creek channels. This type of failure generally involves the upper 1.5-3 m of soil, and slip appears generally to be concentrated along the interface between significant root growth and underlying highly weathered bedrock. Examples of this type of failure are shown in Figure 24.

Figure 25: Typical debris flow, exhibiting a narrow path and long runout.

Another commonly observed failure mode in areas of deep regolith was slump-flow complexes within colluvium-filled swales. If antecedent moisture conditions had not been so severe, it is probable that the significant flow characteristics commonly exhibited by these failures would not have been so prominent. Many debris flows with significant runout distances were triggered by the earthquake, as shown in Figure 25. In several cases, massive debris flows blocked natural drainage courses, forming landslide dams. These events have already resulted in the flooding of villages and infrastructure (Figure 26), and there is potential for large sudden floods to initiate if the landslide dams are breached in an uncontrolled manner.

Figure 26: Inundation of homes upstream of landslide dam (photo:K. Kelson).

Figure 27: Block slide formed by bedding plane (sliding surface) and two sets of vertical joint release surfaces (photo: R. Kayen).

An earthquake-triggered landslide dammed a river about 1 km west of Komatsugura. The landslide was a block slide that formed on a dip slope dipping about 15-20 degrees west. As the block moved downslope, a large graben formed at the head of the landslide; the landslide moved across the canyon and completely blocked the drainage. A lake several kilometers long formed behind the dam and initially the lake was rising 15-20 cm/day despite efforts to pump water over the dam. Several roads and structures had been inundated upstream. An emergency spillway was being constructed to prevent uncontrolled overtopping and catastrophic failure of the dam, which could inundate downstream communities in ten minutes. The landslide material consisted of weakly cemented Pliocene and Pleistocene sandstone and mudstone that is easily erodible.

A classic example of a block slide can be seen in Figure 27. The mould (negative impression) of the block is defined by a bedding surface dipping at about 30° toward the freeface of the slope, along with vertical joint release surfaces intersecting the right side of the bedding plane. The overlying block of bedrock traveled on the order of 30m-50m, riding over the valley floor. This failure occurred along a hogback ridge, and bedding plane slides of similar or larger size were observed at several locations long the hogback.

Figure 28: Deep rotational slump, indicated by a block of back-rotated trees and agricultural land, beneath an approximately 30m-50m foot high headscarp (photo mosaic: R. Kayen).

A major landslide at Shiroiwa (White Rock) drew international attention because a mother and two young children were buried in their car. They were discovered about four days after the quake, with only the four-year old boy surviving.

As the bedrock throughout the area of major landsliding is judged to be sufficiently weak under saturated conditions to permit development of continuous shear on curved surfaces, it is not surprising that deep-seated rotational slides occurred, much like classical soil slumping. Figure 28 shows a deep rotational slide, as evidenced by a block of back-rotated trees and agricultural land bordering an approximately 30m-50m high headscarp to the left. Farther downslope, similar back-rotated blocks were observed, and the estimated maximum depth of the sliding surface is on the order of one hundred meters.

A major question remains regarding the influence of prior rainfall on slope stability. The extent of landsliding is very large, and the authors are not aware of other earthquakes of similar magnitude that have caused slope instability to this extent. If the earthquake had struck under normal soil moisture conditions, or relatively dry conditions, it is likely that the extent of landsliding would have been significantly less.

This emphasizes that risk of prior rainfall should be considered in any evaluation of seismically induced slope instability. Due to the sparse population in the mountainous epicentral region, the number of resultant casualties was surprisingly small. However, seismically induced landslides under saturated ground conditions in areas of the San Francisco Bay and Los Angeles would cause similar damages and many more casualties.

Figure 29: Sand boils at the derailing site of the Johetsu Shinkansen (Oct. 25) (photo: K. Kiyono).

Liquefaction During The 2004 Niigata Ken Chuetsu Earthquake

Evidence of liquefaction was widespread but sporadic, and was primarily confined to rice fields along the Shinano River and to backfill around sewer pipelines. Some sand boils were observed under the Shinkansen viaduct (Figure 29) near the site of the derailment, and under a few bridges. However, there was much indirect evidence of liquefaction. Liquefaction may have contributed to the many ground failures, particularly near Kawaguchi, though no sand boils were observed. Ground settlement on the order of tens of centimeters along the Uono and Shinano rivers, along with levee slumping, could have resulted from liquefaction. Ultimately, the amount of liquefaction and associated ground failure was less than that anticipated by members of the EERI reconnaissance team.

Hillside Fill Damage During The 2004 Niigata Ken Chuetsu Earthquake

The hillside residential area of Takamashi, located on the eastern edge of Nagaoka, experienced significant slope failures during the earthquake. Takamachi is located on a natural hill at the edge of the Shinano valley and the native soil consists of early Pleistocene sand and silt. It is assumed that the area was constructed by cutting the top of the hillside and using this material as fill along the edges. In most places, the fill was confined by a 4m high rigid, concrete retaining wall. Four large sections of retaining wall failed catastrophically, with the soil sliding a significant distance downslope. Figure 30 shows one of the large failures, extending across the road and close to the adjacent homes. Four segments of the concrete retaining wall translated significantly during the earthquake, including one that came to rest within the trees downhill.

Figure 30: Failure of hillside fill in Takamachi residential area (photo: E. Rathje).

In addition to the catastrophic failures, severe cracking due to slope and retaining wall deformations was observed in many areas along the edge of the hill. As much as 1 m of downslope movement was observed, and these deformations caused significant damage to structures. No failures or ground cracking were observed in areas that did not have a retaining structure.

The yellow and red tagged structures within the Takamachi area were almost completely concentrated in areas with adjacent slope failures and ground cracking. Within the interior of the hillside area, only green-tagged structures were encountered. It appears that all of the structural damage in Takamachi can be attributed to the deformations and failures of the hillside slopes.

Building Damage During The 2004 Niigata Ken Chuetsu Earthquake

As a generalization, building damage in this earthquake was surprisingly light given the high apparent ground motions. Traditional single-family Japanese houses of bamboo reinforced mud infill and heavy fired clay tile roofing performed very poorly being prone to pancake collapse. In the Niigata region, houses tend to have larger and more numerous interior columns and heavier roof beams, due to the heavy snows (up to 3 m) every winter. A substantial number of these buildings collapsed in Kawaguchi, although the effects of shaking and PGD were hard to differentiate. Damage in Ojiya was lighter, although there were still some collapses and heavily damaged houses. There was very little to no damage to houses of this type in Nagaoka.

Within the last two decades, a newer type of residential construction has been increasingly built in the region, presumably due to the snow accumulations, in which the entire ground floor exterior wall is of reinforced concrete, with second and third stories of more traditional wooden construction. These buildings are significantly taller and larger than more traditional housing, and are more like U.S. housing in that they have shingle roofing rather than heavy clay tile. They fared very well in the earthquake, having benefited from more modern building codes and construction practices.

Commercial and institutional buildings generally performed well, with some exceptions. A surprising success was a three-story 1960s vintage reinforced concrete (RC) frame school building in Ojiya about 40 m from the 1.33 g PGA seismograph recording. The building was completely un-damaged, with the exception of a cracked brick chimney. Another success story was a large three-story hotel complex situated on the ridge directly above Kawaguchi. Despite having a landslide immediately adjacent, the building sustained no damage, with the exception of some minor pounding at a seismic joint between two parts.

Large "big-box" stores are increasingly prevalent in Japan, and two were observed in Ojiya with precast cladding having fallen away from steel frames. Entry was denied, but extensive salvage and repair operations were observed. A ten-story concrete-clad building was observed to have classic shear cracking of columns, and an electronic chip fabrication plant was reported to have sustained heavy nonstructural damage.

Lifeline Damage During The 2004 Niigata Ken Chuetsu Earthquake

After landslides, damage to lifelines was the most notable result of this earthquake. Roads and highways were damaged at numerous locations, with similar damage to rail lines. A historic first was the derailment at full speed of a Shinkansen (bullet) train. With that exception, transportation structures performed generally well in this series of earthquakes. There were no collapses; damages appeared to be limited and repairable, and not surprising given the level of ground motions. Of the bridge structures crossing the Uono and Shinano Rivers in the epicentral region, all but two of the highway bridges were immediately open for, at least, limited traffic after the earthquake. The other two bridges were open for emergency vehicles.

Figure 31: Typical damage to road in Uonoma Hills. (photo: R. Kayen).

An unusual aspect of this earthquake was damage to transportation tunnels. Water and power systems sustained some damage, but were back in service within hours, except in the hardest hit areas.

Road and Highway Damage During The 2004 Niigata Ken Chuetsu Earthquake

Landslides and permanent ground displacements of varying magnitudes seriously damaged roads at over 6,000 locations throughout the region. Virtually all roads in the Uonoma Hills were cut by landslides (Figure 31) and many pavements in the lowland areas were disrupted by floating manholes, settlements at culverts and bridge abutments, and general disruption of the paved surface.

Figure 32: Derailed Shinkansen (Oct. 31) (photo: C. Scawthorn).

Highway bridge structures generally performed well in the earthquake series, with the exception that significant settlement of approach fills was observed on many bridges. Several highway bridges suffered damage to piers and bearings, but closure of the bridge was not required. A unique feature of the region are pipes, carrying water at 13° C, embedded in concrete along many streets and roads; the water is sprayed on snow in the winter to melt it. Over 600 km of snow-melt piping exists in the region, and much of it was damaged. Snow-plows cannot operate on such roads, so considerable disruption occurred during the first winter in areas where the pipes were broken when the snows came.

There was extensive damage to roadbeds caused by ground failures. Significant damage was observed on the Shinkansen elevated viaduct, as well as on some local railway lines, but all appeared to be repairable. The Joetsu Shinkansen line carries 360,000 passengers per day, and was scheduled to restore service on December 28, 2004. A northbound Shinkansen train derailed just south of Nagaoka City (Figure 32). As the train, traveling over 200 km/hr, was exiting a tunnel, the driver felt the earthquake and applied the brakes. The train passed under a 300-m-long covered section, and began to derail along a viaduct, approximately 500 m from the exit of the tunnel.

The train engine came to rest approximately 1.9 km from the tunnel exit, taking over 1.5 km to stop. There were no reported injuries as a result of the derailment, which occurred entirely along a straight section of elevated, level viaduct through rice farms. The viaduct, constructed in the 1970s, is composed of several different types of segments with varying heights and section design, some of which were damaged in the earthquake. Ground cracking, ground settlement, and signs of significant soil softening were observed at many locations along the viaduct (Figure 29).

Figure 33: Damaged piers of Joetsu Shinkansen Wanazu Bridge (Nov. 1) (photo: S. Ashford).

In the town of Kawaguchi, the Joetsu Shinkansen railway bridge was damaged. Piers supporting the Wanazu Bridge over the Uono River suffered a flexural failure due to a reinforcement discontinuity, as shown in Figure 33. Several columns of a viaduct section just south of the bridge also failed. Tracks of the JR Joetsu Line were also damaged due to minor fill settlement in the Wanazu area. In Kawaguchi, rails were buckled in numerous locations, and several plain concrete piers of the JR Iiyama Line were damaged, while the superstructure remained intact.

Several tunnels were damaged in this event, including the 8.6 km Shinkansen tunnel, which had fallen lining at about mid-length and buckled track. Spalled lining occurred in the Wanatsu Tunnel of National Route 17.

The earthquake cut off all power, gas, water, and telephone service to Ojiya city. Upwards of 300,000 households in the region lost electric power. As of Sunday evening, the day after the earthquake, 98,000 homes in Ojiya and Nagaoka still lacked electric power. Water supplies were cut through most of the affected area, and the lack of telephone service added to the isolation of the mountain areas cut off by landslides. Many areas received water from tank trucks, dispatched from neighboring areas.

Electric power was restored steadily, but as of October 26, 34,000 households were still without power, mostly in Nagaoka and Ojiya. Tohoku Power employed 1,900 repair workers, but they were impeded in some places by damaged roads. Water and gas service took longer to restore, and as of October 26, 108,000 households still remained without running water and 56,000 without gas. Access was impeded by all the road closures. By November 3, power was restored to all but 2,300 households, mostly in evacuated parts of Yamakoshi and Ojiya.

Nagaoka City receives its water from the Shinano River, upstream of the city. Water level in the river is raised by lowering gates across the river, and water is diverted into a pipe that carries the water to a treatment plant downstream of the gates. The earthquake disrupted power to the gates and also caused some damage to the wire rope machinery used to raise the gates, so the gates could not be lowered and the treatment plant received no water. As a result, the plant had to resort to emergency drafting from the Shinano River (Figure 34).

Damage was more extensive at the Ojiya water treatment plant, which also draws its water from the Shinano via an intake structure and over the levee on an approximately 70-m long steel truss bridge. Differential displacements of the supports damaged the bridge, but did not cause collapse. In the plant, there were obvious signs of ground settlements, and the plant had sustained piping damage. The plant was back in operation in hours. From the plant, water is pumped to two large 25m diameter hilltop tank reservoirs, one on each side of the Shinano. Some ground settlements had occurred around one of the tanks, and entry structures had collapsed, but the tank was largely undamaged and in operation. The hilltop location is within 1 km of the 1.33 g PGA recording in Ojiya, and the hilltop had sustained landsliding and damage to nearby houses, and clearly had undergone very strong shaking.

Figure 34: Emergency drafting of water from Shinano River for Nagaoka City Water Treatment Plant (photo: C. Scawthorn).

Approximately 23 km from the epicenter is the Kashiwazaki-Kariwa Nuclear Power Station, at 8,300 MW (7 units) the world's largest Nuclear Power Station (NPS). The October 23 main shock reportedly had no effect on the NPS, but a magnitude 5.2 Earthquake on November 4 caused Unit 7 to shut down automatically (other units operated at the rated thermal power). In Kawaguchi, the Shinkansen has a substation stepping power down from 63kv to 1500 volts(the service voltage for the Shinkansen catenaries). Transformers in the substation were significantly tilted due to liquefaction, but still operating, and otherwise the substation was undamaged.

Social Impacts Of The 2004 Niigata Ken Chuetsu Earthquake

The most seriously affected areas were small towns and villages near Nagaoka, especially the village of Yamakoshi, the town of Kawaguchi, and the city of Tokamachi. As is true in rural areas throughout much of Japan, the population has been in decline, with Yamakoshi and Kawaguchi declining by 11.9% and 5.9%, respectively, from 1995 to 2000. Nearly 40% of Yamkoshi residents and 25% of Kawaguchi residents are elderly. Although the earthquake occurred in mid-autumn, winter was rapidly approaching, and Niigata Prefecture is known to receive some of the heaviest snowfall in Japan.

Because landslides cut off transportation and communication to many areas, it took some time for emergency services to identify damage and assess needs. There were re-ports of family and neighbors rescuing people from collapsed homes. By the morning after the Saturday evening earthquake, the Self-Defense Forces (SDF) opened a disaster headquarters in Ojiya to coordinate relief efforts, and used 300 personnel, 21 helicopters, and 65 vehicles to transport food and water to evacuation sites. They also evacuated tens of thousands of residents to emergency shelters, and used helicopters to airlift stranded villagers from the hamlet of Shiotani.

More difficult was reaching the isolated towns of Kawaguchi andYamakoshi, which initially depended on airlifted food and water until they could be rescued the following day. In Kawaguchi, about 300 people took refuge in an elementary school and awaited assistance. By Monday evening, relief supplies were coming in over the roads, but still with not enough food for the population. In Yamakoshi, 250 residents spent two nights in a gymnasium without power or water before being evacuated. All but six of Yamakoshi's 2,200 residents were evacuated and taken to three sites in Nagaoka. The national government applied the disaster relief law to 29 localities, which meant that government would cover the cost of relief and shelter.

Many people spent the first night in their cars, but by the day after the earthquake, 82,000 were staying in emergency shelters. In Ojiya, 14,500 people took refuge at 93 different evacuation centers, mostly school gymnasiums and public halls. Even in lightly damaged Nagaoka, more than 34,000 people were evacuated to temporary shelters. On Monday, October 25, thousands were airlifted from about 60 mountainous communities, which remained closed to road access. Thirty police and SDF helicopters were needed to evacuate residents of seven municipalities. By Tuesday, October 26, about 320 people were still stranded in five hamlets.

Aftershocks and landslide dams posed continuing problems. A M5.2 aftershock on November 4 halted the bullet train line between Niigata and Nagaoka. It also closed down a section of the bullet train tracks that had just reopened. A M5.9 aftershock on November 8 again stopped the bullet train and closed a portion of the expressway to Tokyo. Continued rain during the ten days following the earthquake raised concerns about water behind the landslide dams in Ojiya and Yamakoshi. The Japan Meteorological Agency set up alarm units and surveillance cameras at five landslide dams, the prefecture prepared pumps to lower the water levels, and the prefecture recommended evacuation of 101households containing 439 residents.

As of November 28, authorities attributed 40 deaths to the earthquake. Although most died from building collapses, approximately 14 deaths were from stress-related illnesses following the earthquake. One hospital patient died when an artificial respirator detached during the earthquake. Five died from complications due to living in their cars, including blood clots from inactivity. As a result, the prefecture encouraged people to move into SDF tents or to stay in accommodations farther away. Elderly residents were especially susceptible to exposure and stress-related illnesses.

Economic Effects Of The 2004 Niigata Ken Chuetsu Earthquake

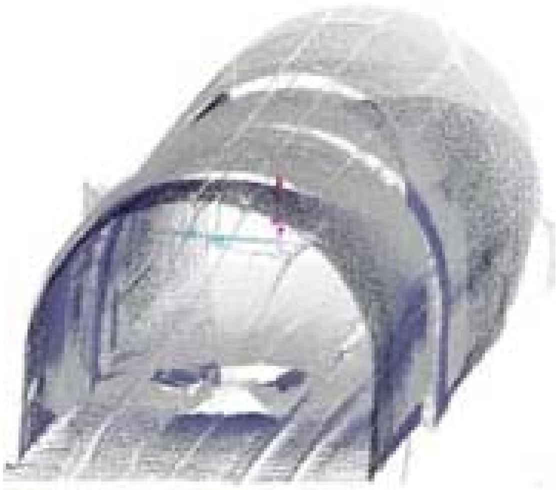
Agricultural activities in Yamakoshi were disrupted by the earthquake, and residents fear permanent consequences. The village's main industry is the raising of carp, which it provides to decorative ponds throughout Japan. The cattle industry is another concern. Residents had to leave behind 1,000 cattle. In order to save his business, the largest cattle owner began ten days after the earthquake to airlift 700 cattle out of the village by helicopter, at considerable expense.

Area industries were also affected. Hokuetsu Paper Mills plant in Nagaoka shut down for several days, as did Matsushita Electric's chip production center. The Niigata Sanyo Electric Plant in Ojiya, which employs 1,500 workers and is Ojiya's largest employer, is closed indefinitely. An auto parts plant has been unable to resume its speedometer assembly line, which caused Honda Motor Company to halt auto production at four plants elsewhere in Japan. Other plants shut down for approximately one week, including Panasonic Communications, and Alps Electric Company.

The Tokyo Stock Exchange fell on the Monday following the earthquake, with the largest losses to Japan Rail East, companies with production facilities in the area, and insurers. On the positive side, the *Japan Times* reported that shares of construction-related companies increased sharply November 1on the Tokyo Exchange, because investors anticipated a supplementary national budget to pay for reconstruction following the earth-quake and recent typhoons. However, reconstruction will be a challenge to homeowners, since only 11.2 % of households in Niigata Prefecture have earthquake insurance, compared to 17.2 % nationally.

First Application of LIDAR Technology for Earthquake Reconnaissance

For the first time, a reconnaissance team utilized LiDAR, a 3-D scanning-laser that can create high-resolution, three-dimensional, digital terrain models of any surface, including earthquake-related ground, structural, and lifeline deformations. Approximately 30 laser scans of damaged roadways, structures, and displaced ground were taken with a tripod-mounted LiDAR apparatus, a portable device that models surfaces to a measurement accuracy of 1-2 cm.



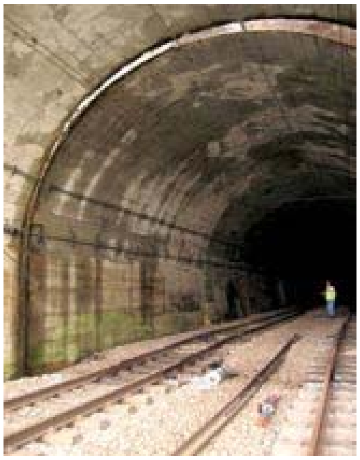


Figure 35: Photograph (below) and LiDAR image (above) of damage to the Juetsu Railroad portal at Kita-Horinouchi from the portal entrance. Lateral displacement of the portal in the *photo is visible and measurable in the LiDAR scan. (: R. Kayen)*

An example of structural damage captured by the USGS LiDAR unit is presented in Figure 35, collected in the damaged portal of the Juetsu railroad tunnel, north of Horinouchi town. The portal is founded on a poorly compacted embankment fill that failed during the earthquake. The portal pulled away from the tunnel, settling vertically, sliding downslope, and rotating. In the photograph, the offset in the portal can be seen along the left wall of the tunnel, and the rotation can be seen in the ceiling. An oblique view of the LiDAR point-cloud data can be seen on the right. The left-lateral offset in the portal is clearly visible in the LiDAR model. In the LiDAR imagery, precise centimeter-scale measurements can be made of the three-dimensional deformation of the structure.

(3) OBSERVATIONS ON THE SEPTEMBER 26, 2003, TOKACHI-OKI EARTHQUAKE

Seismological Aspects Of The 2003 M8.0 Tokachi-Oki Earthquake

The 2003 Tokachi-Oki earthquake was the third event of magnitude 8.0+ to strike the southeastern portion of Hokkaido in the last 50 years. The earthquake hypocenter was located at latitude 41.9° north and longitude144.1° east, at a depth of 42 km (Figure 1). The slip distribution inverted from seismograms shows this as a repeat rupture of the 1952 Tokachi-Oki M8.2 event fault segment. Both events are megathrust earthquakes that result from segmented rupture of the Pacific plate beneath the Hokkaido-Tohoku accretionary prism.

The primary M8.0 event occurred at 4:50 a.m. local time on September 26, 2003, and was followed by a second M7.1 event at 6:08 a.m. Both events triggered ground failures along the southern coastal region of Hokkaido. The primary event produced tsunami run-ups along the shoreline of southern Hokkaido that reached maximum heights of 4 meters in the areas of Taiki and Erimo.

Accelerations recorded by seismic networks of Hokkaido indicate a high intensity motion region from Hiroo area to Kushiro City, with a PGA values in the range of 0.35 to 0.6g (Figure 36). The highest PGA (1.0g) is an apparently anomalous recording at the Hiroo City Hall, behind the bluff overlooking the nearby Port of Tokachi (~0.45 g). Acceleration response spectra for Hiroo and Tomakomai are presented in Figures 37 and 38, respectively. Despite high acceleration levels, the observed ground failure, liquefaction, structural, port, and lifeline damages were remarkably light. The reason for this is not fully understood, but may be associated with the unusually high frequency of the major loading cycles. Ground motion durations were typical of an M8 event. In the southeastern coastal areas close-in to the rupture, significant loading (>0.05g) had durations ranging from approximately 1.5-to-3 minutes. On the Japanese Shindo intensity scale, the region from Urakawa, west of Erimo peninsula to Kushiro felt intensity 5-6. Other portions of Hokkaido and northern Tohoku, Honshu felt motions of intensity 2-4.

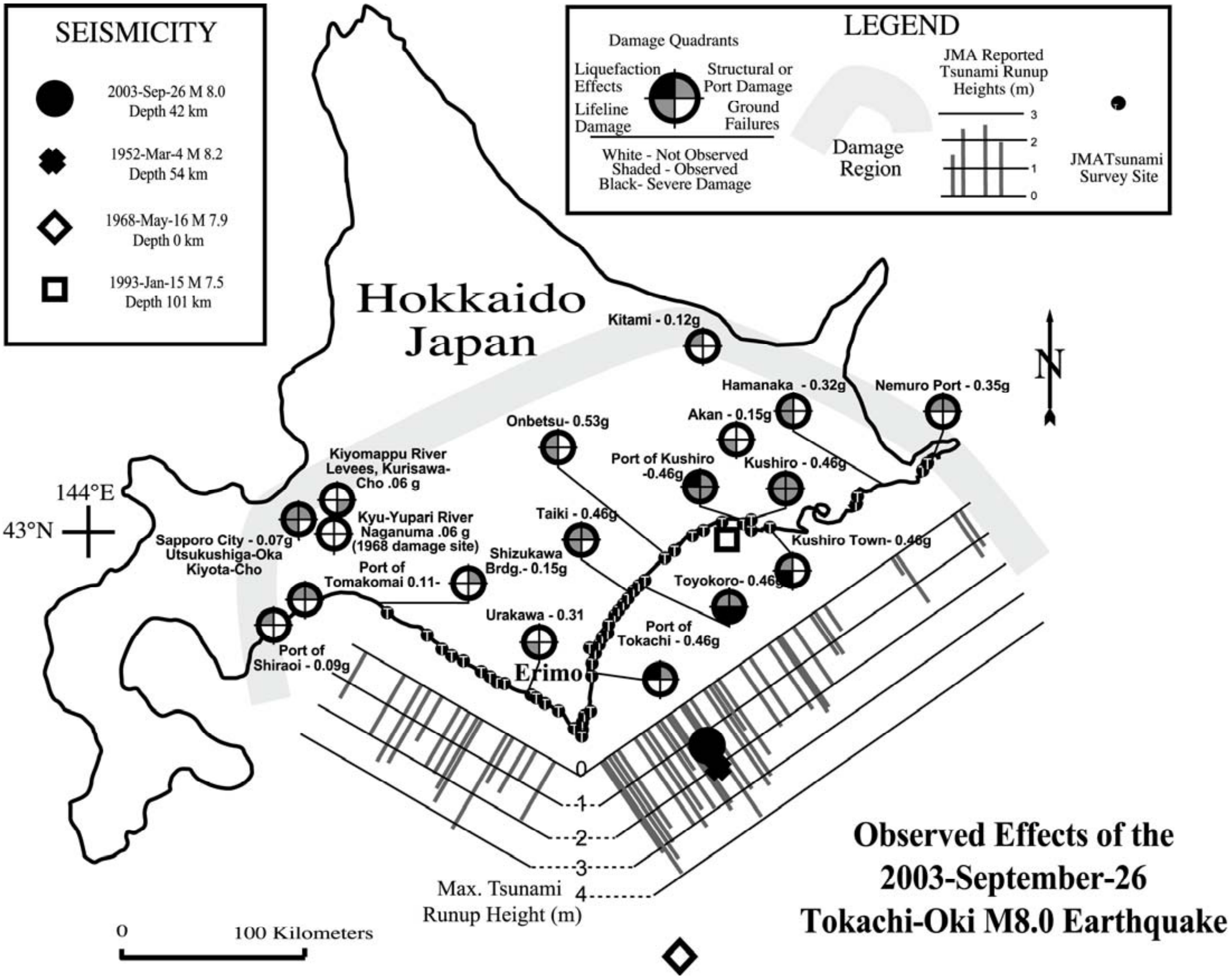


Figure 36: Effects of the 2003 Tokachi-Oki earthquake. Peak ground accelerations and tsunami wave run-up heights were reported by JMA, PARI and other organizations. The region of damaged ground covered a 400 km wide swath along the coastal areas of southern and southeastern Hokkaido. Details and intensity of the damage effects are reported in damage quadrants described in the map legend.

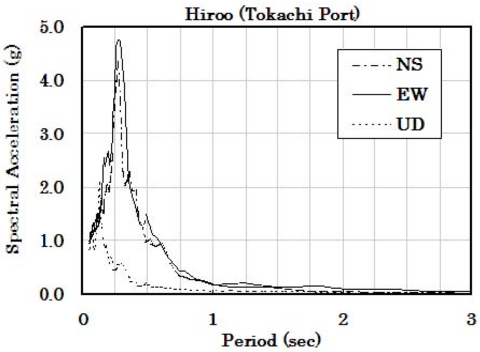


Figure 37: Acceleration response spectra for ground motions recorded at Hiroo at 5% damping.

Liquefaction During The 2003 M8.0 Tokachi-Oki Earthquake

Liquefaction was observed over a broad geographic region, from Sapporo to Kitami, though it was quite dispersed and localized. In addition, it was almost exclusively limited to manmade fills. Locations where liquefaction was observed is presented on Figure 36, and examples are discussed here and in the following sections of the article as well.

Sapporo is located approximately 200 km from the epicenter of the 2003 Tokachi-Oki Earthquake with recorded PGA of 0.07g. Liquefaction and structural damage was observed in Sapporo during the 1968 Tokachi-Oki Earthquake, and it was of interest to compare the performance between the two earthquakes. There was one isolated incident of liquefaction in the Utsukushigaoka suburb of southern Sapporo. Several sand boils were observed in the 2500 m^2 area, in a low spot in the surrounding neighborhood. Seven houses were damaged from settlement, and the most severely damaged had suffered a tilt of up to 2.5 degrees (Figure 39). Specific sites of observed liquefaction in the 1968 earthquake, specifically in the Nishi-Naganuma area between the Ebetsu and Yubari Rivers did not have evidence of liquefaction during the 2003 event. Perhaps the most spectacular example of liquefaction was located in farming country in northeastern Hokkaido town of Tanno, approximately 10 km northeast of Kitami City. Here, four large ground failures occurred over a 1 km^2 area as a result of liquefaction.

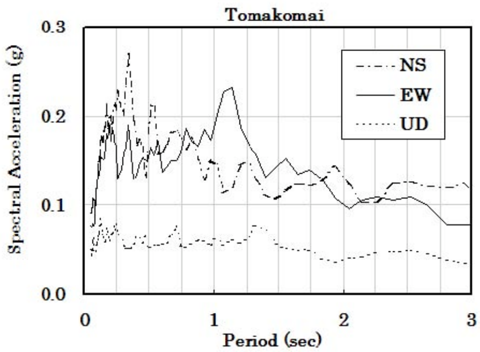


Figure 38: Acceleration response spectra for ground motions recorded at Tomakomai at 5% damping.

Figure 39: Damage to houses in Utsukushigaoka suburb of southern Sapporo from liquefaction induced settlement.

The largest of these was 50 m wide and 200 m long (Figure 40), and 5000 to 10,000 m^3 of material is estimated to have been expelled. Though lateral movement of the 1.5 m soil cap was limited to perhaps 1 m, the cap settled nearly 3 m as a result of the loss and evacuation of the underlying sand, which clogged drainage culverts for 100's of meters down stream. Local weakly cemented volcanic ash deposits were used for the borrow material, and fills as thick as 5 to 8 m were placed 20 years ago over former terraced rice fields for beet production.

Performance of Port and Harbor Facilities During The 2003 M8.0 Tokachi-Oki Earthquake

Three major ports were affected by the earthquake, and for the most part performed very well. In the west, liquefaction was observed in the Port of Tomakomai, but there was no resulting damage. One oil storage tank was consumed by fire, and it is suspected that the fire started as a result of strong shaking.

Figure 40: Flow failure in a farm field near Kitami City, where 5,000 to 10,000 m^3 of volcanic ash fill soil was expelled from a single site as a result of liquefaction (Photo Mosaic: R. Kayen).

The town of Hiroo hosts the Port of Tokachi, and damage in the port and town was relatively minor, even though accelerations as high as 0.6g were recorded in the port. Damage in the town was limited primarily to stucco and plaster damage to older buildings. Sand boils were widespread in new areas where the ground had been placed by hydraulic fill within the last 3 years. However, sand boils were not observed elsewhere at the port, where soil placed prior to 1993 had experienced two liquefaction triggering events during the significant 1993 Kushiro-Oki and 1994 Hokkaido Toho-Oki Earthquakes. The height of tsunami run-up in the port was observed to be 2.5 to 3 m, washing three cars and other debris into the harbor, but not causing structural damage to ports facilities.

The Port of Kushiro was the most severely damaged of the ports on Hokkaido. The Port consists of 4 western piers (Piers 1 through 4 on the west side of the Kushiro River), and several eastern piers including the Fishermen’s Terminal. Piers 1 through 3 and the Fishermen’s Terminal were built prior to 1993, and suffered liquefaction and structural damage from the 1993 Kushiro-Oki and 1994 Hokkaido Toho-Oki Earthquakes. Piers 1 through 3, and to some extent the Fishermen’s Terminal, have been improved by stone columns and/or deep cement mixing since 1994. All have caisson type quay walls.

Figure 41. Lateral movement of 10 cm and settlements of 100 cm were observed at Pier 4 of the Port of Kushiro, causing its closure. Piers 1 through 3 suffered minor damage and were quickly reopened.

Pier 4 was the most heavily damaged, with lateral movements of the 14 m deep quay wall of approximately 10 cm, and settlements behind the wall ranged from 60 to 100 cm (Figure 41). Sand boils were observed in an open area, approximately 30 m from the wall behind a paved area. The paved area was underlain by mixed soil-cement, and it may be that settlement of rubble-fill beneath the soil-cement mixture, rather than liquefaction, was the cause of the observed damage. Directly adjacent to Pier 4 was a well-instrumented quay wall test section to study the behavior of improved and unimproved ground. With over 130 channels of data acquisition, including pore pressure transducers and downhole accelerometers, the data set from these earthquakes as well as many smaller earthquakes should provide a wealth of new information to researchers.

The sections of Piers 1-3 that had undergone improvement performed well. The unimproved areas of Piers 1 and 2 suffered 10 to 15 cm of settlement behind the quay wall, and some signs of liquefaction were observed in the interior of the both of these piers. Liquefaction and smaller settlements less than 10 cm were observed on Pier 3. Piers 1 through 3 were only briefly shut down for inspection directly following the earthquake. One section of Pier 4 with a hybrid caisson-type quay wall was closed for one day, then reopened. The remainder of Pier 4 remains closed and will remain so for months.

Liquefaction and settlements were observed at the Kushiro Fishermen’s Terminal, as well as lateral movement of the quay wall, and this new damage overprints unrepaired damage from the 1993 and 1994 earthquakes. One warehouse at the south end of the pier had suffered severe settlements and tilting from all 3 earthquakes, yet still remains in operation, though leaning badly.

Building Damage During The 2003 M8.0 Tokachi-Oki Earthquake

Building damage was also observed over a large geographic area, but with a localized and relatively limited character. Typical examples of the localized damage are the town halls of Kushiro and Taiki, where recorded PGA's were 0.46g. At the Kushiro Town Hall, the reinforced concrete entranceway collapsed, after the two columns supporting it failed. The windowed roof-observatory of the Taiki Town Hall collapsed as a result of strong shaking. In both cases, no other damage was reported in the main structures. Other buildings observed had been damaged from excessive settlement. The most significant was the Urakawa Elementary School, where spalling on concrete was observed on columns after the entrance settled (Figure 42). Other reported damage includes the airport at Kushiro, which was closed for one day due to the collapse of the non-structural hanging ceilings in the control tower and terminal building. A regional description of structural damage can be seen on Figure 36.

For the most part, bridges performed quite well, with the exception of excessive relative movements between spans that led to shear key damage at the top of several piers, and some settlement of approach fills as noted earlier. All bridges were open to, though some were subjected to reduced speeds and lane closures.

Figure 42. Damage to Urakawa Elementary School.

Bridge Damage During The 2003 M8.0 Tokachi-Oki Earthquake

Examples of damaged bridge structures include the Shizukawa Bridge and the Tokachi-Kako Bridge northeast of Hiroo. The Shizukawa Bridge is located in Tomakomai area where the ground motion had recorded PGA was just over 0.1g, but was of long duration and dominantly long period motion. For this bridge, the relative movement between the abutments and first piers resulted in significant damage to the shear keys (Figure 43), possibly as a result of pounding. Even so, the bridge did not collapse and was still in service. In all cases, no damage was observed in the columns or at the foundation level. All damage was concentrated at the pier-superstructure connection appeared to be the result of excessive relative displacement, either transverse or longitudinal, depending on the bridge.

Figure 43. Damaged shear key from the Shizukawa Bridge near Tomakomai City.

Tsunami During The 2003 M8.0 Tokachi-Oki Earthquake

The main shock produced coseismic uplift of the seafloor southeast of the Hiroo Peninsula, generating a tsunami with shoreline wave heights of up to 4 m, and 2 to 3 m high in numerous locations, as shown in Figure 1. Two fishermen in Otsu were missing immediately following the tsunami, presumably drowned, and three cars were washed into the harbor at the Port of Tokachi. Other than that, the tsunami was responsible for very little damage. In many cases, the waves did not exceed the height of the tsunami barriers, and in locations were the backland was inundated, they were just barely so and damage was light. Of great concern to the Japanese government and tsunami researchers were the high numbers of people not heeding the tsunami warning. Initial surveys indicated that perhaps 50 percent of the coastal residents ignored the issued tsunami warnings.

Landslides During The 2003 M8.0 Tokachi-Oki Earthquake

Reconnaissance carried out from a fixed-wing aircraft combined with automobile and foot traverses through the Hidaka Sanmyaku and other mountainous areas of southeastern Hokkaido failed to yield evidence of much significant landslide activity on natural slopes. The only known, minor damage from such landslides was a rock fall of perhaps a few hundred meters total volume that was reported from a steep slope adjacent to the coastal highway at Hiroo, However, material from this landslide had been rapidly removed after the earthquake. Other landslides from natural slopes observed by the reconnaissance team consisted of scattered small rock falls, rock slides, and debris slides from particularly steep slopes. These had volumes ranging from less than one-to-several thousand cubic meters each, and most were sourced from existing scars where such activity had clearly originated in the past as well.

The earthquake produced several embankment and fill failures in the region around Toyoroko. These failures produced cracks, slumps, and in some cases lateral spreads accompanied by sand boils indicating an association with soil liquefaction. These failures were most common in deep fills for highways that had been constructed to provide a smooth grade for roads passing from valley bottoms to adjacent upland areas. Locally, such fill and embankment failures caused significant damage, especially to roads

Lifelines During The 2003 M8.0 Tokachi-Oki Earthquake

Lifelines covered in this section that were affected by the earthquakes include sewers, roads, and other utilities. By far, the most widespread damage to lifelines was to the storm and sanitary sewer systems. Significant uplift of manholes was reported from Urakawa in the west to Hamanaka in the east. The team observed uplift as high as 2 m in Otsu (Figure 44) and dozens as high as 1.5 m in a single subdivision of Shintoyo-Cho, immediately east of Kushiro City. In all cases, the uplift appeared to be related to liquefaction of the pipeline backfill material, and damage was aligned with the layout of the pipe-network. Though the phenomenon appeared to be widespread, there were no reports of widespread sanitary sewer failures. Many had been repaired by the time the team came through.

While damage to roads was not widely reported, the team observed widespread, but minor, damage to Highway 336 between the Rekifuna River and Tokachi River. The approach fills to numerous small bridges experienced settlement and many had been patched with asphalt. In addition, many slumps were observed along the shoulder of the highway, but none large enough to affect traffic. In Chobushi, the team observed ground failure of Route 912, completely closing the road. This roadway failure appeared to be the result of collapse of a prism of embankment fill built over a lowland and culvert. With the exception of the ground failure on Route 912, most damage to roadways appeared to be relatively minor and more of a maintenance issue.

There were no reports of power or telephone loss due to the earthquakes, though severely tilted telephone poles were observed near Kushiro. The team did observe a severed fiber optic cable on the Tokachi-Kako Bridge, where fill had settled 60 cm relative to the abutment.

Figure 44. Uplifted manhole near a sewage treatment facility in Otsu town, near the Tokachi river.

LESSONS LEARNED

During the period from 2003- 2008 Japan was struck by seven events that resulted in damage ranging from light-to extremely heavy. The three worst events are described in detail in this paper, each with their unique characteristics. The 2007 Niigata Chuetsu Oki event was the first significant and damaging earthquake to strike close in to a large modern nuclear power plant. Damage at the plant has been the focus of intense investigation and documentation by the Tokyo Electric Power Company, the Nuclear Safety Commission Of Japan, and the United Nations International Atomic Energy Agency. In the United States, the US Nuclear Regulatory Commission is documenting the lessons learned from this event in the hopes of improving the US response to earthquakes at nuclear power generating facilities. The 2007 Niigata Chuetsu Oki (offshore) earthquake primarily a “geotechnical earthquake”: liquefaction damage, poor response of dune sand deposits, and lateral spreading of river bank deposits were the major sources of damage.

The 2004 Niigata Chuetsu (onshore) earthquake could be characterized as a “landslide earthquake”. Thousands of large and small downslope landslide and debris flow scars were observed throughout the Uonuma Hills of Central Niigata Prefecture. These landslides shattered the transportation and communication network, isolated villagers in small hamlets in upland hills and hindered emergency response activities. A large rockslide on the banks of the Shinano River destroyed a local transportation route and resulted in several fatalities. Liquefaction damage was relatively light during the event.

The 2003 M8.0 Tokachi Oki earthquake occurred in almost nearly same location as the 1968 offshore earthquake. This event is noteworthy as a “tsunami earthquake” for the wave generated by tectonic uplift of the seafloor and the observed local wave run ups of 1-4 m on beaches along the southeastern shore of Hokkaido island. Despite the large magnitude of the earthuake and accelerations observed near the mouth of the Tokachi River and at Kushiro City, geotechnical and structural damage were relatively light.

ACKNOWLEDGEMENTS

This report is synthesized from the work of scores of Japanese and US researchers who led and participated in post-earthquake reconnaissance of these events. The list of contributors to the earthquake reconnaissance activities of these three events are by no means complete. Any errors or omissions in the list of contributors is entirely the fault of the author. The organizational efforts of the Earthquake Engineering Research Institute, The Japanese Society Of Civil Engineers, the American Society Of Civil Engineers, the US National Science Foundation, the USGS, and the Geo-Engineering Earthquake Engineering Reconnaissance activity of the NSF are greatly appreciated. This report draws heavily from the reports of EERI Learning From Earthquakes, JSCE, ASCE, USGS, and GEER. The author greatly appreciates the invitation by Professor Shamsher Prakash to present these findings at the 6ICCHGE conference. Brad Carkin generously proof read the manuscript and found numerous errors. His careful review is appreciated.

2007 Niigata Chuetsu Oki Acknowledgements

The 2007 Niigata Chuetsu Oki section is taken from the work of the EERI-GEER team led by Robert Kayen of the USGS and Santiago Pujol of Purdue University, including Brian Collins of the USGS; Scott Ashford, Stephen Dickenson, and Yohsuke Kawamata of Oregon State University; Scott J. Brandenberg of UCLA; Norm Abrahamson and Ben Tsai of PG&E; Laurie Johnson of Kyoto University; Mark Yashinsky of Caltrans; Peter Yanev of EQE; Yasuo Tanaka and Hidetaka Koumoto of Kobe University; Kohji Tokimatsu of Tokyo Institute of Technology; Toshimi Kabeyasawa and Kim Yousok of Tokyo University; and Nanako Marubashi of Nagoya Institute of Technology. The active participation and enthusiasm of EERI and GEER's Japanese participants and the Japan Association of Earthquake Engineers (JAEE) was critical for the success of the study. The EERI-GEER team also coordinated with a second team from ASCE-TCLEE. The study was made possibly by funding from the U.S. National Science Foundation Grant Nos. CMMI-0323914 & CMMI-0131895., cost sharing by the U.S. Geological Survey, and volunteer work by the participants. Cooperation with the following Japanese researchers and organizations was invaluable: Kazuo Konagai, University of Tokyo, Toshikatsu Ichinose of Nagoya Institute of Technology, Toshikazu Kabeyasawa, and Toshinori Kabeyasawa of the University of Tokyo, Kobe University and the staff of the Research Center for Urban Safety and Security (RCUSS).

2004 Niigata Chuetsu Acknowledgements

The investigation was led by Charles Scawthorn, and included Scott Ashford; Jean-Pierre Bardet; Charles Huyck, I; Robert Kayen; Scott Kieffer; Yohsuke Kawamata; Rob Olshansky; Paul Somerville; Jim Mori; Ellen Rathje; James Bay; Randy Jibson; Keith Kelson; Robert Pack; N. Kishi. The research was funded under National Science Foundation grant #CMS-0347055, cost sharing by the U.S. Geological Survey, and volunteer work by the participants. The teams were generously assisted by numerous Japanese colleagues, including Professor H. Iemura; Professors M. Hamada; K. Ishihara; Kazuo Konagai; T. Kaino; Y. Yamakawa; Y.Tanaka; I. Towhata; T. Sato; H. Hayashi; K. Kiyono; S. Sawada; Y. Ono; Y. Takahash; R. Honda; N. Inukai; T. Kokusho; and Mr. Hajime Tanaka and Ms. M. Wada. The team also thanks the JR East Railway Company for access to the Shinkansen site; public officials of Niigata Prefecture, Nagaoka City, and the city of Ojiya for their assistance; and the people of the affected region for their generosity and patience.

2003 Tokachi Earthquake Acknowledgements

The EERI Team was composed of Scott Ashford; Robert Kayen; Yohsuke Kawamata; David Keefer; Albert (Keh-Jian) Shou; Takanori Arimura; and Takahiro Sugano. The effort was partially supported with funding from the National Science Foundation under grant # CMS-0131895, as well as the Pacific Earthquake Engineering Research Center and the USGS. The cooperation of the Port and Airport Research Institute is gratefully appreciated.

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