Learning from Earthquakes

Preliminary Observations on the Tokachi-Oki, Japan, Earthquake of September 26, 2003

EERI dispatched a reconnaissance team to Hokkaido, Japan, within days of the earthquake. The EERI team was composed of Scott Ashford and Yohsuke Kawamata from the Department of Structural Engineering at the University of California, San Diego, and Robert Kayen of the Coastal and Marine Geology Unit of the United States Geological Survey (USGS). The EERI team was joined by David Keefer of the USGS, Albert (Keh-Jian) Shou of the National Chung-Hsing University in Taiwan, and Takanori Arimura of Kobe University in Japan, who investigated landslides. Takahiro Sugano of the Port and Airport Research Institute (PARI) guided the team in assessing the performance of port facilities. The cooperation of PARI is gratefully acknowledged. The reconnaissance effort was partially supported with funding from the National Science Foundation under grant # CMS-0131895, as well as by the Pacific Earthquake Engineering Research Center and the USGS.

Introduction

The primary M8.0 tremor occurred at 4:50 a.m. local time on September 26, 2003, and was followed by a M7.1 tremor at 6:08 a.m. The quakes affected a 400 km-wide area along the coastal areas of southern and southeastern Hokkaido Island. Both events triggered ground failures. 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. However, despite the large magnitude and high PGA levels, the observed ground failure, liquefaction, and structural, port, and lifeline damage were remarkably minimal.

The earthquake was the third 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. The slip distribution inverted from seismograms shows this was a rupture of the same fault segment as that of the 1952 Tokachi-Oki M8.2 quake. Both events were megathrust earthquakes that resulted from segmented rupture of the Pacific plate beneath the Hokkaido-Tohoku accretionary prism.

Seismological Aspects

Accelerations recorded by seismic networks of Hokkaido indicate a region of high-intensity motion from the Hiroo area to Kushiro City, with PGA values in the range of 0.35 to 0.6g (Figure 1). 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 Figure 2.

The low damage levels are 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 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.

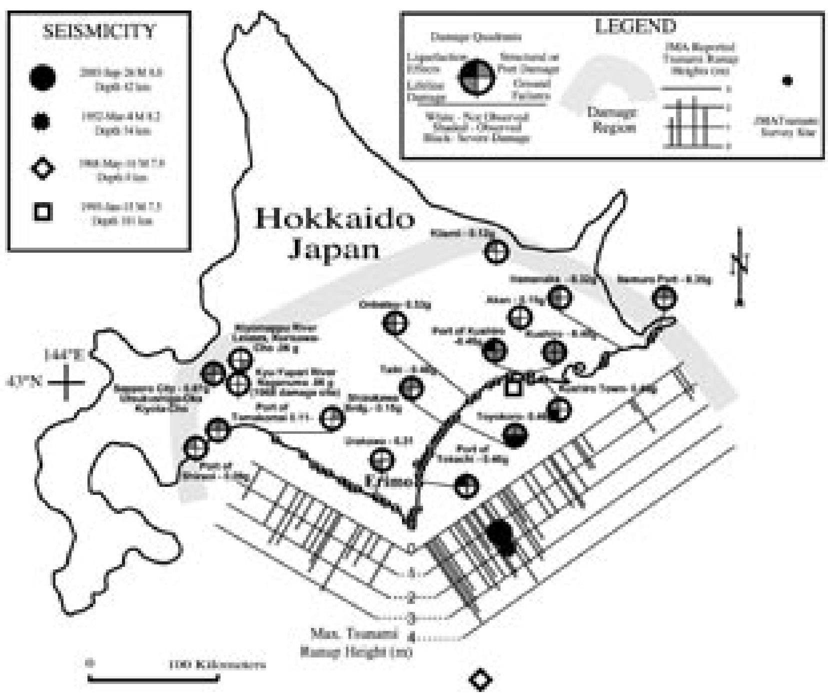
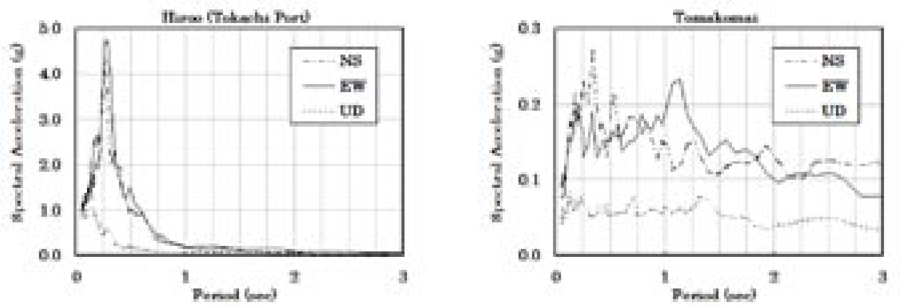


Figure 1. *Observed effects of the earthquake. Peak ground accelerations and tsunami wave run-up heights as reported by JMA, PARI, and other organizations.*



Figures 2a and b. *Acceleration response spectra for ground motions recorded at (a) Hiroo at 5% damping, and (b) Tomakomai at 5% damping.*

Liquefaction

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 man-made fills. Locations where liquefaction was observed are shown on Figure 1. In farming country in northeastern Hokkaido, approximately 10 km northeast of Kitami City, four large ground failures occurred over a 1 km^2 area, the largest being 50 m wide and 200 m long. Between 5,000 and 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 evacuation of the underlying sand, which clogged drainage culverts for hundreds of meters downstream.

Sapporo, located approximately 200 km from the epicenter, had a recorded PGA of 0.07g. The team observed one isolated incident of liquefaction in the Utsukushigaoka suburb of southern Sapporo. Several sand boils were observed in the area, a low spot in the surrounding neighborhood. Seven houses were damaged from settlement, with the most severely damaged tilted up to 2.5 degrees (Figure 3). Liquefaction and structural damage were also observed in Sapporo after the 1968 Tokachi-Oki earthquake. The team visited sites where liquefaction had occurred in the 1968 earthquake, specifically in the Nishi-Naganuma area between the Ebetsu and Yubari Rivers, but no evidence of liquefaction was observed.

Landslides

Reconnaissance carried out from a fixed-wing aircraft, as well as by automobile and foot, failed to yield evidence of much significant landslide activity on natural slopes. The only known incident was a rock fall of 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 removed before members of the reconnaissance team arrived at the locale. Other landslides from natural slopes observed by the reconnaissance team consisted of scattered small rock falls, rock slides, and debris slides on particularly steep slopes. These had volumes ranging from less than 100 to 10,000 cubic meters each, and most were sourced from existing scars where such activity had clearly originated in the past as well.

The earthquake caused 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 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.

Tsunami

The main shock produced coseismic uplift of the seafloor southeast of the Hiroo Peninsula, generating a tsunami with shoreline wave heights of 2 to 3 m in numerous locations, and 4 m in a few places. 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, it was just barely so and damage was light.

Figure 3. *Settlement in the Utsukushigaoka suburb of southern Sapporo.*

Of great concern to the Japanese government and tsunami researchers was that many people did not heed the tsunami warning. Initial surveys indicated that perhaps 50% of the coastal residents ignored the issued warnings.

Performance of Port and Harbor Facilities

Three major ports were affected by the earthquake, but most performed very well. The Port of Kushiro was the most severely damaged of the ports on Hokkaido. It consists of four western piers 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 had 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.

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 from 60 to 100 cm (Figure 4). 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. The 130 channels of data acquisition, including pore pressure transducers and downhole accelerometers, should provide a wealth of new information for researchers.

The sections of Piers 1-3 that had undergone improvement performed well. The unimproved areas of Piers 1 and 2 suffered 10-15 cm of settlement behind the quay wall, and some signs of liquefaction were observed in the interior of both of these piers. Liquefaction and smaller settlements of 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 rest is 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; this new damage overprints unrepaired damage from the 1993 and 1994 earthquakes. One warehouse at the south end of the pier suffered severe settlements and tilting in all three earthquakes, yet still remains in operation, though it is leaning badly.

Figure 4. *Pier 4, Port of Kushiro.*

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. Damage in the town was primarily to stucco and plaster in older buildings. Sand boils were widespread in new areas filled hydraulically within the last three years. However, sand boils were not observed elsewhere at the port, where there had been liquefaction in the 1993 and 1994 earthquakes. The height of tsunami run-up in the port was observed to be 2.5-3 m, washing three cars and other debris into the harbor, but not causing structural damage to port facilities.

In the west, liquefaction was observed in the Port of Tomakomai, but there was no resulting damage. One oil storage tank was consumed by a fire, which is suspected to have resulted from strong shaking.

Lifelines

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 uplifts as high as 2 m in Otsu (Figure 5) 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. Many sanitary sewers had been repaired by the time the team came through.

While damage to roads was not widely reported, the team observed

Figure 5. *Uplifted manhole near sewage treatment facility in Otsu.*

minor damage to Highway 336 between the Rekifuna and Tokachi Rivers. The approach fills to numerous small bridges experienced settlement, and many had been patched with asphalt. Many slumps were also observed along the shoulder of the highway, but none large enough to affect traffic. In Chobushi, the team observed that ground failure on Route 912 had completely closed the road. This failure appeared to result from collapse of a prism of embankment fill built over a lowland and culvert. 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 the team observed severely tilted telephone poles near Kushiro and a severed fiber optic cable on the Tokachi-Kako Bridge, where fill had settled 60 cm relative to the abutment.

Bridges

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 traffic when the team came through, though some were subjected to reduced speeds and lane closures.

Northeast of Hiroo, there was damage to two bridges. In the Tomakomai area, the ground motion was just over 0.1g, but it was of long duration and dominantly long period motion. On the Shizukawa Bridge, the relative movement between the abutments and first piers resulted in significant damage to the shear keys (Figure 6), possibly as a result of pounding. Even so, the bridge did not collapse and was still in service. In no case was damage observed in the columns or at the foundation level, but it was concentrated at the pier-superstructure connection. This appeared to be the result of excessive relative displacement, either transverse or longitudinal, depending on the bridge.

Buildings

Building damage was also observed over a large area, but it was localized and relatively limited. There was localized damage to the town halls of both Kushiro and Taiki, where recorded PGAs were 0.46g. At Kushiro, 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 were damaged by excessive settlement, for example, the Urakawa Elementary School, where concrete spalled on columns after the entrance settled (Figure 7). The airport at Kushiro was closed for one day due to the collapse of the nonstructural hanging ceilings in the control tower and terminal building.

Figure 6. *Damaged shear key from the Shizukawa Bridge near Tomakomai City.*

Conclusions

The localized nature of the damage is striking, considering the relatively high levels of ground shaking caused by this earthquake. The performance of the Port of Kushiro piers, compared to the failures in the 1993 and 1994 earthquakes, is worthy of further study. This earthquake adds significantly to our knowledge base on the initiation of liquefaction, as many of the sites that liquefied in prior earthquakes did not do so here. Also of significance is the lack of response to the tsunami evacuation warning. This will certainly lead to additional public education and may affect worldwide disaster planning.

Figure 7*. Damage to Urakawa Elementary School.*