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Technical Report NCEER-93-0023

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ABSTRACT

A magnitude 7.8 earthquake occurred offshore, southwest of the Island of Hokkaido in Northern Japan on July 12, 1993.

The earthquake caused moderately strong ground shaking over a wide area. A peak ground acceleration of 0.50g was recorded about 100 km from the edge of the offshore aftershock zone.

The shock was followed by a large tsunami, which caused water run-ups of up to 30.5 m and extensive shoreline damage on the Island of Okushiri and along the southwest coast of Hokkaido. The tsunami devastated the town of Aonae, on the southern tip of Okushiri Island.

The tsunami was followed by a fire, which destroyed much of the town of Aonae.

The earthquake shaking caused light to moderate damage to structures on Okushiri Island, light to moderate damage to infrastructure and industrial facilities, and extensive damage to roads and ports from ground failures up to about 110 km from the edge of the aftershock area.

The primary lesson of the earthquake is that the triple hazards of earthquake shaking followed by tsunamis and uncontrolled fires can be devastating to modern cities.

TABLE OF CONTENTS

SECTION 1
INTRODUCTION

The Hokkaido Nansei-oki Earthquake (offshore of southwestern Hokkaido Island, Japan) had a magnitude (M_W) of 7.8 and struck at 10:17 P.M., local time, on July 12, 1993. It affected an area of about 100 by 150 km in southwestern Hokkaido, east of Okushiri Island.

The earthquake affected a lightly populated part of the least populated major island of the Japanese archipelago, but it was a microcosm of what can happen to Tokyo and other cities of Japan and North America. The primary lesson of the earthquake is that the triple hazards of earthquake shaking followed by tsunamis and fires can be devastating to modern cities.

The main earthquake occurred at a depth of about 27 km in the Sea of Japan, north of Okushiri along a subduction zone that is speculated to be the boundary of the Eurasian and North American plates. The aftershock area around Okushiri extended over 170 km north to south and about 40 km east to west. As much as 150 km of faulting may have occurred along the causative fault zone.

Several strong-motion instruments in southwestern Hokkaido recorded more than 60 seconds of strong ground motion. The highest recorded horizontal acceleration is reported to be 0.50g at Kuromatsunai, west-southwest of Sapporo and about 100 km from the eastern edge of the aftershock zone. The strongest ground motions probably occurred on Okushiri, where there were no instruments, but peak accelerations in excess of 0.40g have been estimated. The strongest aftershock ground motion to date was recorded at Otobe-cho, with a peak horizontal acceleration of 1.59g.

The earthquake caused a large tsunami, which hit the coast of Okushiri less than 5 minutes after the earthquake. The settled areas along the coast of the island were inundated by tsunami run-up typically from 5 to 12 m high. The higher wave run-up along the southwest coast was about 30.5 m in a limited area. The tsunami caused extensive damage on the island and lesser but locally severe damage along the southwest coast of Hokkaido. Most of the populated areas hit by the tsunami were protected by tsunami walls (up to about 4.5 m high), which may have moderated the overall tsunami effects but were ineffective for the highest waves.

Most of the casualties in this earthquake were caused by the tsunami. As of July 24, the official death toll was 196, with about 50 people still missing. Most of the deaths were on Okushiri. Since the island is a tourist area, the number of missing might be higher than the estimate.

As of July 19, the University of Tokyo's International Center for Disaster-Mitigation Engineering reported that 540 houses were destroyed by tsunami or fire, 154 were significantly damaged, and 1,826 were partially damaged. Thirty-one public buildings were damaged, some severely; railways were disrupted at 124 locations; and highways were damaged in at least 365 locations. Serious damage occurred to schools, industrial structures, bridges, port facilities, and all other types of infrastructure.

Most of the financial loss was caused by the tsunami. That damage was concentrated on Okushiri and along the west coast of Hokkaido opposite the fault rupture. Ground shaking produced relatively light direct structural damage; however, extensive damage, as much as 110 km from the eastern edge of the aftershock zone, was due to ground failures, including liquefaction, lateral spreading, settlement, and landsliding. Large landslides occurred throughout the strongly shaken areas on Okushiri and Hokkaido.

SECTION 2
THE RECONNAISSANCE TEAM AND ACKNOWLEDGEMENTS

Peter Yanev (EQE International and representing the National Center for Earthquake Engineering Research) visited the earthquake-affected area on July 21-24 as part of the U.S. team investigating the earthquake. The overall U.S. team was led by Riley Chung of the National Institute for Standards and Technology (NIST) and included Richard Bukowski of NIST; Eddie Bernard, Frank Gonzales, and Dennis Sigrist of the National Oceanic and Atmospheric Administration (NOAA); David Tyree of the American Forest and Paper Association; Charles Barnes of the American Plywood Association; Edwin Harp of the U.S. Geological Survey (USGS); and the Earthquake Engineering Research Institute (EERI) team leader Les Youd (Brigham Young University) and EERI team members Jane Preuss (Urban Regional Research), Charles Scawthorn (EQE International), and Paul Sommerville (Woodward-Clyde Consultants).

The team was organized under the U.S.-Japan Panel on Natural Resources (UJNR). The field investigations were organized and supported by the Public Works Research Institute of the Ministry of Construction of Japan and were led by Yutaka Ido and supported by Kazuhiro Kawashima, Susumu Iai, R. Tsunaki, S. Unjoh, T. Nakajima, and several others.

The authors are particularly grateful to Dr. Kawashima, who organized and provided generous field support so that they could conduct individual investigations in order to optimize their limited time and resources. Appreciation is also due to Professor H. Iemura of Kyoto University, who provided initial information on the damage.

SECTION 3
THE AFFECTED REGION

The epicenter of the earthquake occurred about 160 kilometers (km) west of Sapporo, which is the principal city of the Island of Hokkaido, and about 60 km north of the Island of Okushiri in the Sea of Japan, at latitude 42^{o} 47' north and 139^{o} 12' east, at a depth of 27 km. The hypocenter is located on the subduction zone east of Hokkaido, which defines the boundary between the Eurasian plate and the North American (or Okhotsk) plate, which contains about half of the Japanese Archipelago.

Figure 3-1 shows the locations of the 1993 epicenter and those of the larger earthquakes along the fracture or subduction zone since 1940. The present location is number 6 in the figure. Figure 3-2 shows the main shock and aftershocks for the period of July 12 to August 8, 1993. The severely affected Island of Okushiri is located near the southeastern end of the aftershock plane. The plane indicates a fault length of about 150 km and an average width of about 40 km. The approximate aftershock area and the strongly shaken region are shown in more detail in Figure 3-3. Several of the investigated areas are indicated in the figure. Structural damage due to shaking was observed along the western shores of Uchi-ura Bay, up to 80 km from the eastern edge of the illustrated aftershock area, whereas severe ground failure were observed as far as the large city of Hakodate near the southern tip of Hokkaido, 110 km or more from the aftershock area and some 160 km from the epicentral area. The damaged region on Hokkaido is about 150 km (N to S) by 100 km (E to W). Except for damage caused by landslides or rockfalls, the structural and infrastructure damage was almost entirely in the areas of recent soft soils. The worst damage, outside the island of Okushiri, was along the narrow flat coastal areas of Hokkaido.

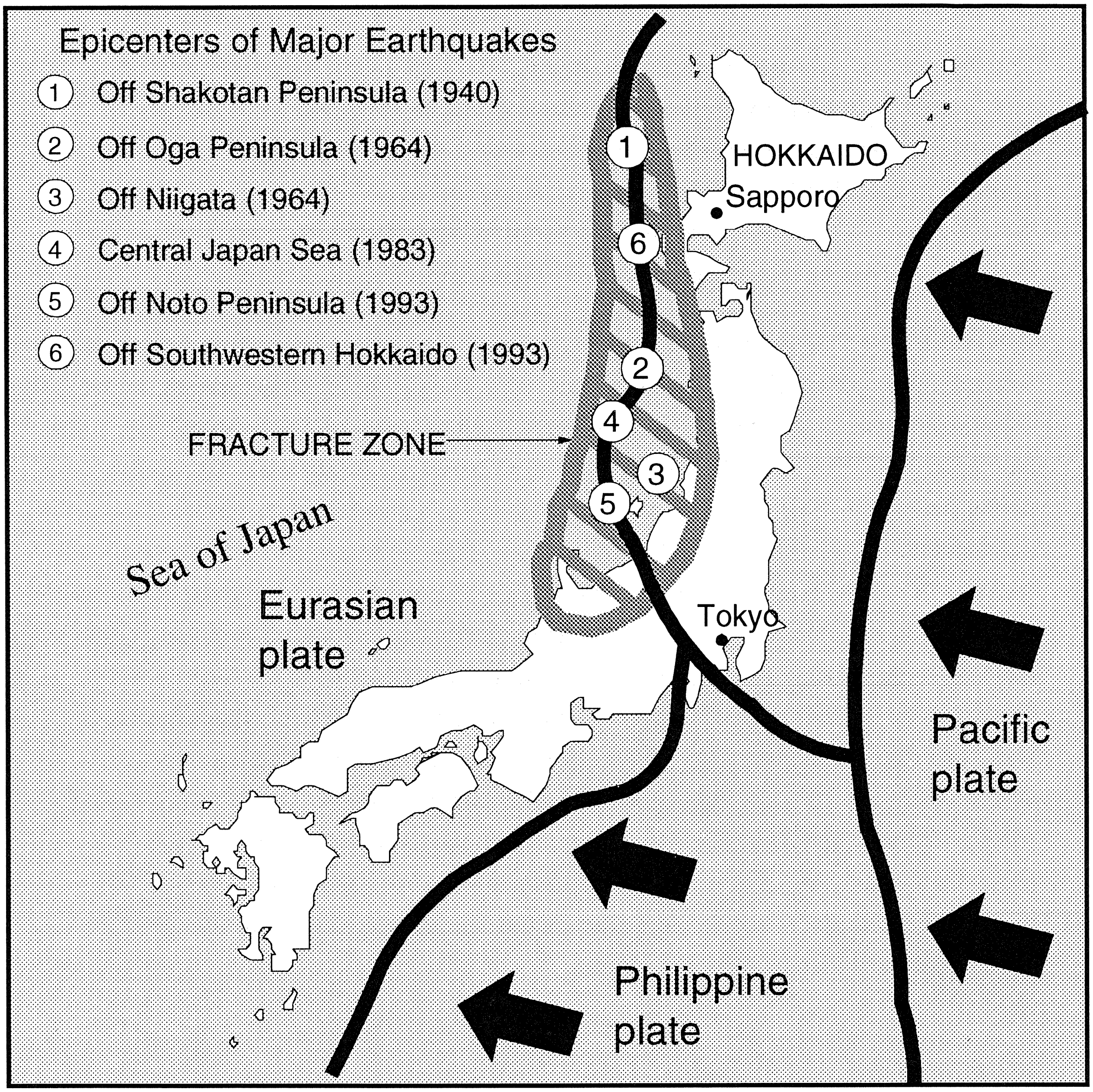


Figure 3-1: Historical epicenters of larger earthquakes on the Sea of Japan fracture zone. The July 12, 1993, earthquake is number 6 on the map.

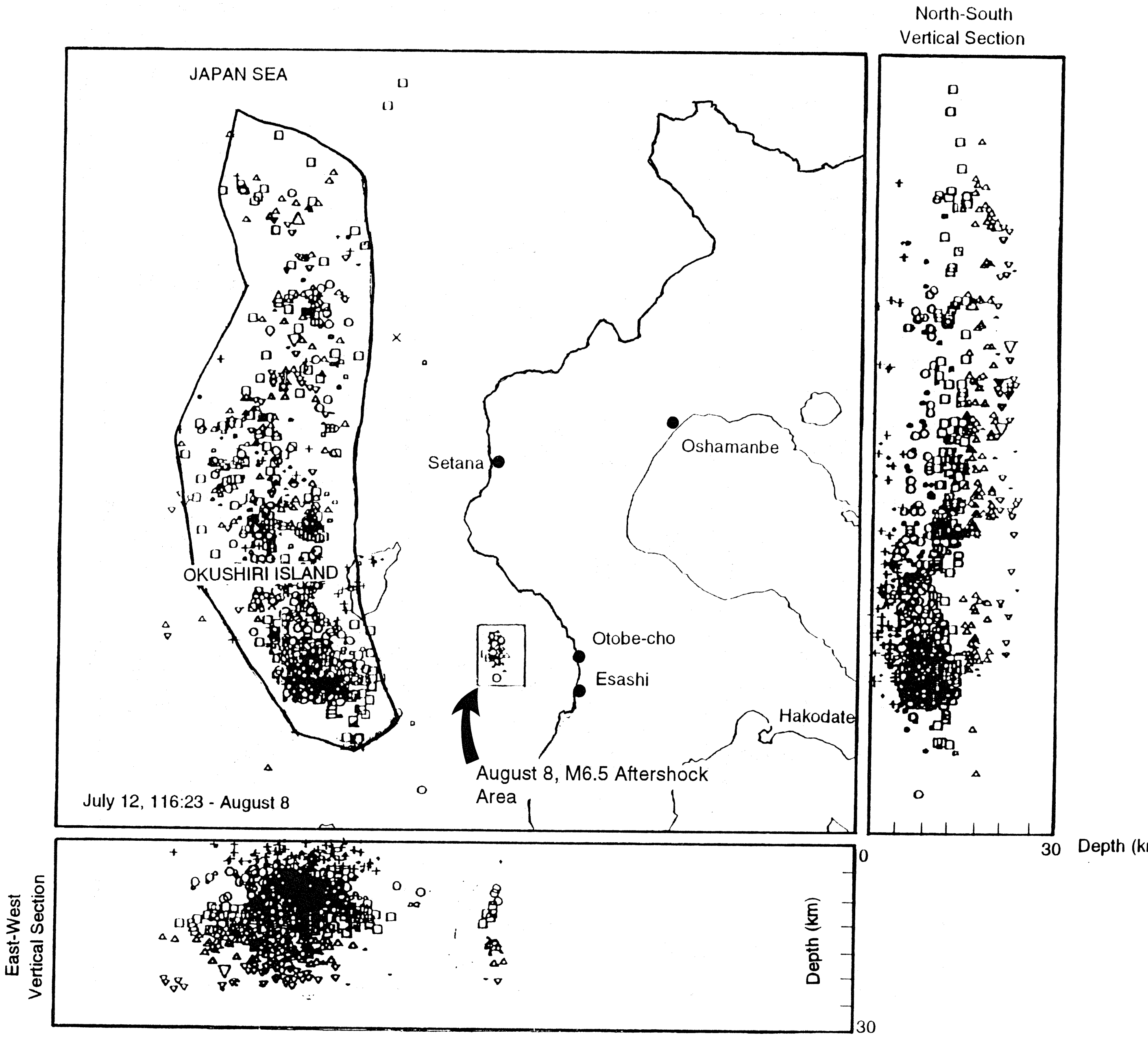


Figure 3-2: Mainshock and aftershock locations for July 12 to August 8, 1993. Source: Hokkaido University and EERI (Reference 1).

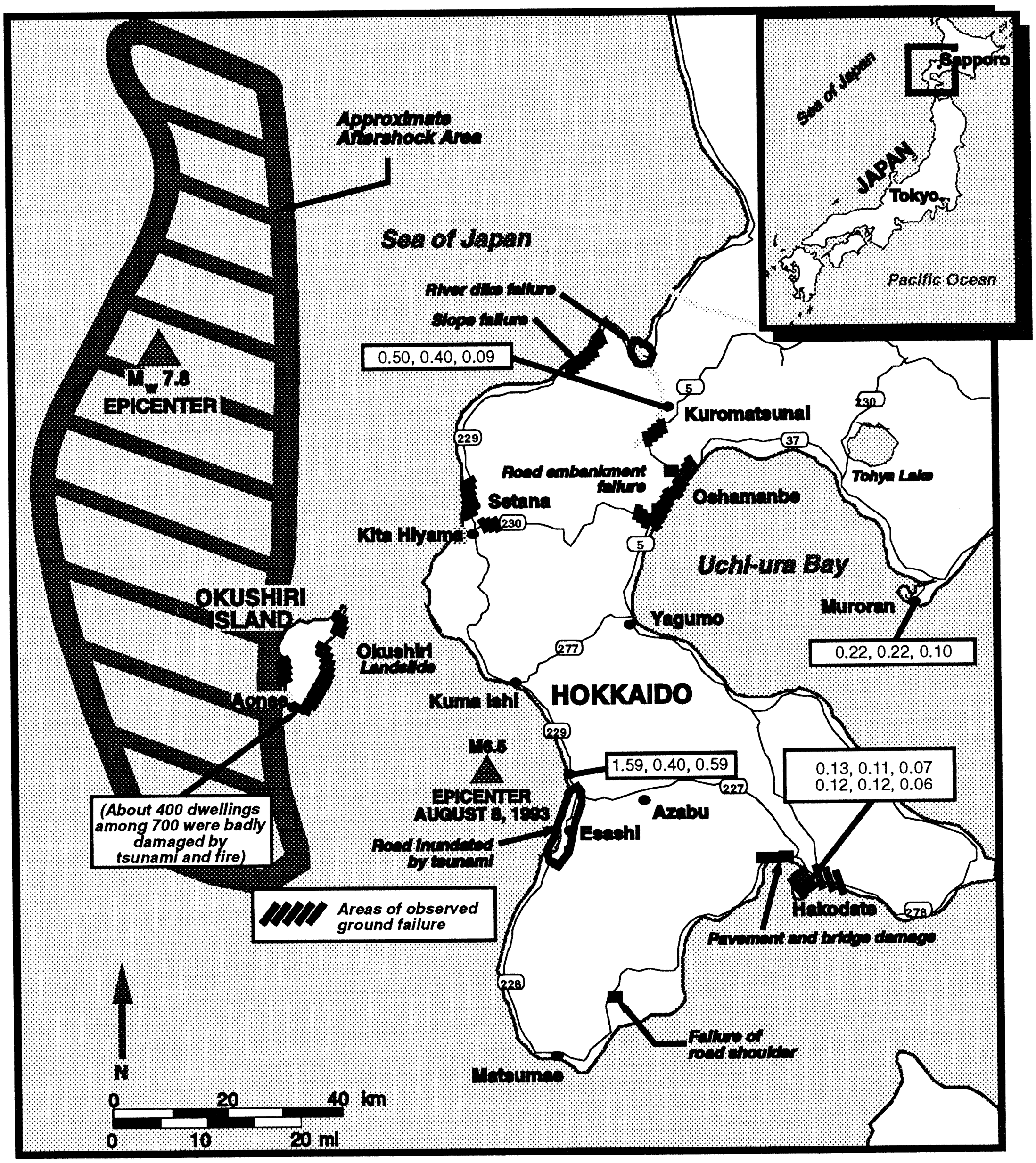


Figure 3-3: Map of the affected region showing various damage locations and selected (uncorrected) peak ground accelerations (in g's).

SECTION 4
STRONG GROUND MOTION

Many strong ground motion records were obtained by various Japanese organizations. Unfortunately, no instruments were located on Okushiri Island, which probably experienced the strongest ground motion. Typical estimates, based on observations of damage on the island, range from 0.40g to 0.50g peak ground acceleration. Figure 3-3 shows the location and the peak accelerations for the two horizontal and the vertical components of four available records nearest the source of the earthquake.

The highest ground acceleration was recorded at Kuromatsunai, which is about 80 km directly east of the boundary of the aftershock zone. The three component peak accelerations are 0.50g and 0.40g horizontal and 0.09g vertical. The time histories of this record are not yet available. Figure 3-3 also shows the location and peak accelerations of three of the available records. Muroran, about 130 km east of the aftershock zone, recorded an average peak horizontal acceleration of 0.22g. The port area of Hakodate, at a distance of 100 km from the aftershock zone, recorded an average horizontal peak acceleration of 0.12g. The time histories of two of the records are shown in Figures 4-1 and 4-2. In the case of the Muroran record, with a peak horizontal acceleration of 0.22g, the duration of the record in excess of 0.10g is about 35 seconds. Generally, the duration of stronger ground motion appears to have been less than or equal to about 60 seconds.

An aftershock (or perhaps a separate but related earthquake) with a magnitude of 6.5 occurred on August 8 between Okushiri Island and the mainland of Hokkaido. The location of the event is shown in Figure 3-2. An accelerometer at Otobe-cho, on Hokkaido and about 20 km from the epicenter, recorded peak accelerations of 1.59g (EW), 0.40g (NS) and 0.59g (Vertical). The record is shown in Figure 4-3. The duration of the strong motion is about 7 seconds.

The following observations regarding the intensity of the ground motion are based on observations of damage and the lack of damage in the affected region. Only the Island of Okushiri exhibited damage to engineered structures on stiff, competent soils or on rock. Even here, the intensities were not high enough to cause widespread structural damage. Damage on good soils or rock was sporadic. On Hokkaido, all of the observed significant structural damage was on very soft soils, typically on recent coastal deposits or on fills, such as in the port of Hakodate. Damage on competent soils was minor even in locations that recorded high peak horizontal ground accelerations such as Kuromatsunai (0.50g) and Muroran (0.22g). That observation is limited to low-rise (up to three-story) buildings, as there were very few taller buildings observed in the area outside Hakodate.

The more significant structural damage on Okushiri Island can be correlated to local amplification on soft soils, such as the Aonae Elementary School, the Okushiri Concrete Batch Plant at Aonae, and the Aonae Sewage Treatment Plant, and possibly, to local amplification due to topographic effects such as at the Aonae lighthouse, which is located on the edge of a bluff overlooking the town. All of these structures are discussed later in the text.

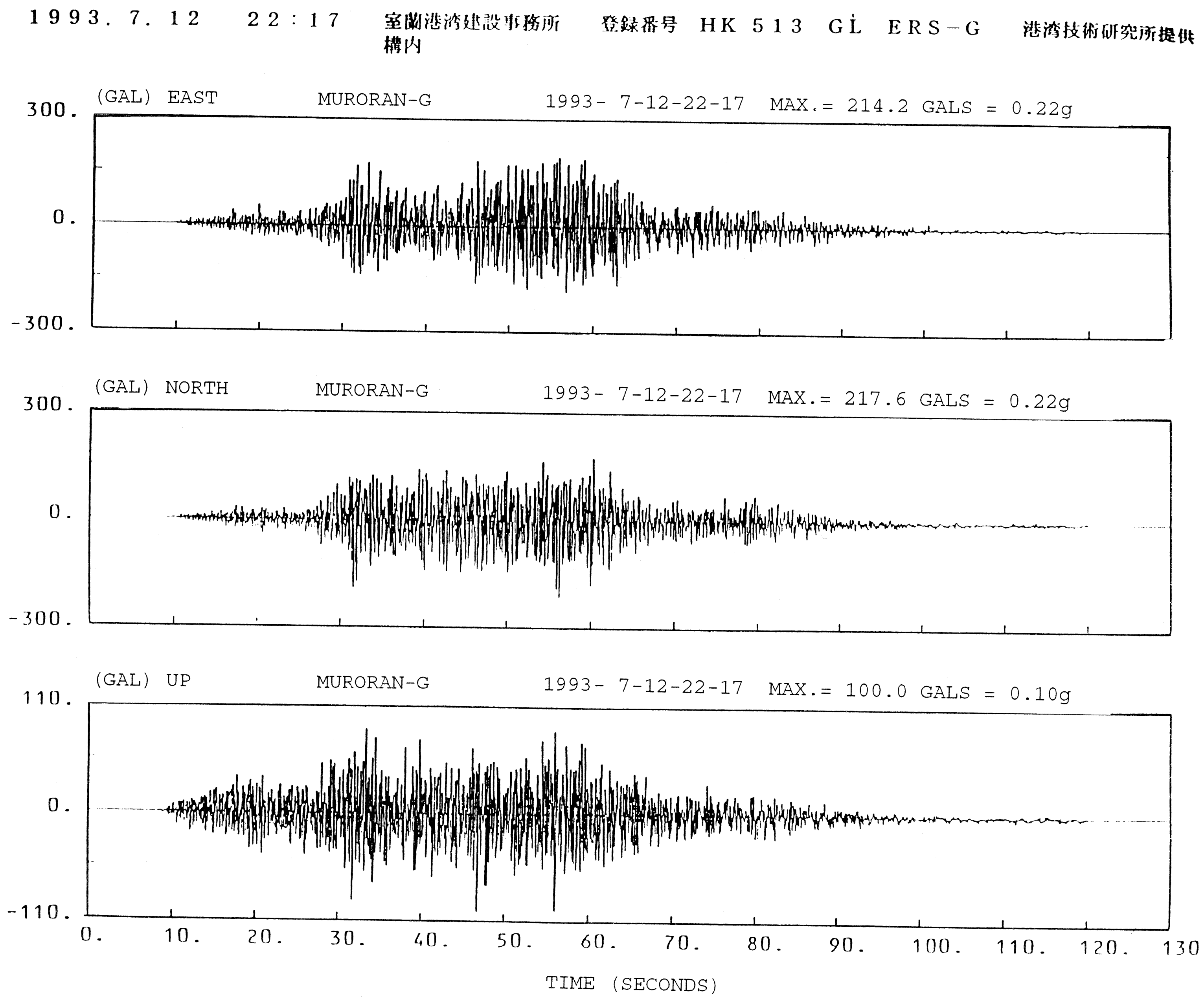


Figure 4-1: The strong motion record at Muroran. The peak ground accelerations are 0.22g and 0.22g horizontal and 0.10g vertical (Reference 3).

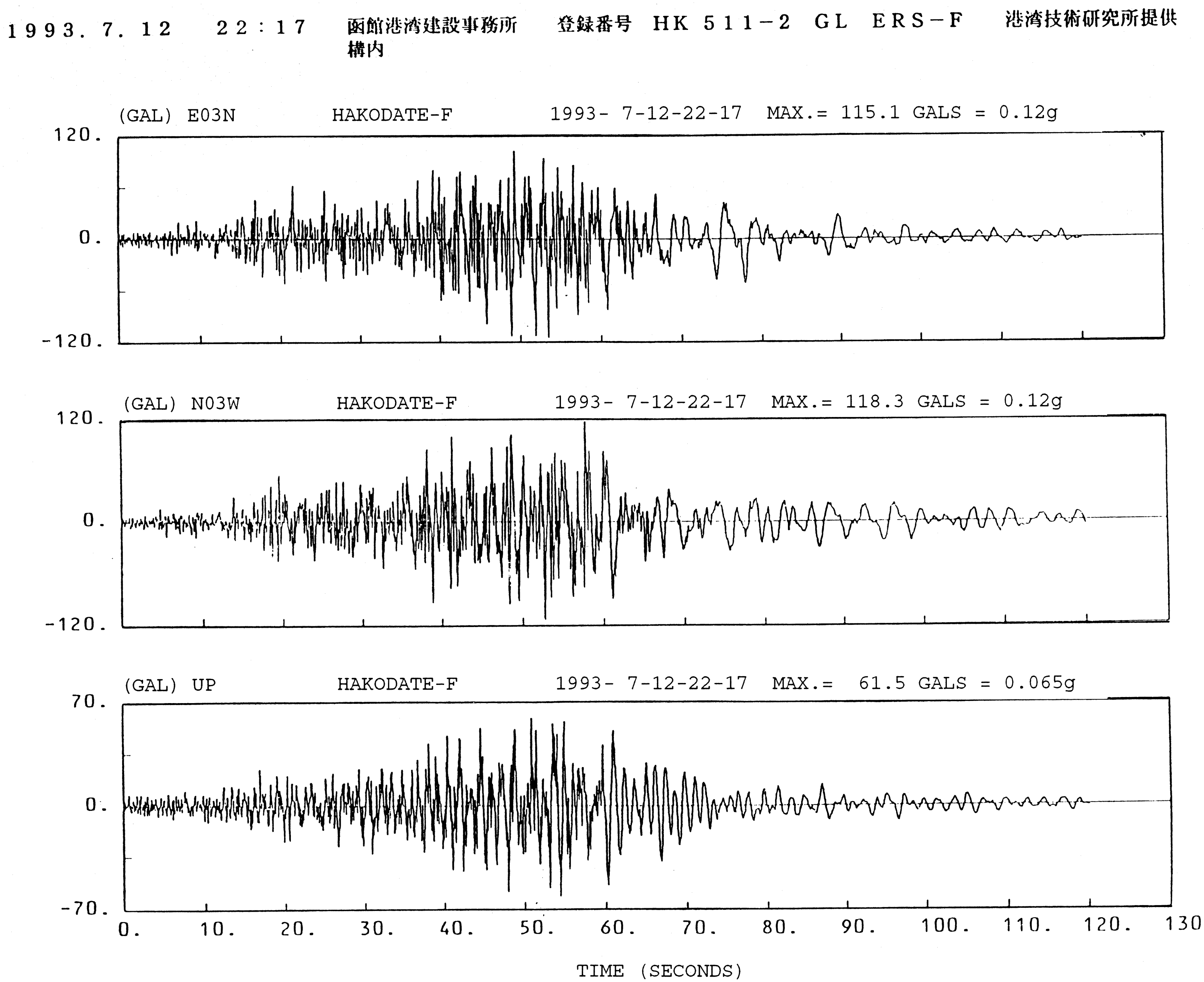


Figure 4-2: One of the strong-motion records from the city of Hakodate. The peak ground accelerations are 0.12g and 0.12g horizontal and 0.065g vertical (Reference 3).

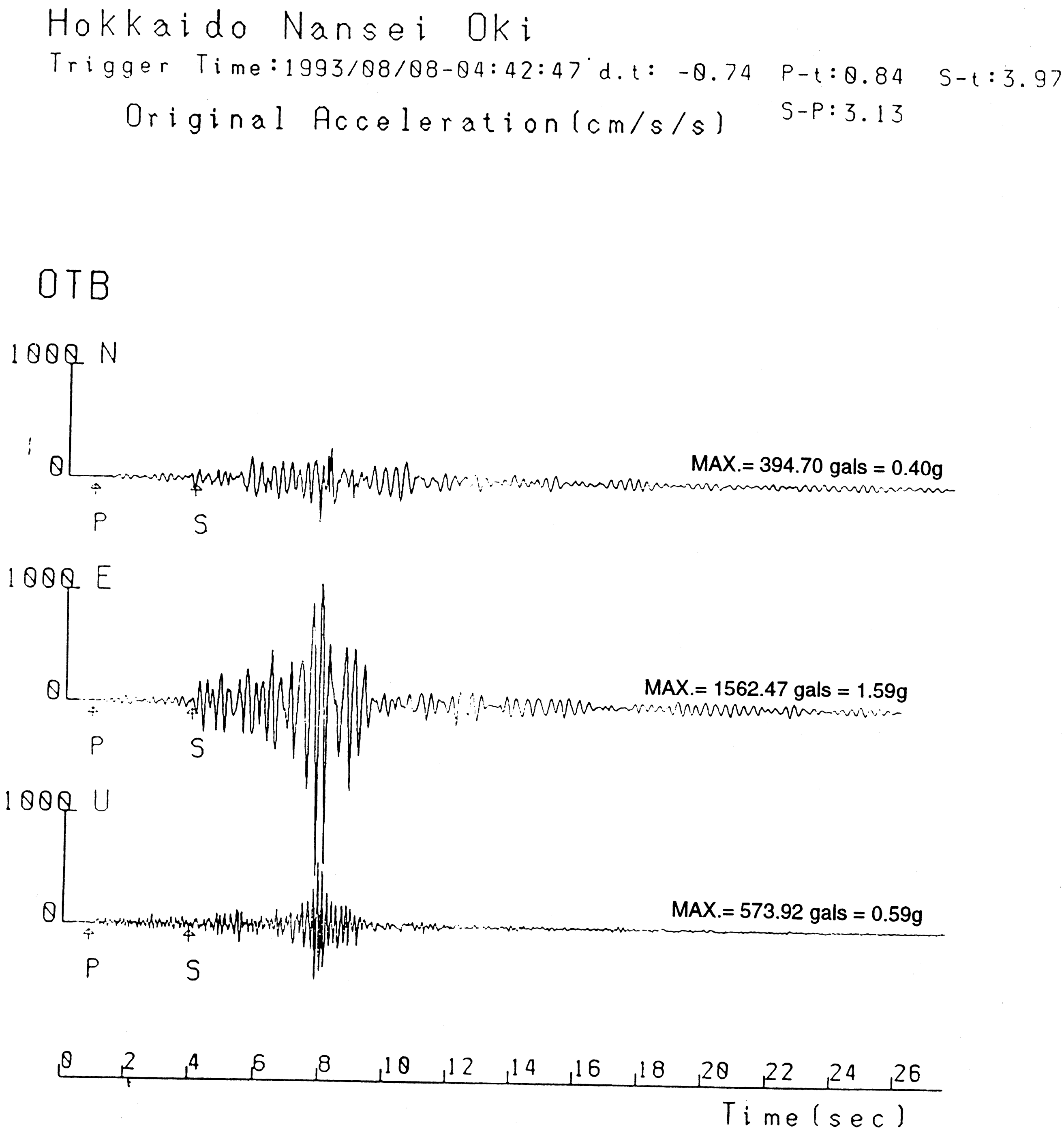


Figure 4-3: The strong-motion record at Otobe-cho on Hokkaido from the M6.5 aftershock of August 8, 1993. The peak accelerations are 0.40g (NS), 1.59g (EW), and 0.59g (Vertical). Figure courtesy of T. Katayama.

SECTION 5
TSUNAMI

From an engineering perspective, the major tsunami that was generated by this earthquake is the most interesting and instructive aspect of the event. The tsunami caused both most of the direct damage from the earthquake and, as of July 21, 1993, at least 120 of the 185 fatalities reported at that time.

The tsunami was caused by a slip of the aftershock area on the Eurasian plate, which averaged about 2.5 m. The waves generated by the vertical component of the slip can travel in open, deep water at speeds exceeding 650 km per hour. These low-amplitude waves grow in amplitude as they move from deep into shallow water. Approaching a coast, the waves slow down, shorten in wave length, and rise in height. For most tsunami-genic events, several large waves are generated, at intervals of 10 to 20 minutes.

The tsunami affected primarily Okushiri Island and the western coastal areas of Hokkaido facing the island. The worst effects were felt on Okushiri.

Several Japanese teams have surveyed the effects of the tsunami, and detailed data should be available in the future. The following is a brief summary based on data from the combined Japanese/U.S. UJNR team and the authors' observations.

Figure 5-1 shows the tsunami wave run-ups along the coast of Okushiri Island. Water run-up in the area of Aonae, at the southern tip of the island, was from 10 to 20 m high--equivalent to the height of three- to six-story buildings. The highest recorded run-up in Okushiri was about 30.5 m--roughly equivalent to a 10-story building. That occurred on the west coast of the island, just north of the town of Aonae. Figures 5-2 and 5-3 show typical effects of the tsunami run-up along the west coast of Okushiri.

The UJNR team describes the effects at Aonae (Reference 1):

> "The tsunami was refracted by the shoaling bathymetry at both ends of the Island. Hardest hit was the town of Aonae (population 1,600), where the first tsunami wave flooded the southern tip of the island and the entire first row of houses in the harbor area within 4-5 min after the main shock. Tsuji (Ed: University of Kyoto) reported (based on eyewitness interviews) that the tsunami arrived from the northeast, with flooding of

> 3-7 m throughout the town. About 7 min after the first wave, a second, larger wave hit from the east carrying boats into the main town. The second wave completely flooded the first three rows of houses, and run-up was measured around 5-10 m throughout the town. The UJNR survey team found battery-operated clocks in this area that had stopped at 22:37 and 22:38. At 22:40, fires broke out; the combination of a strong northeast wind and an ample supply of propane and kerosene (used for heating) quickly spread the fire, which burned throughout the night and destroyed 340 homes. Autopsies revealed that only 2 of the 114 deaths in Aonae were caused by fire. This section of Aonae was the hardest-hit developed area in spite of the fact that a massive, 4.5 m breakwater and 10 m high sand dunes were very effective in reducing the run-up to 5-10 m along the southeastern tip of the peninsula. The UJNR team observed that run-up values rose rapidly again to the 15-20 m level a short distance northeast of Aonae; this is undoubtedly due to the absence of breakwaters or sand dunes along this part of exposed coast."

The tsunami also affected the west coast of Hokkaido within 5 minutes of the earthquake with maximum run-up of about 9 m. The Ota Bay area was the hardest hit. Tsunami run-up of 1 to 4 m was reported in Russia within 30 min, and run-ups of 1 to 2 m were reported in South Korea within about 90 minutes.

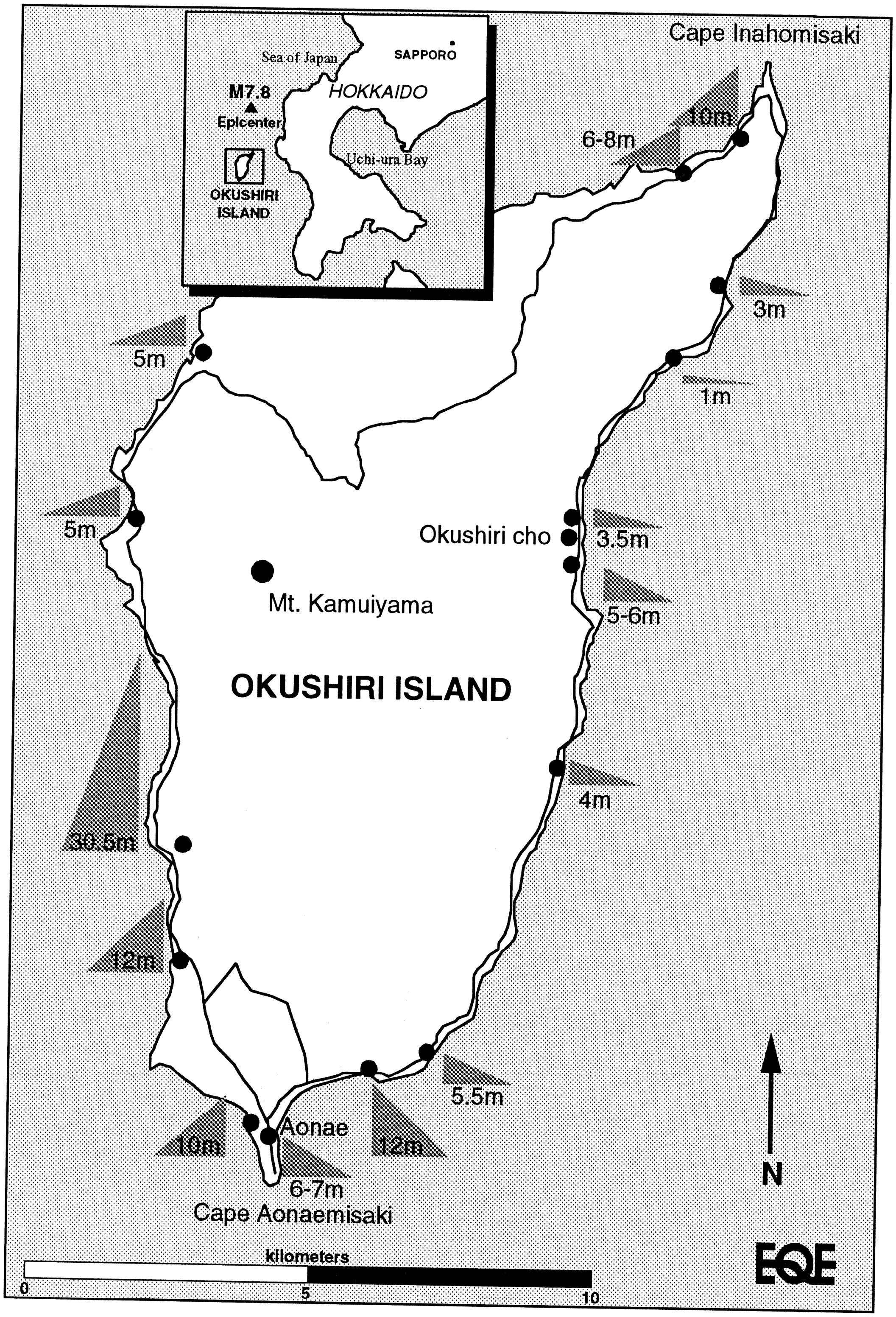


Figure 5-1: Map of Okushiri Island, showing the run-up height of the tsunami along the shoreline. The height is shown in meters on the vertical side of the triangles. In the area of Aonae, the tsunami height was up to the equivalent of a three-story building. The maximum height was about 30.5 m, roughly equivalent to the height of a 10-story building.

Figure 5-2: View of tsunami run-up at the mouth of a small canyon where the maximum run-up of about 30.5 m occurred. That is just to the left of the lower photo. The poles are new. Note how sea- and tsunami-borne debris backfilled along the base of the retaining wall/tsunami wall.

Figure 5-3: Evidence of tsunami inundation along the western shoreline of Okushiri Island just north of Aonae town. The run-up is about 15 m. All the telephone power lines are new; the old ones were destroyed. The vegetation remains along the road railing are from the tsunami. All buildings in this area along the coast at or near sea level were destroyed (lower photograph; courtesy of K. Kawashima).

SECTION 6
DAMAGE FROM THE TSUNAMI

The tsunami was devastating to the town of Aonae, as well as to many other communities along the coast of Okushiri. In the areas of run-up in the range of 5 to 15 m, most wood- frame buildings were obliterated. In Aonae and the small villages north along the west coast, the only evidence that typical wood-frame buildings had existed were their reinforced concrete foundations. In several instances, anchor bolts at the sill of the buildings were observed to have been stripped of any wood.

In Aonae, half of the 690 buildings were washed away by the tsunami, even though most were bounded by recently constructed tsunami walls, which were typically about 4.5 m high.

Several concrete and steel buildings were also damaged. Typically, in these more substantial buildings, the interiors and the architectural finishes on the ground floor, and sometimes higher, were destroyed, whereas the structural frames were not substantially damaged and are easily repairable. The damage potential of a major tsunami to light structures in its path far exceeds that of either an earthquake or a windstorm.

Figures 6-1 through 6-16 illustrate the effects of the tsunami in the town of Aonae.

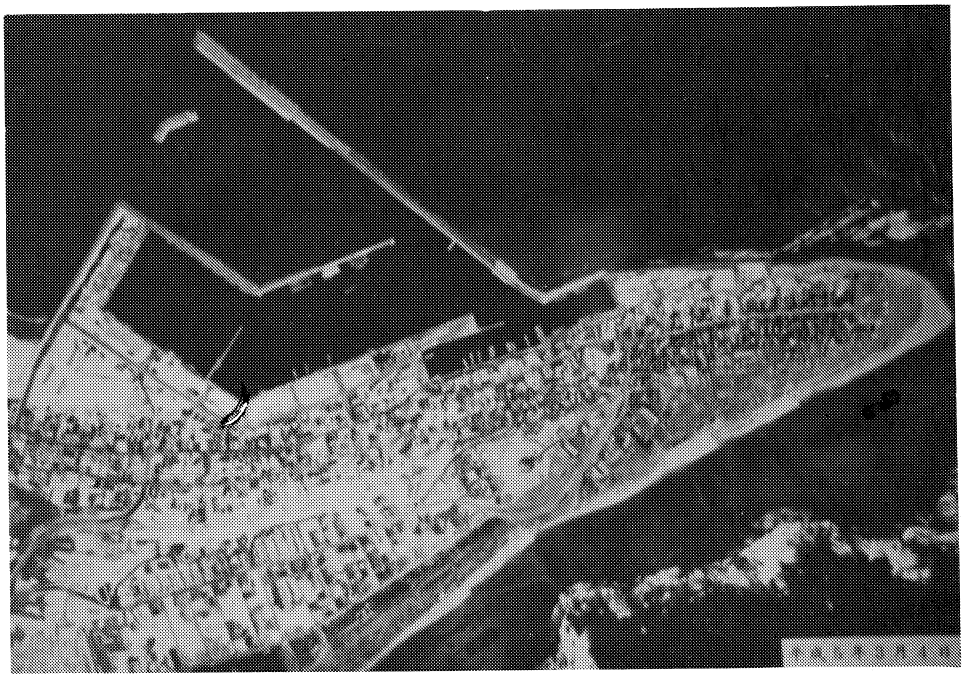


Figure 6-1: Aerial view of the town of Aonae before the earthquake. The left portion is at about sea level, protected by a tsunami wall (height of about 4.5 m). The center is on a bluff about 20 m high. The remaining portion is at about sea level and wraps around the port--which has sea walls that are much higher than the 4.5-m-high tsunami walls.

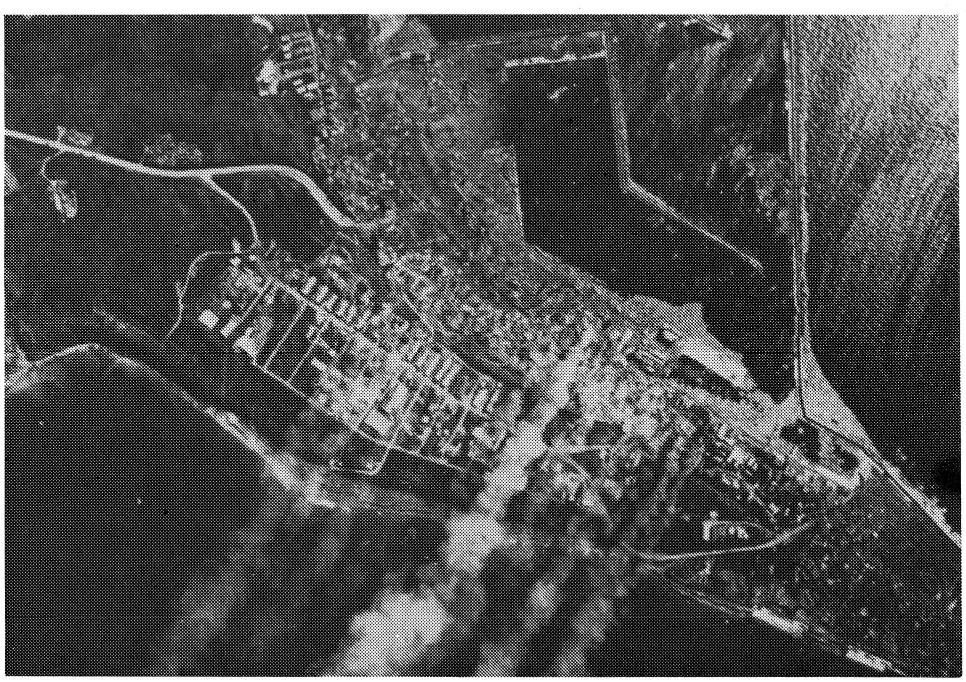


Figure 6-2: View of Aonae soon after the earthquake with smoke from the fire, debris of (primarily) wood-frame buildings in the port, total destruction in the low-lying area on the left, and heavy tsunami and fire destruction along and behind the port. The tsunami run-up here was on the order of 10 to 15 m high.

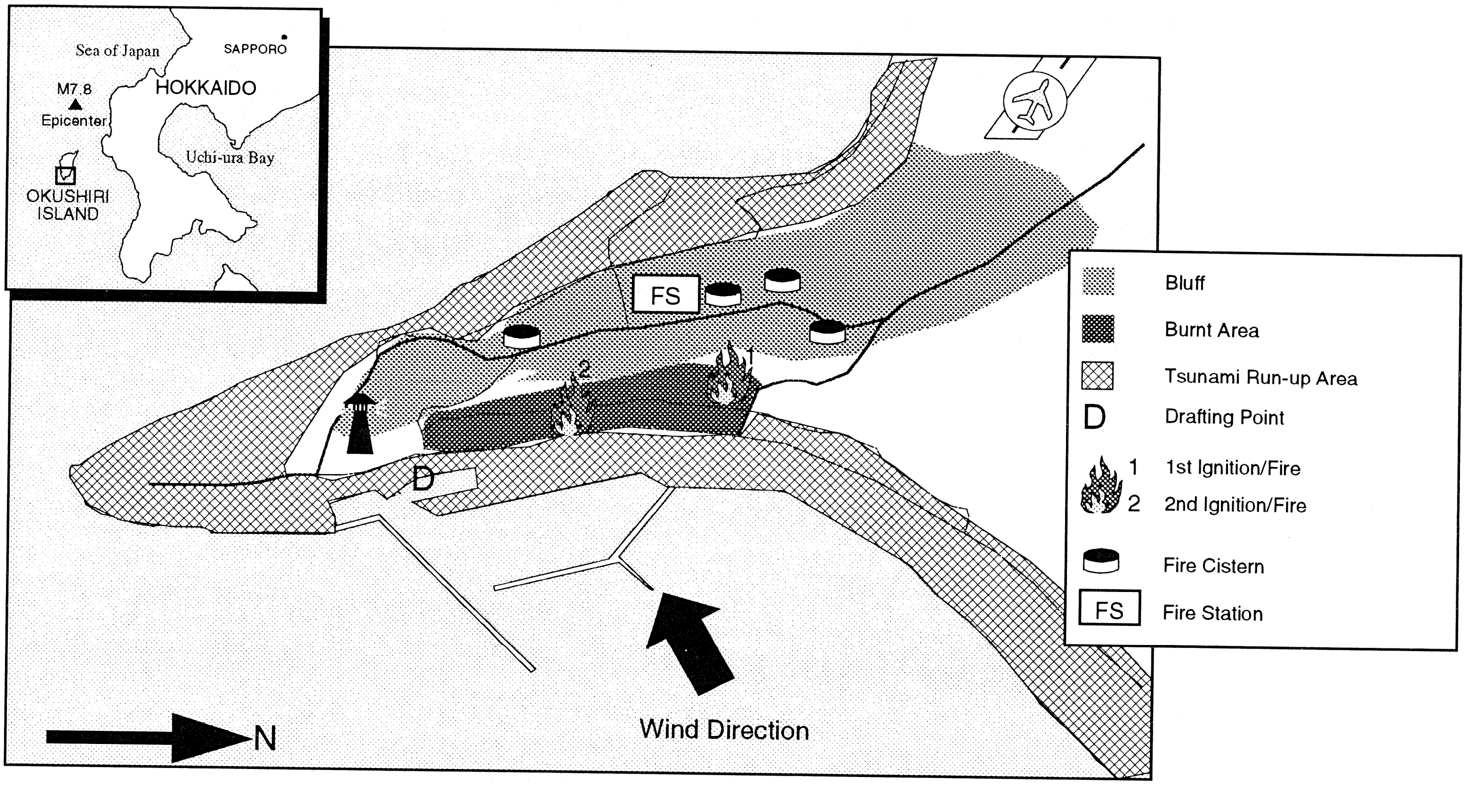


Figure 6-3: Map of tsunami and fire damage areas of Aonae. The crosshatched darker areas show regions with buildings nearly totally destroyed by the tsunami. The white areas are low-lying regions lightly affected or not affected by the tsunami. The light gray is the bluff--unaffected by the tsunami and fire but with light shaking damage. The collapsed lighthouse is shown to the left. The dark gray is the burned area from the fire that followed the earthquake and tsunami. The fire area includes two possible fire-ignition locations. The map also shows the location of cisterns (underground water tanks) used to fight the fire, the location of the fire station in the bluff area, and the location of drafting of water by the fire department on the morning following the earthquake, which occurred at 10:17 P.M. the previous evening.

Figure 6-4: The sea-level southern tip of Aonae showing near total destruction of buildings. All destroyed buildings, mostly two-story, were wood frame. Note that the area is completely surrounded by protective, up to 4.5-m tsunami walls. They were ineffective in preventing the destruction, although they probably moderated the height of the run-up, which was 10 to 15 m high. The lower photograph shows much of Aonae, looking south. Photographs by K. Kawashima.

Figure 6-5: A partial view of the area in the previous photograph. The somewhat intact remains are roofs and the upper floors of two (or more) story buildings. These remains have been transported many meters away from their original locations.

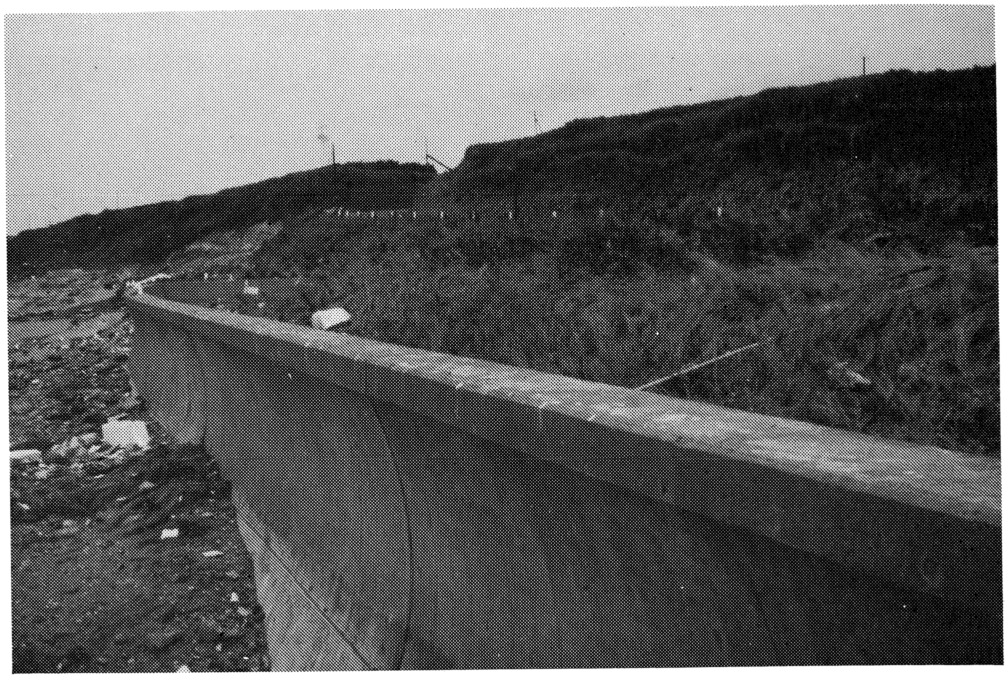


Figure 6-6: Two views of the tsunami walls surrounding the west side of the southern tip of Aonae. Note how the walls have been partially backfilled with sea-borne debris--much of it before the tsunami of the July 12, 1993, earthquake.

Figure 6-7: Fire and tsunami damage in the central area of Aonae. The area in the forefront has been burned. Note that the tsunami did not topple buildings whose chimneys are still standing. The area in back of the street in center has been obliterated by the tsunami.

Figure 6-8: Wood-frame building and contents debris littered and choked the port of Okushiri on the morning after the earthquake.

Figure 6-9: Overturned cars and a heavy bulldozer in the port area of Aonae.

Figure 6-10: Tsunami effects and tsunami-borne debris at the edge of the severe damage in the port area of Aonae. The boat was transported about 100 m.

Figure 6-11: Damage to wood-frame buildings from tsunami run up in Aonae at the far edge of the heavily damaged area.

Figure 6-12: Tsunami devastation in the southeastern part of the port area of Aonae. The building foundations in the forefront have been stripped of any wood. Many foundation anchor bolts without any remaining wood-framing were observed throughout the devastated area. The cars (in center) have been rolled over several times. Several people were trapped and killed or drowned in their cars. About 10 days after the earthquake, search teams were still looking for vehicles and trapped victims along the shores of Okushiri Island.

Figure 6-13: A partial view of the central part of Aonae showing tsunami destruction and a surviving steel-frame building on the left. It protected a small wood-frame building (shown in the next photograph)--the only such survivor in this area.

Figure 6-14: The only observed steel-frame building in the tsunami-devastated parts of Aonae. The building suffered some settlement damage (lower photograph), probably due to shaking. Its first-floor interior finishes were damaged extensively, and at least 15 cm of sand was deposited on the ground floor slab. The building is probably repairable, the estimated loss is less than 50% of value. Note the surviving wood-frame building, which was saved by its steel neighbor.

Figure 6-15: The ground floor of the steel-frame two-story building shown in the previous photographs.

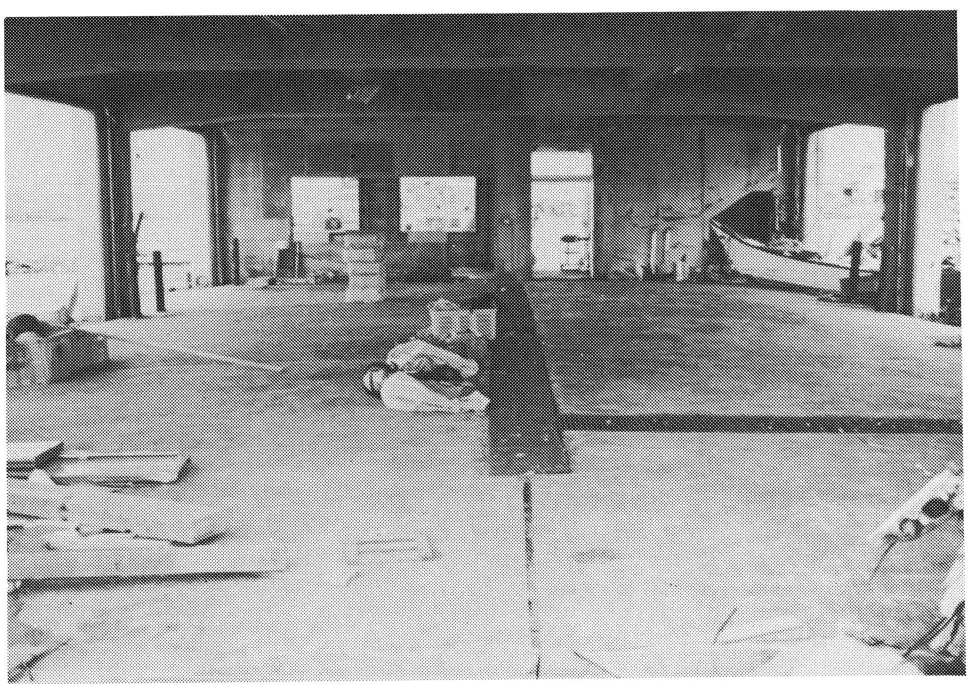


Figure 6-16: A two-story concrete-frame building survived the earthquake and tsunami with light structural damage. It is located at the front of the harbor. The ground floor finishes were completely destroyed. The damage to the left concrete wall is probably from tsunami-borne debris such as the overturned forklift in the center. The ground-floor concrete slab of the building was severely distorted from settlement, probably induced by the shaking--not by the tsunami. The structure appears to be repairable.

SECTION 7
FIRE

The only known fire ignitions during the earthquake occurred in Aonae on the southern tip of Okushiri Island. Most of the town is oriented north-south and sited on or almost on the beach, only a few meters above sea level. The rest of the town is located on a central bluff about 20 m high where a lighthouse, the town offices, and the fire station are sited, as shown in Figure 7-1. The lower part of Aonae is densely built-up with narrow streets and typical building spacings of about 3 m. The buildings are generally one and two story, typically with Japanese wood post and beam construction, although some steel and concrete structures were also present. Exterior coverings are often non-combustible stucco or cement board over wood, with corrugated metal roofing. Large amounts of exposed wood trim, however, compromise the fire protection. Occupancies are generally commercial closer to the wharf area and residential behind (at the base of the bluff), although many buildings are mixed occupancies.

The town is protected against fire by a 38-member trained volunteer fire department headed by a full-time professional. The apparatus consists of two engines of typical Japanese size and configuration--each pumper has a 2,000-liter booster tank and carries 10 lengths of 20-m-long 65-mm-diameter hose. The capacity of the pumps is approximately 2,600 liters per minute. Each engine also carries two 4-m lengths of hard suction hose equipped with bamboo strainer baskets. Relative to U.S. equipment, these fire engines are smaller in dimensions and capacity. This smaller size expedites passage through narrower Japanese streets, such as those in Aonae. A third fire engine was present in Aonae at the time of the earthquake; this engine was in poor condition, however, and was parked at the south end of town where it was destroyed by the tsunami.

Fire hydrants are located around the town but are not used because the water mains are insufficiently sized and pressured to provide adequate water for fire control. Small fires are fought from engine booster tanks, while the main fire emergency water is stored in underground cisterns sited throughout the town. Individual cistern capacity is 40,000 liters, which is accessed through a concrete manhole cover.

Shortly after the earthquake, the fire department made a circuit of the town looking for fires. Seeing none and concerned about a possible tsunami, they returned to the fire station. Within a few minutes following the earthquake, the tsunami swept through the lower area wrecking many buildings and scattering debris over a wide area. The tsunami also destroyed the main water line at its attachment point near a bridge (Figure 7-3). At approximately 10:40 P.M. the fire department received a citizen alarm of a fire in the lower area. A brigade of 10 men immediately responded and attempted to reach the fire by driving down the main street but found the street blocked by debris. They then returned to the top of the bluff and took a second route down the southern part of the bluff.

The probable causes and the effects of the fire are illustrated in Figures 7-3 through 7-9.

The fire began in a structure above the area directly affected by the tsunami, so it likely began as a result of the earthquake. The precise site of initial ignition is unknown, although the approximate location is shown in Figure 7-1. The initial source of the ignition is also unknown (at this time); however, villagers told of earthquake shaking turning over all of their furniture, so numerous ignition sources were available (e.g., cooking and heating appliances, and fuel storage tanks). At the time of ignition, wind was from the east at about 1.5 meters per second with gusts up to about 5 meters per second.

Firefighting was from hand lines supplied from the pumpers on top of the bluff, drafting from the cisterns. Fire progress was southward (cross-wind) and relatively slow; suppression efforts significantly impeded fire progress, but the firefighters were unable to stop the fire. Fire progress was aided by flammables normally stored in each home, as well as the fact that almost all houses had outdoor 490-liter elevated kerosene tanks for heating [e.g., propane tanks (20 kg) for cooking]. The kerosene tanks were quite likely a principal factor in the fire spread. All such tanks were found empty after the fire, most having vented safely through the top vent pipe. The venting was most likely caused by radiant heat causing the kerosene to boil. Eight exploded propane tanks and two ruptured kerosene tanks were documented (Figure 7-6). Reportedly, every time the fire department seemed to be gaining headway, the fire would flare up again, probably due to successive involvement of these tanks. Additional materials fueling the spread of the fire were considerable scrap wood in and among the buildings, and numerous vehicles, which added gasoline, tires, and flammable interiors to the conflagration.

Fire spread was southward at about 35 meters per hour, with firefighting on the downwind edge. Two hours into the fire, a second fire ignited behind the fire line. At about 4 A.M. (6 hours after the earthquake), available water from the cisterns was exhausted. Citizen volunteers assisted in moving the hose over debris from the bluff top to the port, where the two pumpers drafted from the harbor. At this point, the advancing fire front was about 90 m wide. The fire department used equipment to move debris and two buildings, creating a firebreak. Leading four hand lines from the drafting pumpers, the fire was successfully stopped at about 9 A.M., saving several dozen houses that were in the path of the advancing fire.

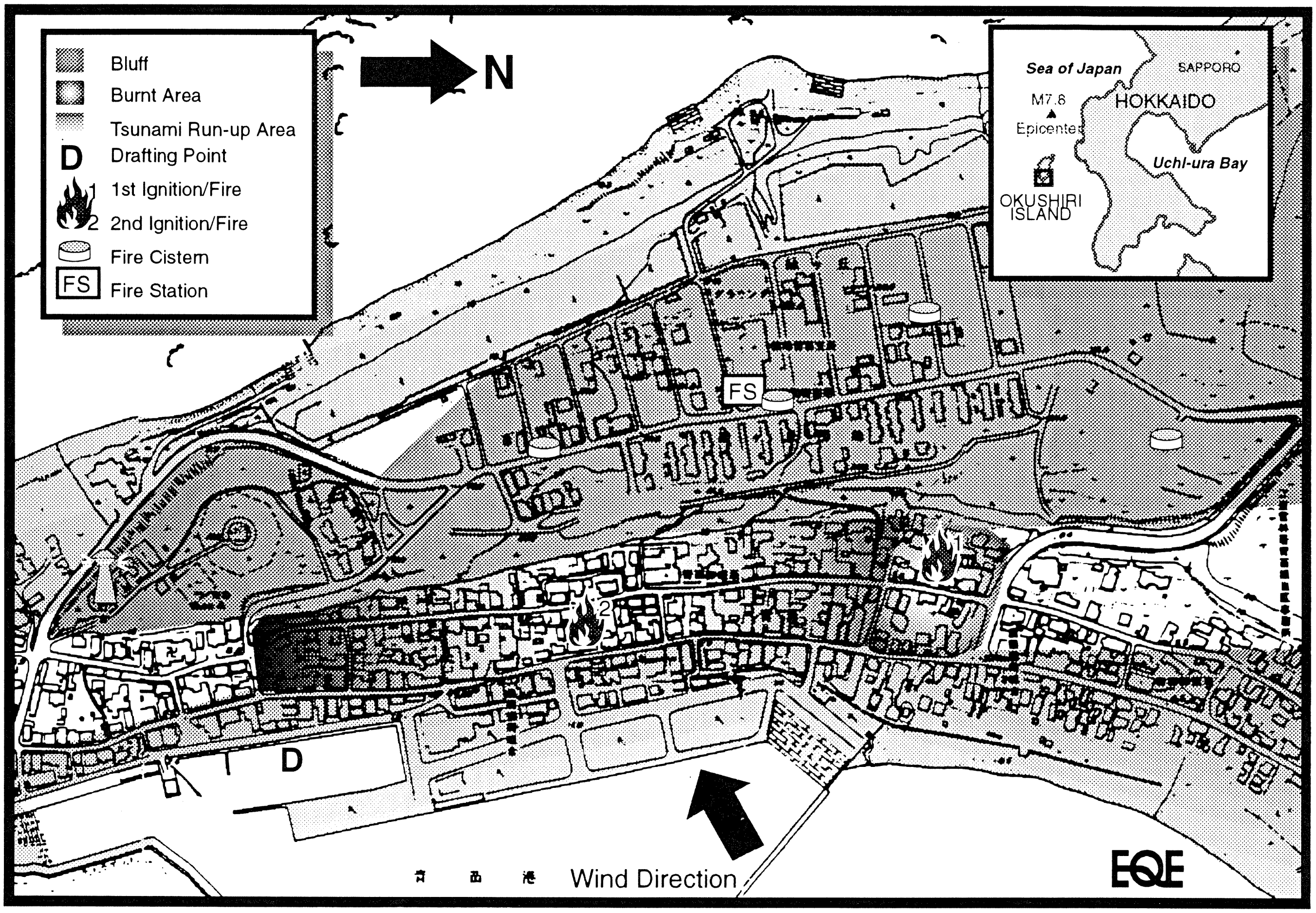


Figure 7-1: Tsunami and fire-damaged areas in central Aonae, Okushiri Island.

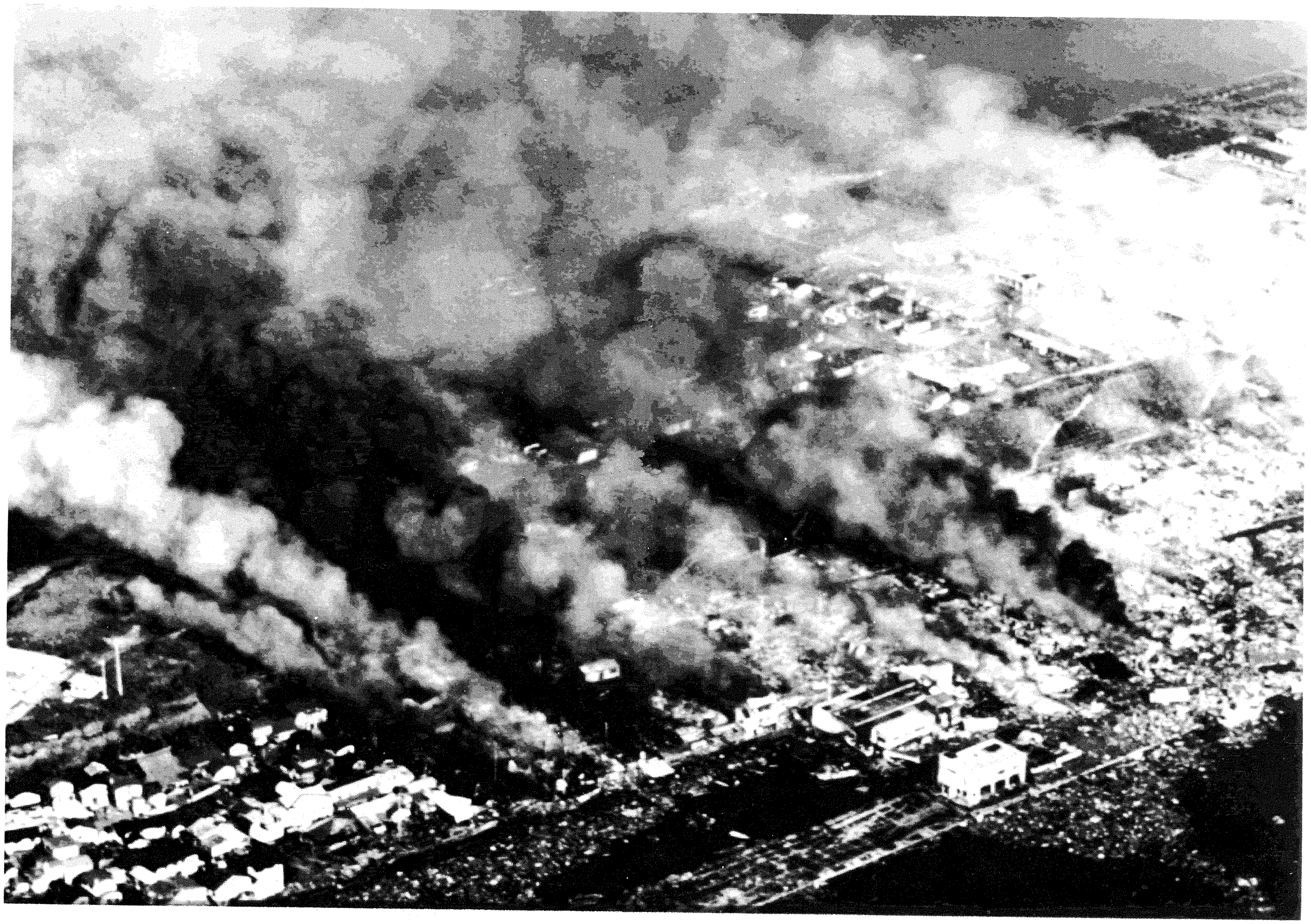


Figure 7-2: A view of Aonae and remains of the fire on the morning following the earthquake. The building from the previous photograph can be seen in the lower right corner.

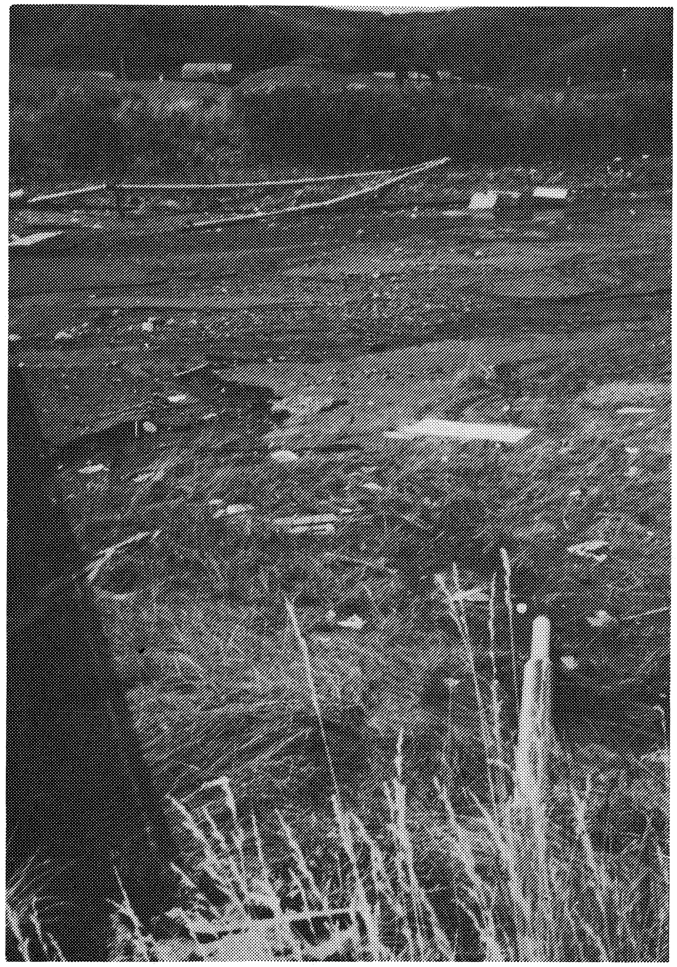


Figure 7-3: The main water line for Aonae was destroyed by the tsunami. This shows views from a bridge of portions of the approximately 20-cm line.

Figure 7-4: A typical kerosene tank for a small building. The fuel is used for heating in Japan (including Tokyo). This tank, in Aonae at the lighthouse, was not anchored and tipped over, severing the small fuel line which is typically about 1/4 inch (0.5 cm) in diameter. Numerous such tanks, many tipped over, were observed on the Island of Okushiri and on Hokkaido (following figure). They are very hazardous and contributed to the fire that destroyed much of the town of Aonae following the earthquake and tsunami. There seemed to be no enforced requirement to anchor such tanks. That practice needs to be changed.

Figure 7-5: An overturned exterior kerosene tank in the town of Kuromatsunai. The highest horizontal acceleration recorded in the main earthquake (0.50g) occurred a few meters away from the tank.

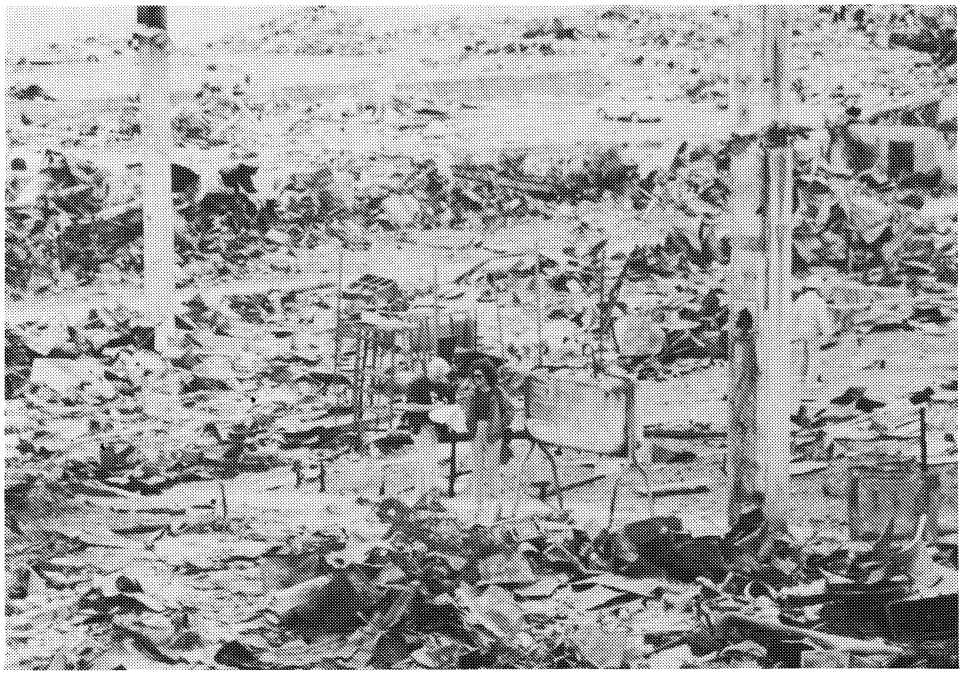


Figure 7-6: A view of a small part of the burned out area of Aonae (top photograph). Note the standing kerosene tank. These and other such tanks, containing fuels, added much fuel to the fire. The vertical columns are chimneys (of wood-frame buildings), which survived the earthquake, tsunami, and fire. Note that the roads have been cleared of debris. The lower photograph shows an exploded kerosene tank.

Figure 7-7: Many boats were deposited far inland, some among buildings. It is believed that much fuel was spilled in this way, contributing to the fire and its spread.

Figure 7-8: A view, looking southeast, of the central port area of Aonae showing tsunami and fire devastation. The only surviving buildings are more substantial concrete-frame buildings. No steel buildings were found in this area.

Figure 7-9: A view of Aonae, looking northeast. The surviving steel building of Figure 6-14 is in the center. The concrete batch plant and the sewage treatment plant (Figure 9-25) are to the right in the back.

SECTION 8
STRUCTURAL DAMAGE DUE TO SHAKING: BUILDINGS AND INDUSTRY

With a few exceptions, the structural damage caused by the shaking was moderate to light. The more instructive failures occurred on Okushiri Island. Due to the limited field investigation, significant damage may not be reported here.

One exception to the general lack of shaking damage was agricultural structures. In contrast to most of Japan, Hokkaido and Okushiri Island farm buildings resemble U.S. barns, including cylindrical silos strikingly similar to, although smaller than, U.S. farm silos. Japanese silos are typically of unreinforced concrete hollow-cell masonry unit construction. These structures suffered severely in this earthquake. About half of the silos observed on Okushiri Island had collapsed. That implies that Okushiri experienced intensities as high as MMI-VIII. Typical collapses of silos are shown in Figure 8-1.

8.1 OKUSHIRI-CHO

Okushiri-cho is the main port of Okushiri Island. At mid-island on the east coast, it is perhaps the closest point to Hokkaido. Residential construction is conventional Japanese one- and two-story wood-frame buildings. In the Hokkaido region, these buildings usually have corrugated metal roofing rather than heavier clay tile. Shaking damage to Okushiri-cho's residential construction in the July 12 event was minimal, with no known building collapses and a few chimney collapses (chimneys were generally lightly reinforced concrete). The commercial buildings are also typically one- and two-story wood frame. They also performed well (Figure 8-2).

Specific buildings of note in Okushiri-cho included the Ferry Building, a two-story reinforced concrete frame with relatively large, approximately 40-cm columns. Located on the main pier, the building's first story was inundated by the tsunami (Figure 8-3), which swept away large glass windows and all interior furnishings. The building sustained settlement of one column on the south side, resulting in shear cracking of beams, but was otherwise structurally undamaged, with the second floor relatively undisturbed. The City Offices (Figure 8-4) are a two-story, stuccoed, wood-frame building, probably built in the 1950s and located approximately 1 km from the shore, up a river valley on apparently firm soils. There was no observable structural damage to the building other than some lost stucco on the west side, which revealed badly decayed wood. Directly to the west is the two-story fire station, of similar vintage but of reinforced concrete construction--it had no observed damage. Directly to the west and north of the fire station is a stone stairway leading to a hillside wooden one-story Shinto Temple. At the base of the stairs is a granite *torii*, or gateway, whose stone cross-member had broken. At the top of the approximately 25-m flight of stairs is an almost identical torii of concrete, whose cross-member was undamaged. The wooden temple structure itself was undamaged. Directly across the street to the south is the two-story elementary school (Figure 8-5), built in 1970 and of reinforced concrete-frame construction. This approximately 30-by-100-m building was being used to house refugees, and had sustained very minor cracking in columns and spandrels. Directly to the west of the school is the gymnasium, an approximately 25-by-40-m steel-frame structure with a barrel arch lattice-truss roof. The gym, which had no observable damage, was being used for housing for police officers brought in from other districts. Some spalling of stucco cover over concrete was observed on a one-story structure connecting the school and gym, at the junction of the structure with the school. To the south of the school is the undamaged NTT telephone exchange building (discussed in Section 9) (Figure 9-30). Lastly, directly opposite the ferry landing had been the two-story Hotel Yo Yo, approximately 25 by 50 m, which was buried under a massive landslide (discussed in Section 11).

8.2 AONAE

Aonae and its surrounding area contained the more instructive examples of structural damage from the earthquake. A lighthouse is located on the bluff, about 20 m above the port area, and overlooking the south end of the island and town. Its 8-m-high tower failed at the base, allowing the tower to rotate en masse onto the one-story building. The tower came to rest at approximately a 45^{o} angle (Figure 8-7). Our inspection indicated an apparent bond failure of plain J anchorage bars (approximately 24 mm in diameter).

There appeared to be a concentration of damage around the lighthouse. Because of its location right on the edge of the bluff, it may have experienced local site amplification.

Two schools--an elementary and a junior high school, were briefly surveyed. They are located on the north side of Aonae. The junior high school is located on a slight elevation, above the beach and appeared to have suffered no substantial damage. The two buildings of the school, a classroom building and a gymnasium, were being used for the shelter of families who had lost their homes and/or relatives from the tsunami, fire, and earthquake.

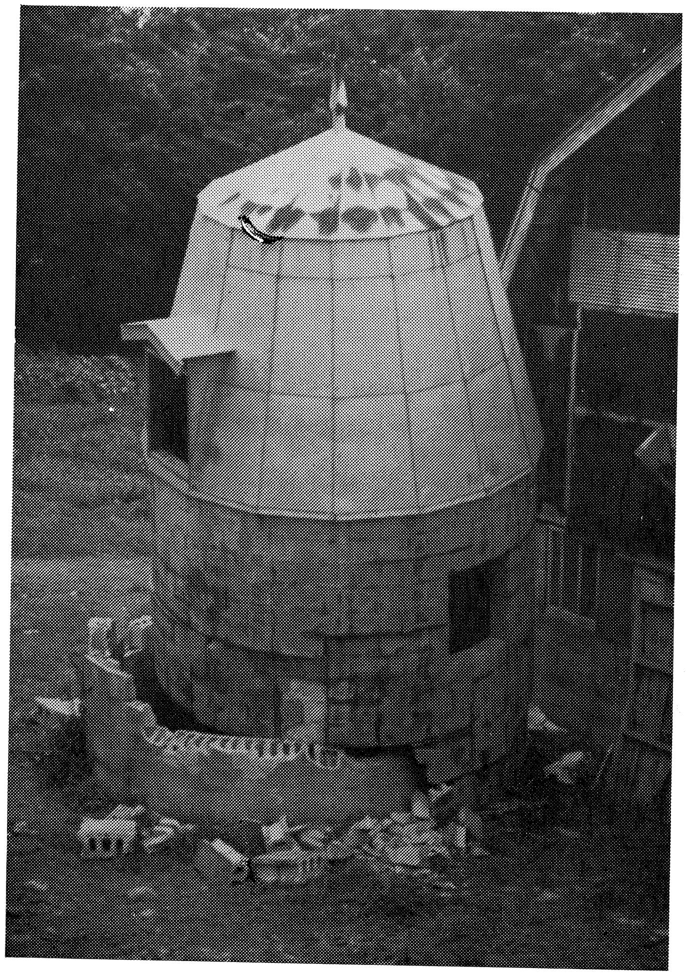
The elementary school, also with two very similar buildings, was located on lower ground, practically at sea-level elevation or possibly filled ground. The late 1960s or early 1970s three-story main classroom (Figures 8-9, 8-10, and 8-11) structure, suffered cracking to its spandrels. The cracking then proceeded into the main structural columns, severely damaging the building. The grounds around the building suffered extensive liquefaction and settlement, as shown in Figure 8-12.

The Okushiri Concrete Batch Plant (OCBP) is located near the elementary school, on a flat site just above sea level (Figure 8-13), near the beach. It is protected by high sand dunes and was not affected significantly by the tsunami. The small site consists of two steel silos, a small office building, and a tall truck-loading hopper with an associated conveyor structure. The site experienced strong ground motion and suffered a loss of about 20% of replacement value. The strong motion at this site was probably due to site amplification from the underlying soft sandy soils.

The hopper structure consists of a first-story steel moment frame (which permitted trucks to enter between columns), with about 20-m-high braced steel framework above, supporting a hopper. This framework consisted of large cold-formed steel angular column sections, braced by hot-rolled steel angle diagonal bracing. The columns had buckled at the junction of the braced structure with the first-story moment frame, resulting in the braced structure tilting about 5^{o} out of plumb (Figures 8-13 and 8-14). Figure 8-15 shows one of the four corner columns that buckled and shortened by about 50 cm. The weak columns had inadequate capacity to sustain the additional vertical loads from the earthquake. It is somewhat humorous that the structure had well-designed diagonal bracing that was less damaged than the main load bearing columns. Connected to the hopper at the top is a conveyor structure, which slopes downward from there to the ground, with a total length of about 60 m. The conveyor has a cylindrical steel duct wind shield, approximately 1 m in diameter, which is vertically supported at mid-span by a steel A-frame truss. Due to the large displacement of the canted hopper, the wind shield had been displaced downward and sideways at its junction at the top of the hopper, resulting in buckling of the cylindrical steel wind shield at its junctions with the A-frame (Figure 8-16).

Other damage at the plant included movements of various unanchored equipment and secondary damage to piping because of the partial collapse of the hopper structure (Figure 8-17).

The two vertical steel silos were anchored to their foundations. All of the lightly corroded anchor bolts for both silos either pulled out partially or broke (Figure 8-18). It was apparent that the silos had rocked and slipped during the earthquake. One of the silos buckled near its base (Figure 8-19). At the time of the earthquake, the silos were more than 2/3 full.



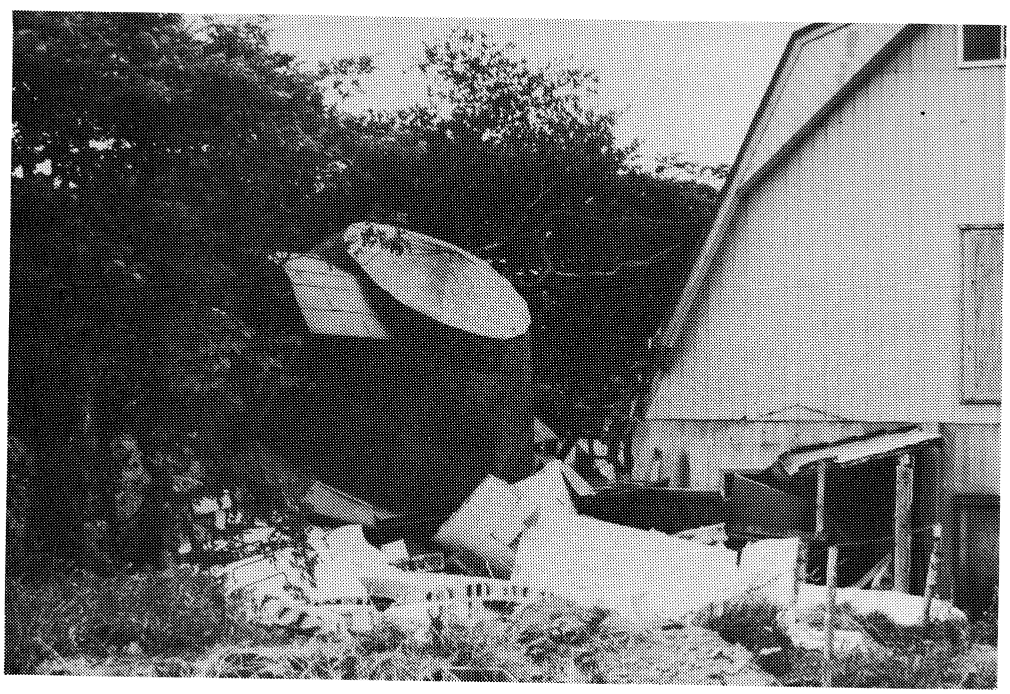


Figure 8-1: Typical collapsed unreinforced concrete-block silos a few kilometers north of Aonae.

Figure 8-2: Lightly damaged commercial buildings in Okushiri-cho. Typically these buildings are wood-frame with stucco. Note the damaged stucco and brick veneer.

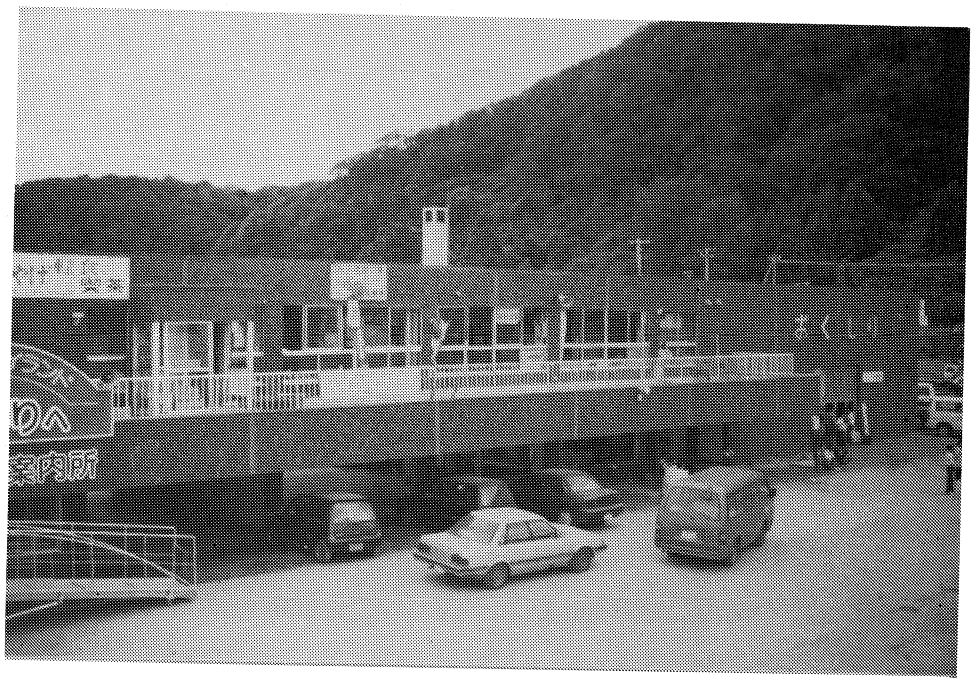


Figure 8-3: The reinforced concrete-frame Ferry Building in Okushiri. The ground-floor finishes were extensively damaged by the tsunami. The building had some damage due to local settlement in one corner.

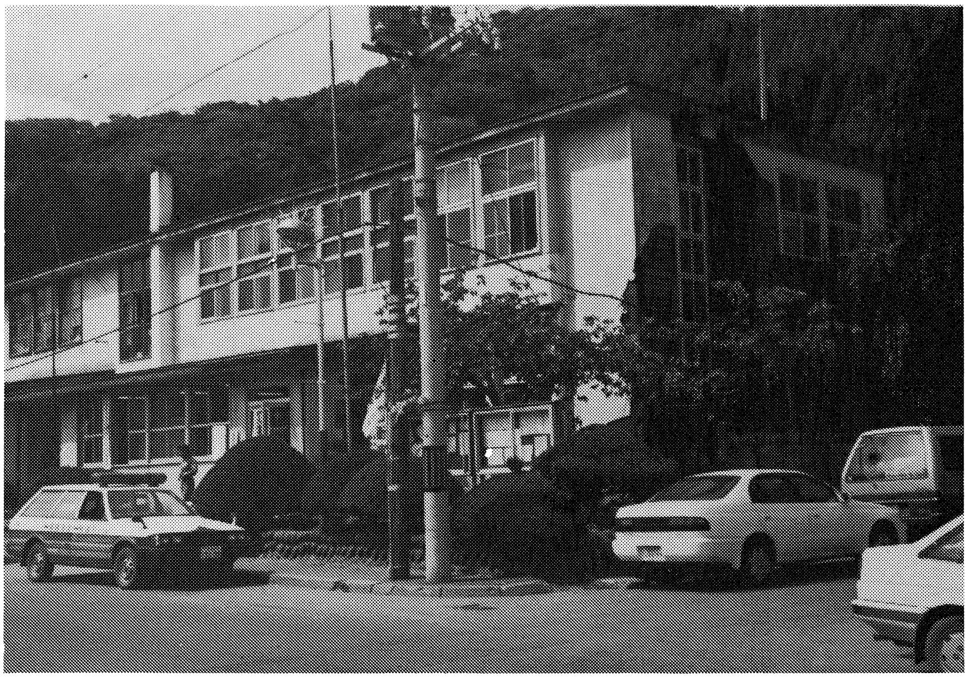


Figure 8-4: The light wood-frame and stucco City Offices Building in Okushiri-cho (upper photograph) and a smaller building (lower photograph) suffered extensive damage to their stucco facades but not major structural damage. These rather flimsily built structures suffered probably as much damage from shaking as any building observed in the town.

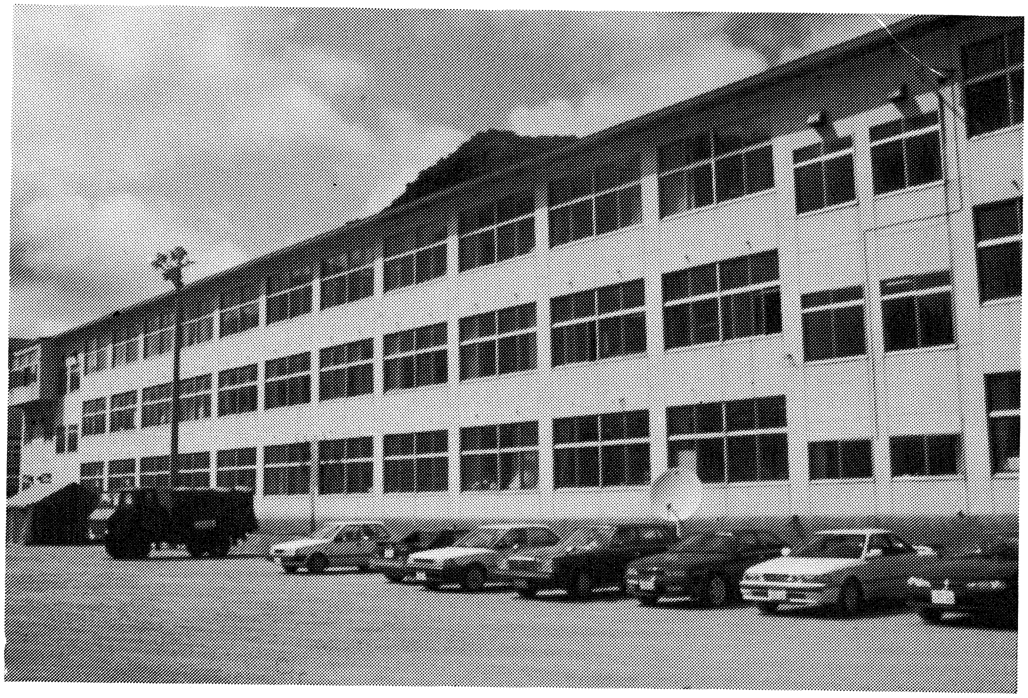


Figure 8-5: The apparently undamaged 1970 reinforced concrete-frame Okushiri-cho elementary school.

Figure 8-6: Undamaged five-story reinforced concrete shear wall apartment buildings in the outskirts of Okushiri-cho. Minor settlement of fill around the buildings was observed. Several large landslides in steep terrain were visible from the buildings.

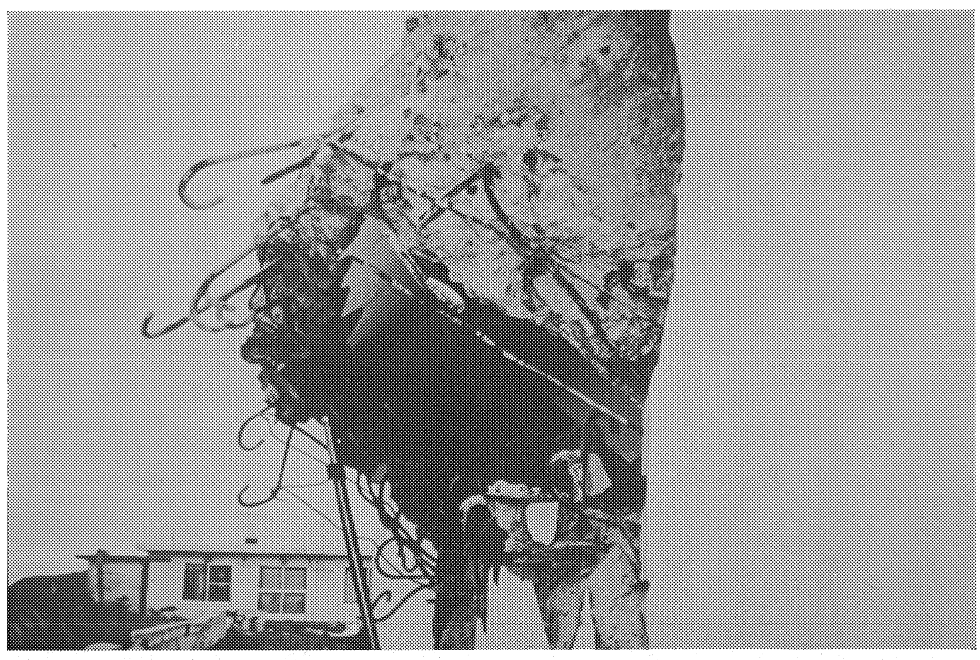


Figure 8-7: The Aonae lighthouse collapsed during the earthquake. The failure was caused by fracture of the tower structure at the base, along with pull-out of reinforcing steel dowels from the foundation. The inspection indicated an apparent bond failure of plain J anchorage bars (approximately 24 mm in diameter).

Figure 8-8: A practically undamaged temple building, which was not affected by the fire and the tsunami. This is probably structurally one of the weakest wood-frame buildings in Aonae, indicating that the intensity of the ground motion on rock or stiff soils was not high in the central port area. The temple is located below the Aonae lighthouse.

Figure 8-9: Aonae Elementary School, a typical 1950s through early 1970s nonductile concrete-frame building (preceding the lessons learned from the 1971 San Fernando, California, Earthquake). The school, on level ground at sea level, suffered extensive cracking of frame and concrete-block infill-wall elements. These types of buildings have historically suffered extensive damage in Japan (Sendai Earthquake of 1978) and California in 1971, 1979, 1989, etc.). Extensive strengthening of these kinds of buildings has been carried out for all California public schools of similar construction.

Figure 8-10: Aonae Elementary School damage.

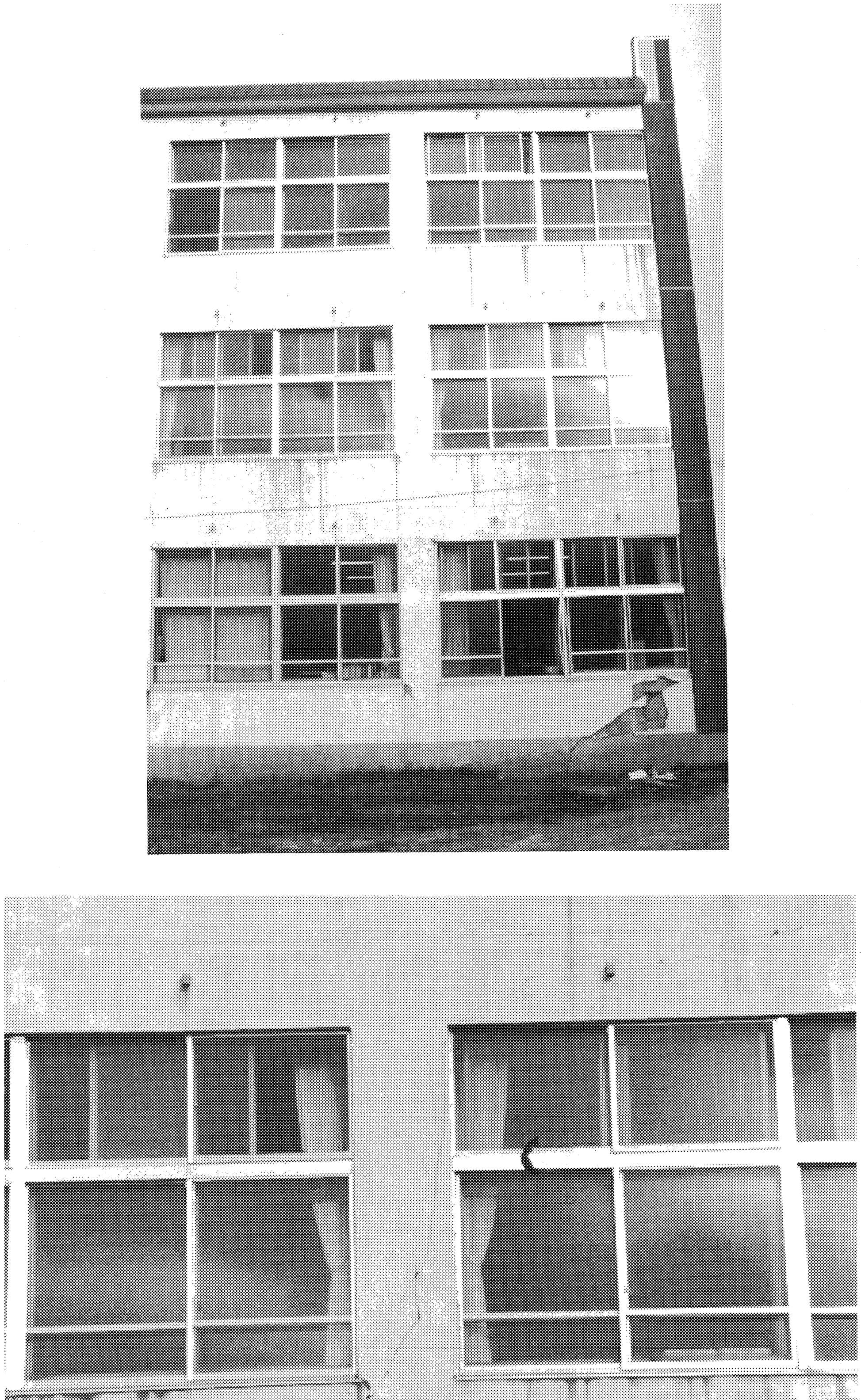


Figure 8-11: The damaged west facade of the Aonae Elementary School. Spandrel and other infill wall cracking has propagated into the columns.

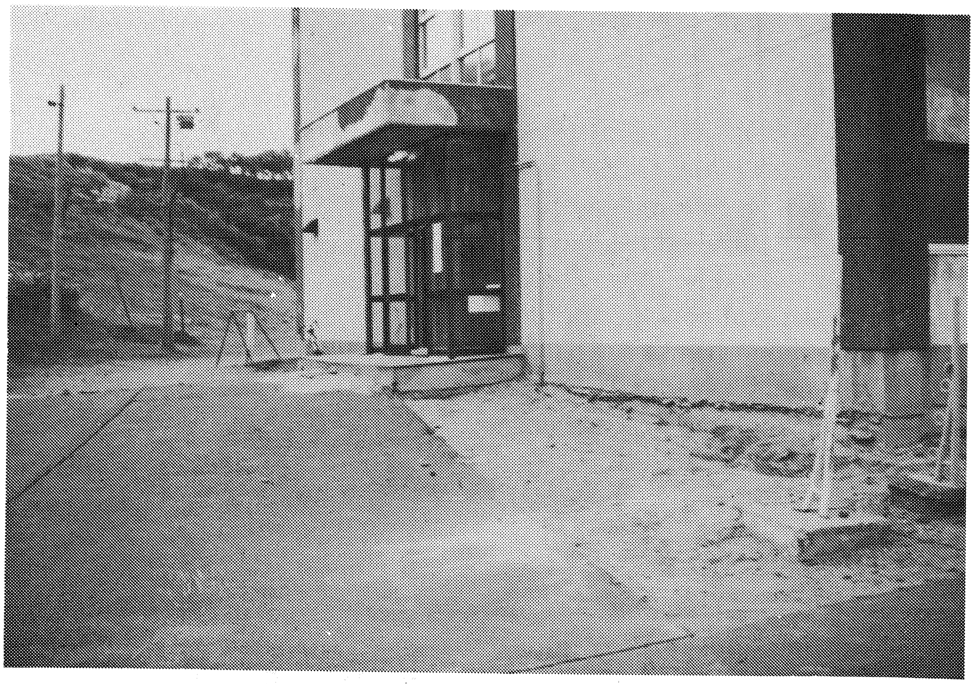


Figure 8-12: Aonae Elementary School. Settlement of fill in the southeast corner of the three-story building (upper photograph) and a cracked floor slab (lower photograph) indicate that the ground failure extended below the structure.

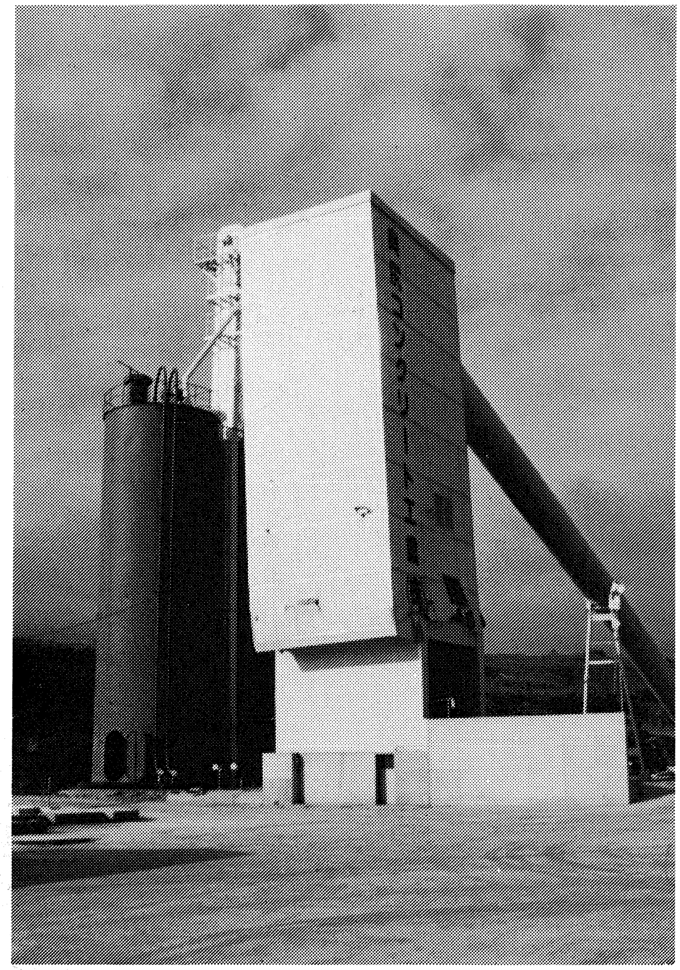


Figure 8-13: The Okushiri Concrete Batch Plant (OCBP) at Aonae suffered severe structural damage to its elevated hopper. The steel structure buckled at the second level. The two silos on the left tore their anchorages, but did not displace laterally permanently. Most of the anchorages were torn (tension failure). The loss is approximately 20% of the value of the plant, according to the plant manager. The plant was not affected by the tsunami. The estimated ground acceleration at this site is about 0.30g to 0.50g.

Figure 8-14: OCBP; close-up of the steel-frame hopper superstructure that buckled. The ground-level columns appeared undamaged. Note that the superstructure has dropped about 50 cm.

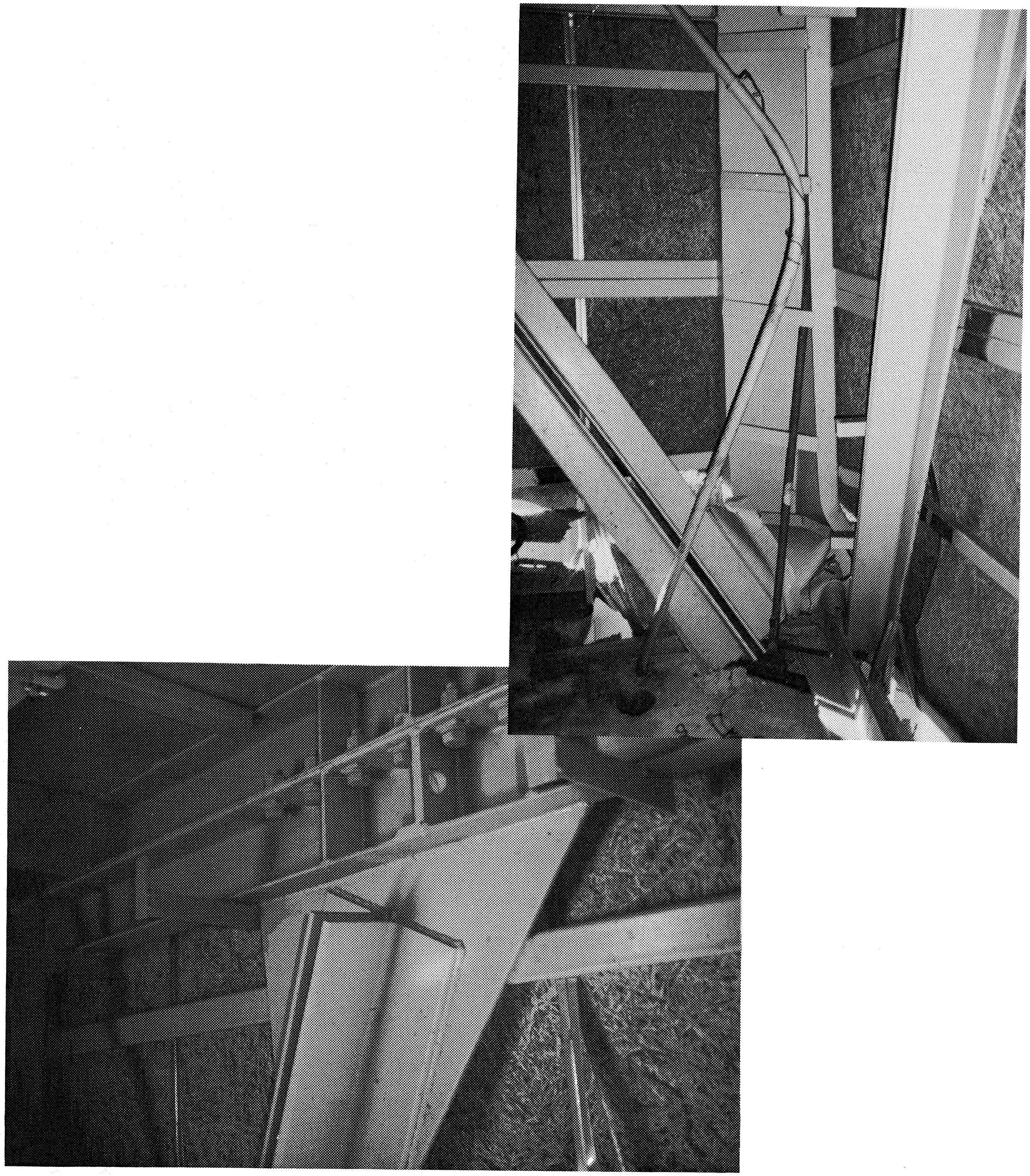


Figure 8-15: Interior view (upper photograph) of one of the four columns of the superstructure of the hopper at OCBP. The cold-formed corner thin-plate column has buckled and shortened by about 50 cm. Note that the seismic diagonal braces are undamaged. The hot-rolled angle diagonal steel braces are much heavier than the corner columns (about twice as thick). In effect, the designer designed against large earthquakes (lateral forces) but neglected to detail properly the vertical system. The lower photograph shows the well-detailed and undamaged brace connection.

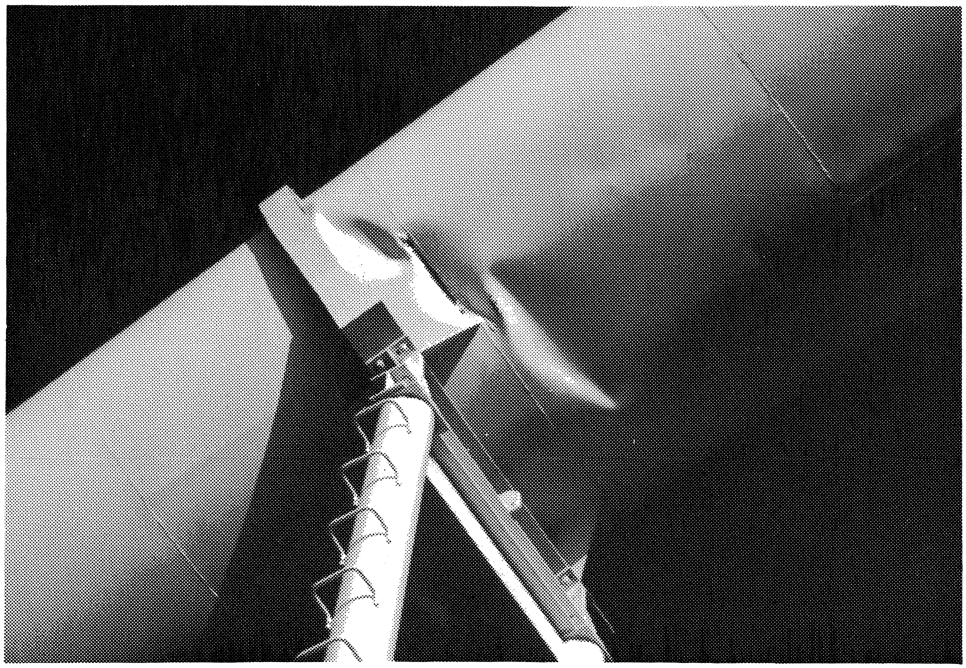


Figure 8-16: OCBP; damage to the large-bore hopper ducting due to differential displacements at its supports--caused by the buckling and shortening of the hopper structure.

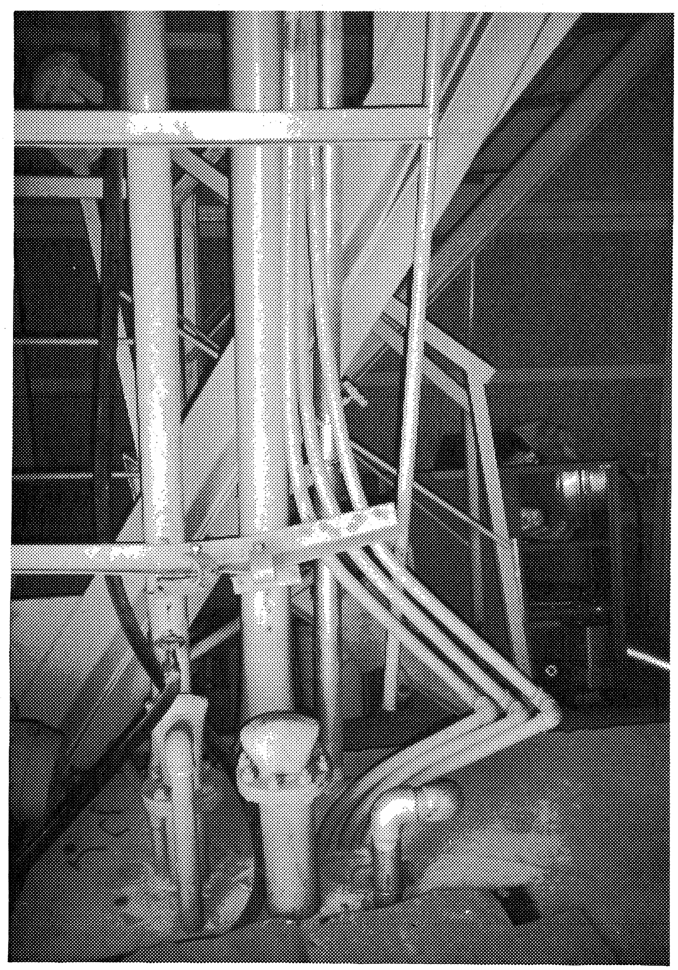


Figure 8-17: OCBP; buckled small-bore piping on the second floor of the partially collapsed hopper structure. The piping has been compressed on the order of 50 cm; some of this compression is taken through the piping floor penetration. Note the large ductility of threaded steel piping when the couplings do not pull apart.

Figure 8-18: OCBP; typical anchorage damage to the two steel silos at the plant. The anchors are somewhat corroded.

Figure 8-19: OCBP; buckling at the base of one of the two cement silos. Note the damage to the anchorage.

SECTION 9
EFFECTS TO LIFELINES AND ASSOCIATED STRUCTURES

Because the earthquake had a large magnitude, a long duration, and affected a large area, extensive damage to lifelines and their associated structures occurred. What was most remarkable was the speed with which much of the damage was being repaired. That subject could not be addressed by the authors adequately because of the lack of time during the investigation.

Aside from damage caused by the tsunamis, which is covered elsewhere in the report, much of the damage to lifelines occurred at long distances from the faulting and typically in areas of recent, soft soils and various fills. Most of the damage to lifelines can be attributed to failures of the ground which, in turn, affected structures.

Because so much of the damage to lifelines was caused by liquefaction of the ground, the subject and effects of liquefaction, lateral spreading, and ground settlement are covered in this section of the report.

Okushiri Island is small and has limited infrastructure to support its fewer than 6,000 inhabitants. Most of the effects observed were on the large island of Hokkaido.

9.1 HIGHWAYS

All of the observed affected highways were two-lane roads, which are adequate to support the low population density of the region. The authors did not survey the larger highways and highway structures in Hakodate; however, at the time of the investigation, there were no reports of notable damage.

In general, highway performance was very good, with most damage to pavements due to general ground settlement, settlement at approaches to bridge abutments, etc. Repairs were ongoing 10 days after the earthquake, with a large number already accomplished. Lateral spreading and settlement affected many primary roads in Hokkaido, up to about 90 km from the faulting. Some of the many locations of more extensive damage are shown in Figure 3-3. The coastal stretch of National Highway 5 south of Oshamanbe, for example, was damaged at many locations, including long stretches of embankment near sea-level elevations (Figure 9-1). Typically, the fill of the embankment spread laterally, destroying the asphalt roadway. Most of these types of failures occurred along beaches or in agricultural areas, where either one or both sides of the road are rice paddies or other fields. Another section of Highway 5, Figure 9-2, near Kuromatsunai where the 0.50g peak horizontal acceleration was recorded, collapsed, taking out the two-lane road embankment and a nearby railroad embankment. That failure occurred in hilly terrain.

Local streets in low-lying areas in towns along Uchi-ura Bay and Okushiri Island also suffered extensive damage. Typical examples from Oshamanbe are shown in Figure 9-3.

Highways were also affected by many of the hundreds of landslides triggered by the earthquake. Figures 9-4 and 9-5 show such examples in Hokkaido and Okushiri Island.

The tsunami also caused direct damage to highways. In many locations, the water scoured or uplifted sections of pavement. Slabs of asphalt were deposited many meters from their locations before the earthquake.

Damage from liquefaction was continuing to occur to roads in the area. Figure 9-6 shows an example of damage from buoyant underground structures that was occurring about 10 to 12 days after the earthquake as the softer soils continued to settle.

9.2 BRIDGES

Because of its wet climate and mountainous topography, the affected region has many bridges. Most are short, one- and two-span reinforced concrete two-lane bridges; several longer, multi-span straight and curved bridges were observed. Most of the bridges are in Hokkaido, a few one- and two-span structures were observed on Okushiri Island.

Several bridges were inundated by the tsunami. No bridges that were observed suffered serious structural damage due to tsunami run-up. The bridge leading to Aonae along the east shore coastal road from Okushiri-cho is an example (Figure 9-7).

Many bridges suffered minor damage to their concrete abutments from girder movement and impact or fill settlement (Figure 9-8). Road embankments at bridge abutments typically experienced minor settlement--most of this damage had been repaired within 10 days of the earthquake. A few bridges suffered major settlement of abutment fill, leading to traffic disruptions for about two weeks following the earthquake.

The most heavily damaged bridge observed was a six-span, two-lane, 1970-vintage steel plate girder highway bridge over the Azabu River, at Azabu-cho (length about 166 m, width 8.0 m), Figures 9-9 to 9-14. Lateral spreading was observed on the south bank of the bridge, which did not, however, appear to affect the superstructure. Significant cracking was observed just above the waterline at the 1.75-m-diameter reinforced concrete bridge piers founded in the river, with the northernmost in-river pier having significant spalling and broken hoop reinforcement.

9.3 TUNNELS

No tunnels were observed on Okushiri Island. A snowshed structure, which was built to function like a tunnel, collapsed on the plateau north of Aonae (Figures 9-16 to 9-21). The snowshed is a two-lane wide barrel vault arch, constructed of two quarter-circle precast curved reinforced concrete planks forming a three-hinged arch (Figure 9-16). The individual planks are about 2 m wide. The total structure is about 300 m long. The structure is built on a slightly elevated embankment, which crosses rice paddies. It is founded on continuous spread footings with stem walls. A portion of a footing and its stem wall is shown in Figure 9-17; the footing was excavated after the earthquake to search for damage and the cause of the failure of the structure. The middle third of the structure failed, and the concrete arch collapsed onto the highway (Figure 9-19). The front third was near collapse (Figure 9-20) (the end third was not surveyed). The site experienced large lateral spreading, which was probably the initiating cause of the failure. As the spreading of the fill and soil occurred, the two stem walls pulled apart, causing further rotational forces on the stem walls and footing, resulting in the total failure, or rotation of the east stem wall of the middle third of the structure onto the footing (Figure 9-18). Further, the exposed connection between the footing and stem wall in Figure 9-17 was cracked, indicating that it is most probable that the stem wall for the middle third had broken due to inadequate vertical reinforcement and rotated off its footings.

The investigators observed many tunnels throughout Hokkaido, and particularly on the west coastal highway facing Okushiri Island. The performance of these tunnels was good, with few tunnels sustaining more than minor damage. The most heavily damaged tunnel observed, and reported, was the Shiroito Tunnel about 15 km north of Setana on Highway 229 (Figures 9-21 to 9-24). The structure is a combination tunnel and a talus shed. It is a cast-in-place segmented concrete tube. The individual longitudinal segments did not appear to be interconnected. The tunnel was intended to protect the highway against rockfalls; this rockfall was bigger than designed for. The adjacent sections to the collapsed section were laterally displaced because of the lack of positive connections between the sections.

The rockfall contained large pieces of andesitic breccia, some of which were greater than 4 m in diameter. The total volume is estimated to be several hundred cubic meters. The fall occurred at the closest distance in Hokkaido to the edge of the aftershock zone, about 35 km, on a near vertical cliff about 60 m above the highway (Reference 1).

9.4 POWER

Electric power does not appear to have been significantly impacted in this event, with the exception that many distribution poles in the tsunami-inundation areas, particularly on Okushiri, were swept away by the tsunami. However, not all poles were destroyed, and some overhead lines were observed with vegetative debris hanging from the lines, clearly deposited by the tsunami. From this, we infer that poles were probably destroyed by debris carried by the tsunami. New poles and lines were generally replaced within 10 days following the earthquake.

9.5 WATER AND WASTEWATER

Water supply to Aonae is furnished by a 20-cm-diameter underground pipe, along the east shore from the north (source was not determined). A river channel about 1.5 km north of Aonae is bridged by a highway bridge, with a clearance of about 6 to 7 m above the river. The bridge, Figure 9-7, was not damaged by the tsunami. The water pipe crossed the river near the bridge, with a clearance of about 4 m above the river. The tsunami swept away the water pipe, severing the main water supply to Aonae.

Numerous other buried water line breaks or leaks were observed throughout Hokkaido. All of these were in soft soils and presumably were caused by various ground failures.

The Aonae Sewage Treatment Plant (ASTP) is located about 2 km north of the town on the east coastal road. It is set back from the shore about 300 m and is protected from tsunami effects by high sand dunes. The plant has several smaller one-story and 1 two-story reinforced concrete buildings, two 10-m-diameter and 5-m-high (approximately) concrete digester tanks, an elevated methane gas holder, a tall reinforced concrete stack, and an outfall pipe into the ocean (Figure 9-25).

The plant is constructed on a level site, probably on sandy soils. Liquefaction was observed on the site and settlement of up to about 30 cm occurred around the structures. The settlement caused light structural damage and damage to surface paving and underground concrete pipeways or culverts (Figure 9-26). The buildings suffered moderate, repairable nonstructural damage from pounding between adjacent buildings and between buildings and the elevated digester tanks. The tanks and the stack were not damaged. Piping was not braced for seismic loads but appeared to have suffered no damage, with the exception of a large-diameter, short ducting pipe which spanned between two structures (a building and the tall stack) and buckled without rupturing. The buckling was caused by differential movements between the buildings, which compressed the pipe (Figure 9-27). Since it was not designed for such loads, it buckled. The main reported damage to equipment was the failure of a transformer, which was located on the second floor. The transformer, which was enclosed in a cabinet, toppled within the enclosure (Figure 9-28).

The sand dunes in front of the plant protected it from the tsunami. The run-up at the nearest buildings was only a few centimeters and caused no direct damage. However, the basement of the main structure, which contained pumps, piping, and some electrical panels, was flooded to a depth of about 1.25 m due to tsunami flooding via the outflow structure (piping) (Figure 9-29). That is, seawater entered the basement room by forcing its way through the outflow piping, a distance of more than 350 m. The flooding inundated pumps, motors, electrical control equipment, etc., incapacitating the plant for several weeks. Tsunami protection against such incidents can and should be provided for high-value facilities with outflow structures. That could be accomplished with one way valving or screens.

9.6 TELECOMMUNICATIONS

Two remote control switches (RCSs) are located on Okushiri Island in the town of Okushiri-cho and in Aonae. The Okushiri-cho RCS is housed in a two-story reinforced concrete shear wall box-like building in the western end of the town, approximately 1 km from the shore and up a narrow river valley, probably on firm soils (Figure 9-30). The building supports a 40-m (approximately) freestanding steel truss microwave tower (Figure 9-31). The equipment in the building includes typical telecommunications equipment and various support equipment such as emergency batteries, diesel generators, various other building support system equipment, piping, and well-braced overhead distribution systems such as cable trays. All the equipment was designed and/or anchored for earthquake loads (Figure 9-32). No damage or any problems were observed or reported with the building, the tower and the microwave, telecommunications, electrical, HVAC, or other equipment. In particular, the telecommunications equipment was well braced in both directions to floors and ceilings or walls. The backup diesel generators functioned properly following the earthquake.

Telephone distribution on Okushiri was severely impacted by the tsunami. Lines are carried on the same poles as the electrical distribution, and were destroyed in places by the tsunami, with considerable time required to splice new lines.

9.7 UNDERGROUND FUEL LINES

Repairs were observed (Figure 9-33) being made to a buried welded steel fuel line approximately 20 cm in diameter, in the southern part of the port of Okushiri-cho. The line was in the tsunami run-up zone as well as in an area of apparent extensive settlement, so that the damage was probably caused by permanent ground settlement coupled with tsunami scour.

9.8 PORTS AND HARBORS

Many of the ports visited suffered extensive damage to their waterfront facilities (Figures 9-34 through 9-39). This includes the ports of Setana, Esashi, and Hakodate on Hokkaido and all of the ports on Okushiri Island--in particular Okushiri-cho and Aonae. Many of the quays and bulkhead walls of these ports were destroyed or nearly destroyed, primarily by liquefaction or liquefaction-induced lateral spreading. The latter was a factor in increasing the lateral forces on walls, causing tilting and often collapse.

The port of Hakodate, in particular, experienced extensive damage (Figure 9-34). It is located at least 100 km from the boundaries of the aftershock zone and Okushiri Island. The peak horizontal accelerations in the port were 0.12g to 0.13g with strong duration of at least 35 seconds. The data from this earthquake show the very high vulnerabilities of typical, older and newer waterfront port structures to long-duration ground shaking. This was also the case for San Francisco's 1989 Loma Prieta Earthquake, except that event was much shorter in duration. Major facilities at long distances suffered severe damage, such as the port of Hakodate. If the earthquake had been much closer to the port, the damage would have been devastating.

The ports of Esashi, Aonae, and Okushiri-cho (and many other ports along the Hokkaido and Okushiri coasts) were further impacted by the tsunami. Ferry service from Esashi Port was prevented for several days due to debris, such as sunken automobiles, in the port. Aonae Port had substantial debris in the port area, as well as general destruction of shoreside shops and facilities. Breakwaters at Esashi and Aonae did not appear to be seriously damaged. Okushiri-cho Port had debris problems (Figure 6-8); additionally, portions of the northern concrete breakwater were severely damaged (Figure 9-35). This consisted of concrete sections of the breakwater being overturned and displaced several meters. These sections were approximately 3-by-6-m concrete blocks, presumably displaced by lateral spreading, although tsunami wave action may have played a role.

Japanese engineers were collecting detailed data on the damage to port facilities. Some of the data were made available to the U.S. team; much more will be available in the near future.

9.9 TANKS

In general, few tank failures were observed. Figure 9-38 shows gas holding tanks in the Oshamanbe area on soft soils. The tanks were not damaged, but the underground piping had been damaged by ground settlement. Note the excavated piping. Similar damage was observed throughout the affected area.

Figure 9-39 shows fuel oil tanks in the port of Okushiri. The tank on the left buckled due to landslide impact (the same landslide that caused the collapse of the Hotel Yo Yo)--note that the tank on the right is undamaged.

Figure 9-1: Typical damage to roads, at Highway 5 south of Oshamanbe, from liquefaction and/or lateral spreading. Many of the coastal stretches of the road had a roller-coaster appearance following the earthquake.

Figure 9-2: The embankment of Highway 5 near Kuromatsunai failed in a flow-slide, taking out both the road and a railroad embankment (which is at the bottom of the upper photograph). Upper photograph by K. Kawashima.

Figure 9-3: Many town streets suffered settlement damage, affecting both paving and various underground utilities. These are examples from Oshamanbe and Setana on Hokkaido.

Figure 9-4: Landslide damage to a retaining wall along Highway 230 near Setana.

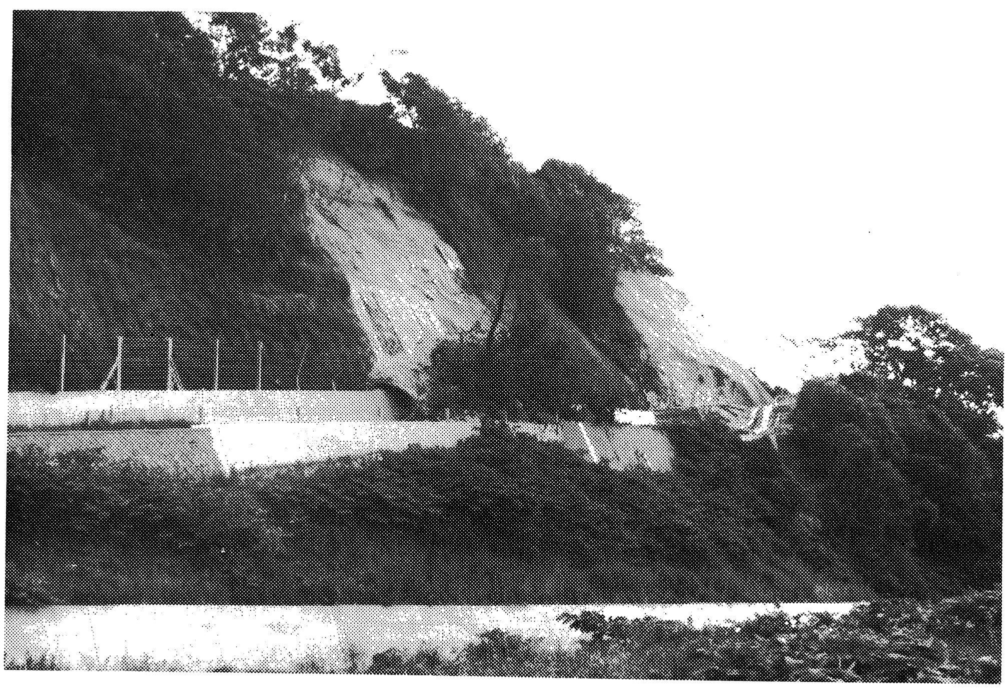


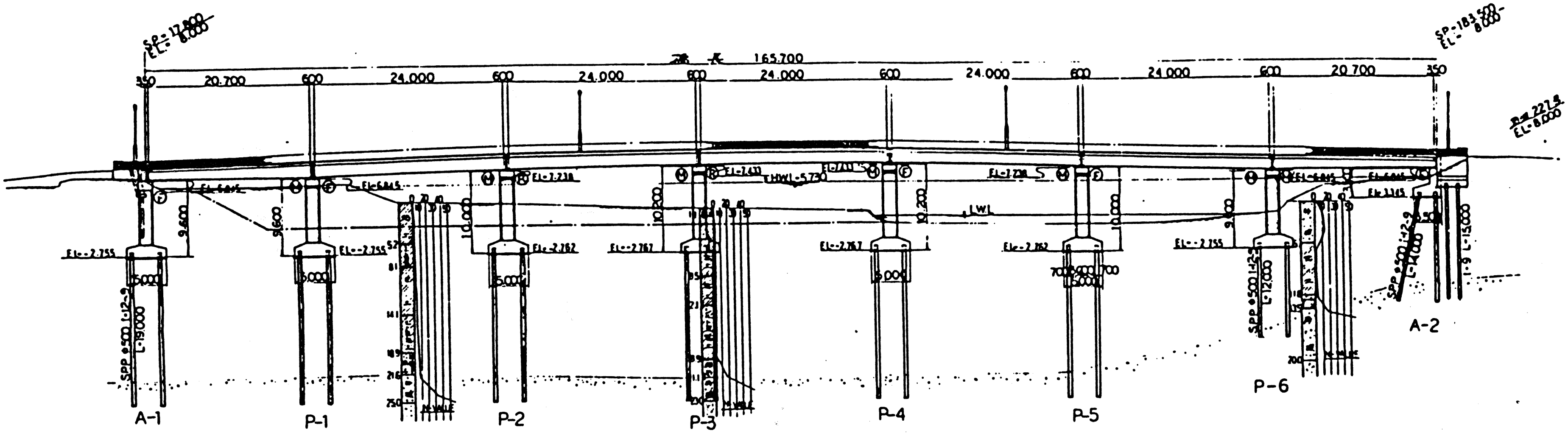
Figure 9-5: Large landslides severed a local road on Okushiri Island, on the plateau north of Aonae in an area of generally higher ground-motion intensities. Several unreinforced hollow-block masonry silos collapsed in this area (see Figure 8-1).

Figure 9-6: Manhole pushed up in Oshamanbe area from settlement. This 30+ cm settlement occurred mostly about 10 to 12 days after the earthquake and was continuing to increase.

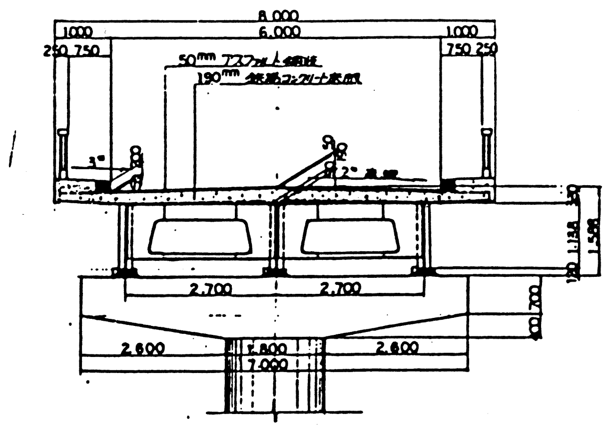
Figure 9-7: A two-lane bridge at Aonae on the coastal road from Okushiri-cho. The bridge was inundated by the tsunami. It suffered minor damage, such as slumping and erosion of abutment fill. One- and two-story wood-frame structures in its vicinity were obliterated by the tsunami.

Figure 9-8: Typical road surface damage and abutment fill settlement at a bridge in Okushiri.

Figure 9-9: A six span, two-lane, 156-m-long, 1970 steel plate girder bridge at Azabu on Highway 277. The bridge suffered severe shear damage to all visible columns, which are about 2 m in diameter. The bridge is located about 70 km from the eastern edge of the aftershock zone. No significant damage to the superstructure was observed. The following figure shows drawings of the bridge.



（a）　断面図

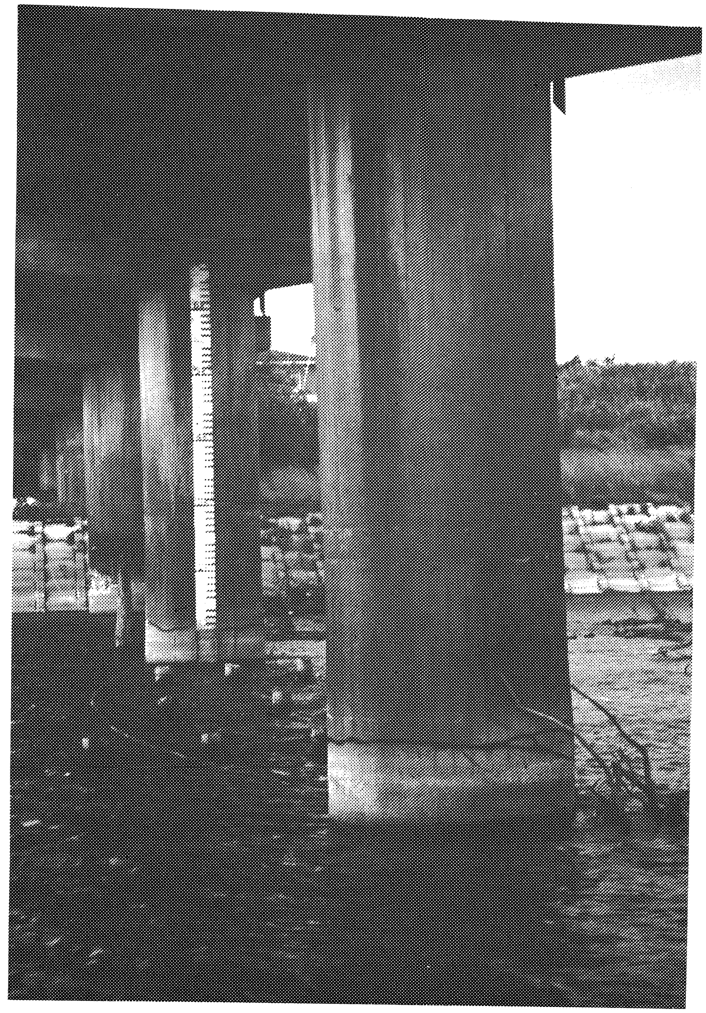


（b）　側面図

図－４．４　基栄橋の一般図

Figure 9-10: Engineering drawings of the damaged bridge at Azabu on Highway 277; courtesy of PWRI.

Figure 9-11: View of the Azabu Bridge piers--note the cracking and spalling near the waterline.



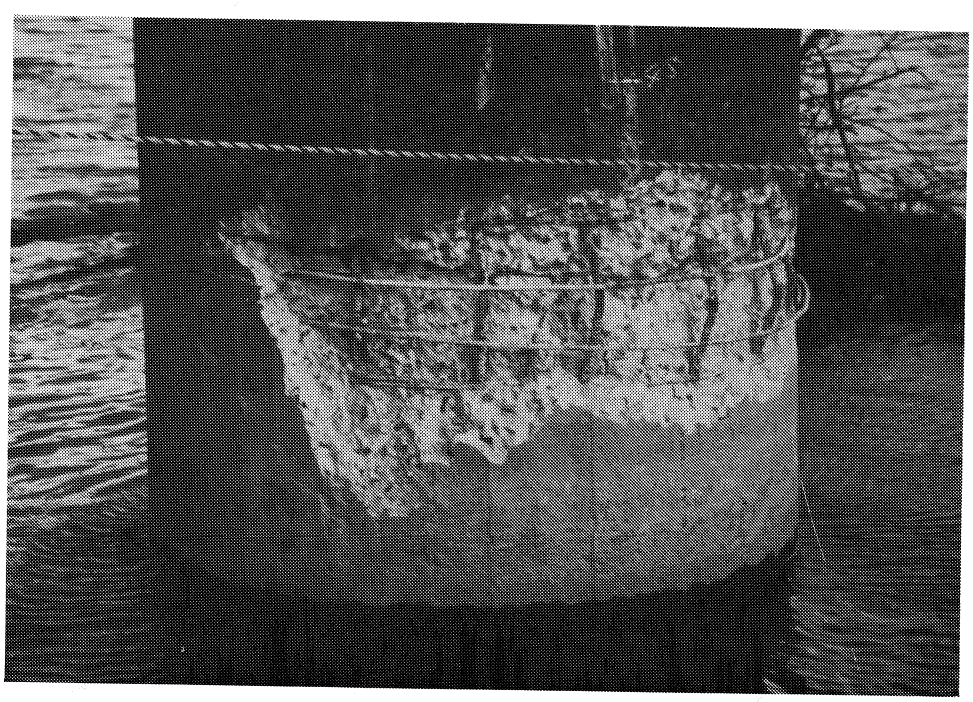


Figure 9-12: Detail of a damaged column of the bridge over the Azabu River. Note the buckling of the vertical reinforcing steel and the wide spacing of shear (horizontal) reinforcement.

Figure 9-13: Extensional cracks in the ground from later spreading of river deposits. The photograph is taken from the Azabu Bridge.

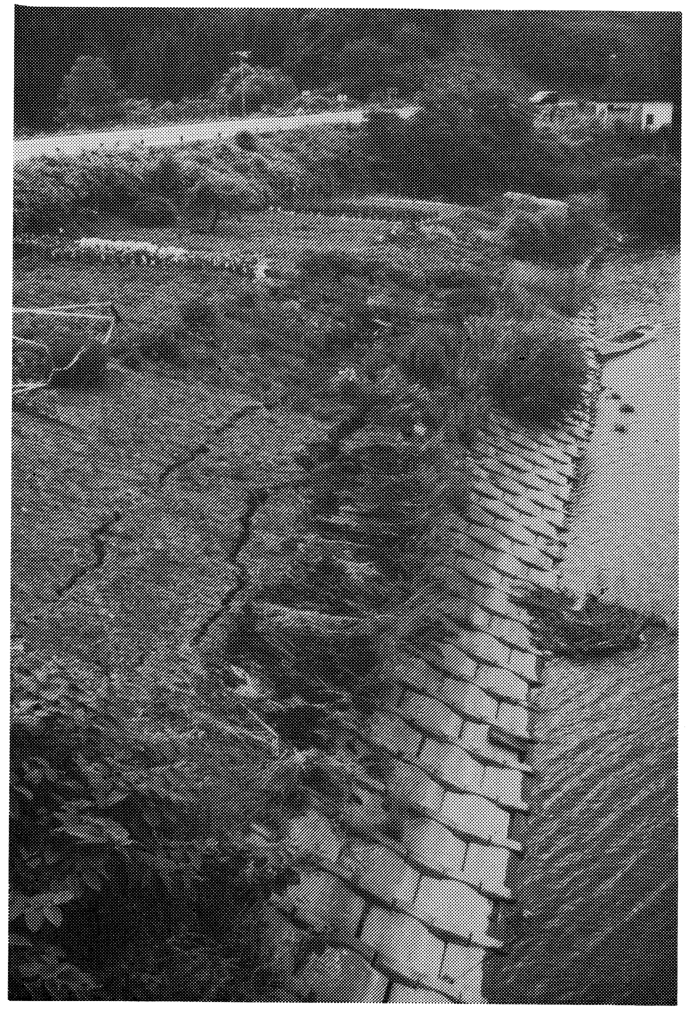


Figure 9-14: Azabu Bridge--settlement of fill (below the paving) away from a bridge pier due to lateral spreading of the fill into the river.

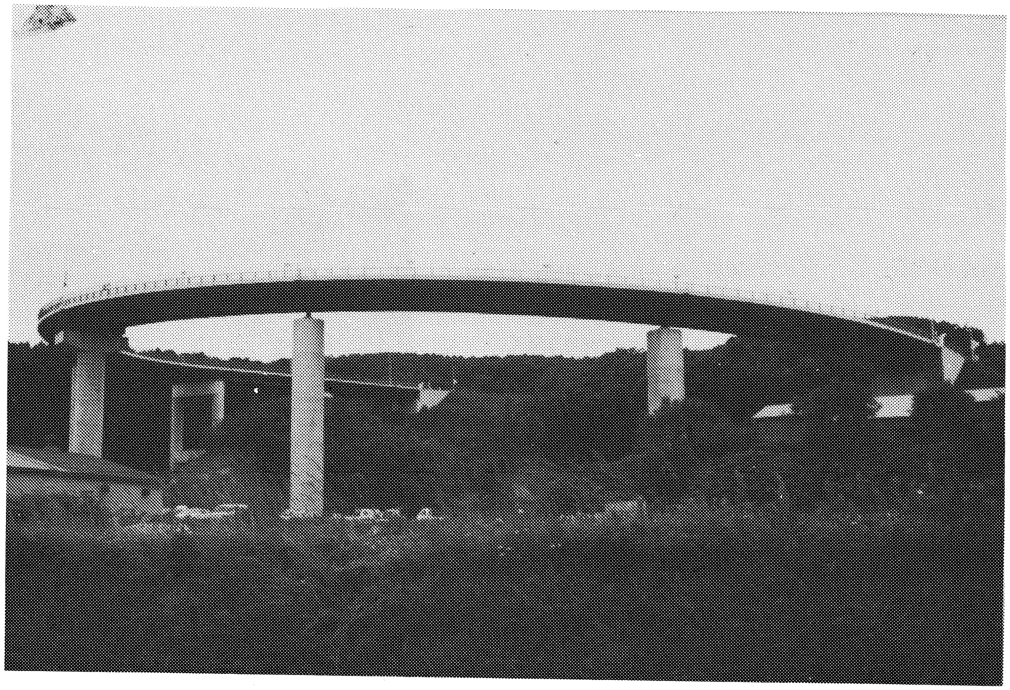


Figure 9-15: An undamaged curved bridge near Setana in Hokkaido, about 40 km from the eastern edge of the aftershock zone.

Figure 9-16: A collapsed snowshed (tunnel) north of Aonae. The just-completed structure is on fill in rice paddies. About one-third of the three-hinged arch structure collapsed. The rest is severely damaged. The approximately 2-m-wide quarter-circle panels are precast concrete and are bolted to the footings and to each other at the top.

Figure 9-17: Exposed footing and stem wall of the snowshed shown in the previous figure. The joint between the footing and the wall is cracked. Note that the arch has fallen away to the right.

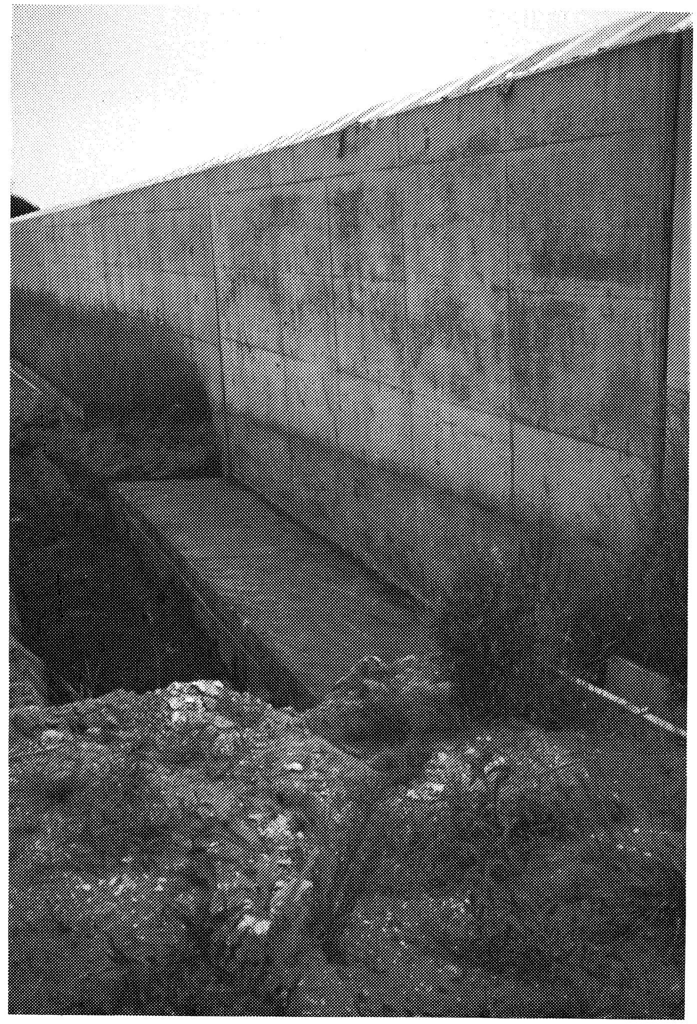


Figure 9-18: Failed east side of the snowshed. Lateral spreading of the fill and/or liquefaction caused spreading of the footings, rotation of the stem wall, and failure of the stem wall.

Figure 9-19: Although the arch has collapsed and dropped the precast planks onto the pavement, the planks are relatively undamaged, testifying to the general quality of construction of the superstructure.

Figure 9-20: Damage at the seat of the precast planks onto the stem wall. The photograph is from the front one-third of the snow shed structure that did not collapse.

Figure 9-21: Collapsed Shiroito Tunnel north of Setana on Highway 229. Collapse was caused by a large rockfall from above. The tunnel was intended to protect the highway against rockfalls; this rockfall was bigger than designed for. Note that adjacent sections of the collapsed portion of the tunnel have been displaced. Photograph by K. Kawashima.

Figure 9-22: Close-up of the failed section of the Shiroito Tunnel.

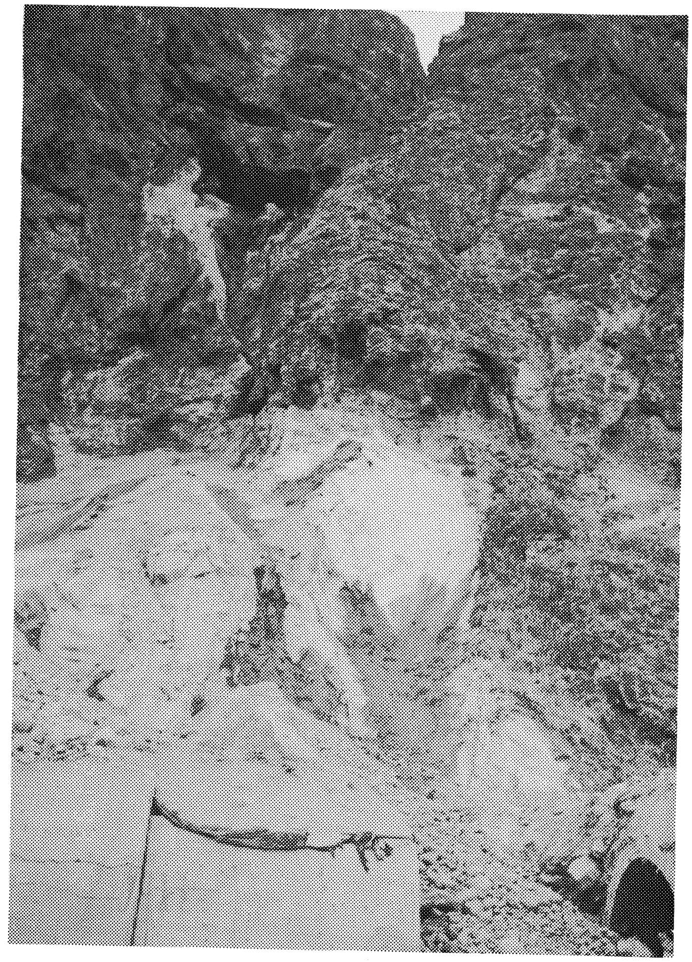


Figure 9-23: View of the Shiroito Tunnel and the slope above showing the path of the rockslide into the tunnel.

Figure 9-24: The south entrance to the Shiroito Tunnel, with Japanese and U.S. team members. (Photographs courtesy of UJNR)

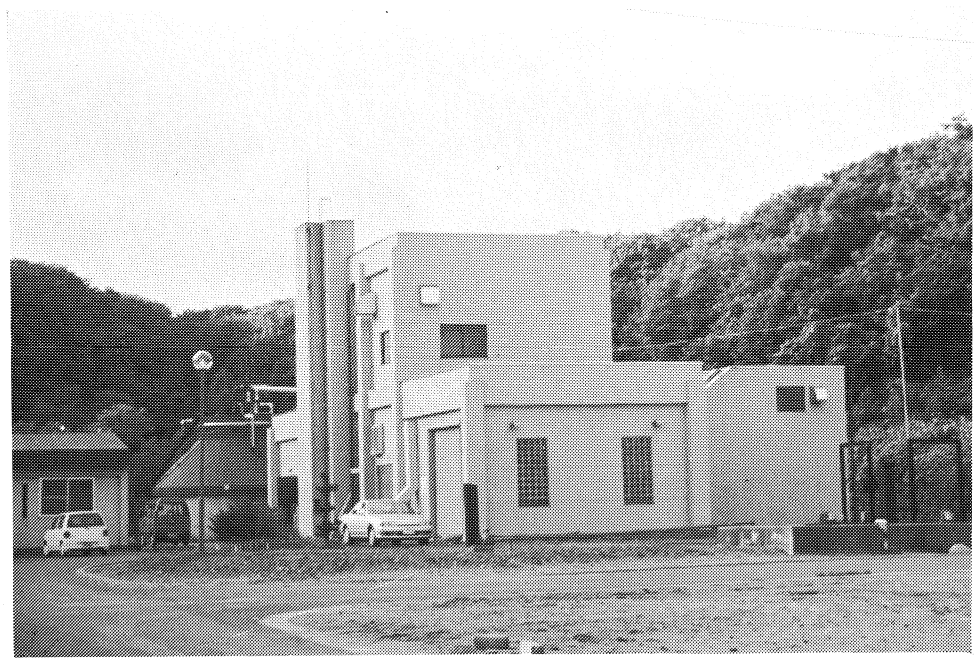


Figure 9-25: Aonae Sewage Treatment Plant (ASTP). The plant is located just north of the town, on soft soil and behind natural sand dunes, which prevented the tsunami from directly affecting the plant. The structures suffered light, easily repairable damage from settlement and pounding. Some unanchored equipment tipped over, but overall, the direct earthquake damage was small.

Figure 9-26: ASTP; ground settlement of the main structure of about 30 cm (upper photograph) and damage due to settlement and pounding between a structure and a digester (lower photograph).

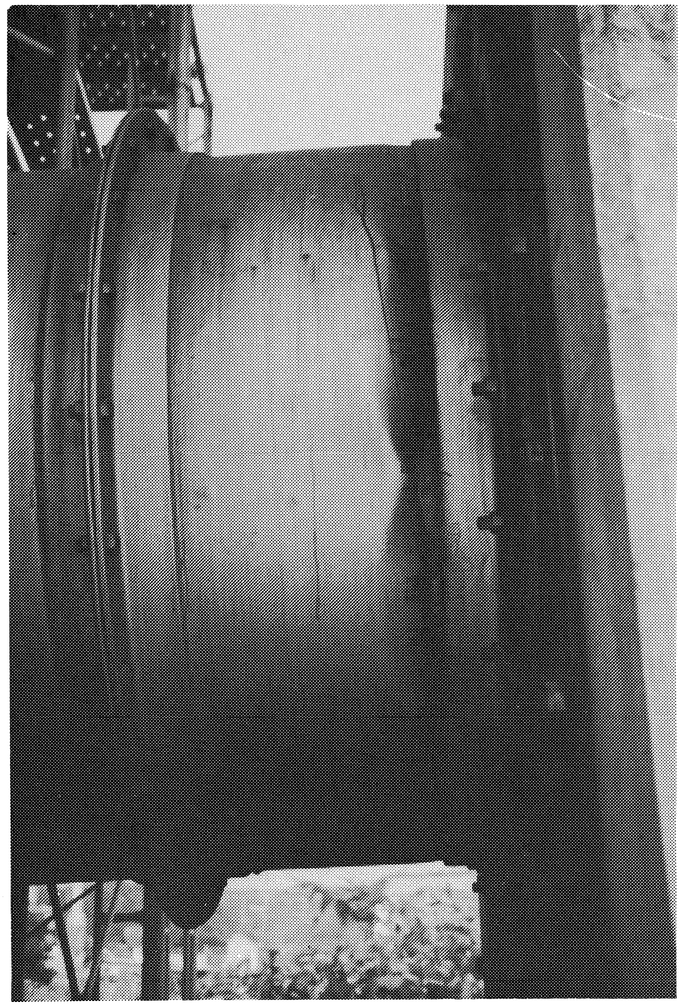
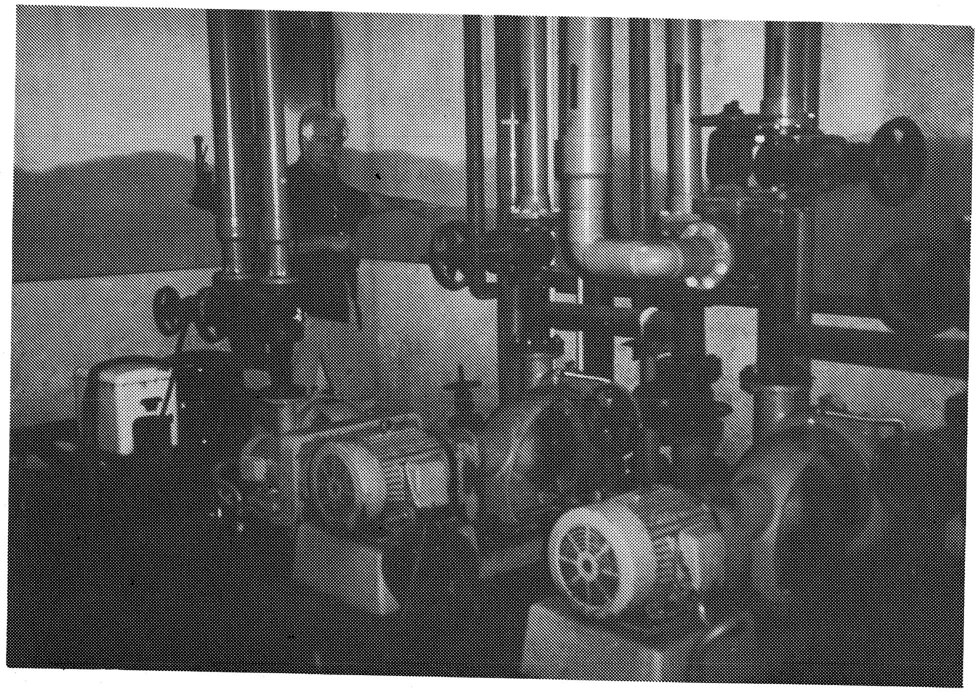


Figure 9-27: ASTP; buckling of a large-bore ducting pipe spanning between a building and the plant stack.

Figure 9-28: ASTP; this transformer overturned. It was housed in the cabinet to the left. It is located on the second floor of the main structure.



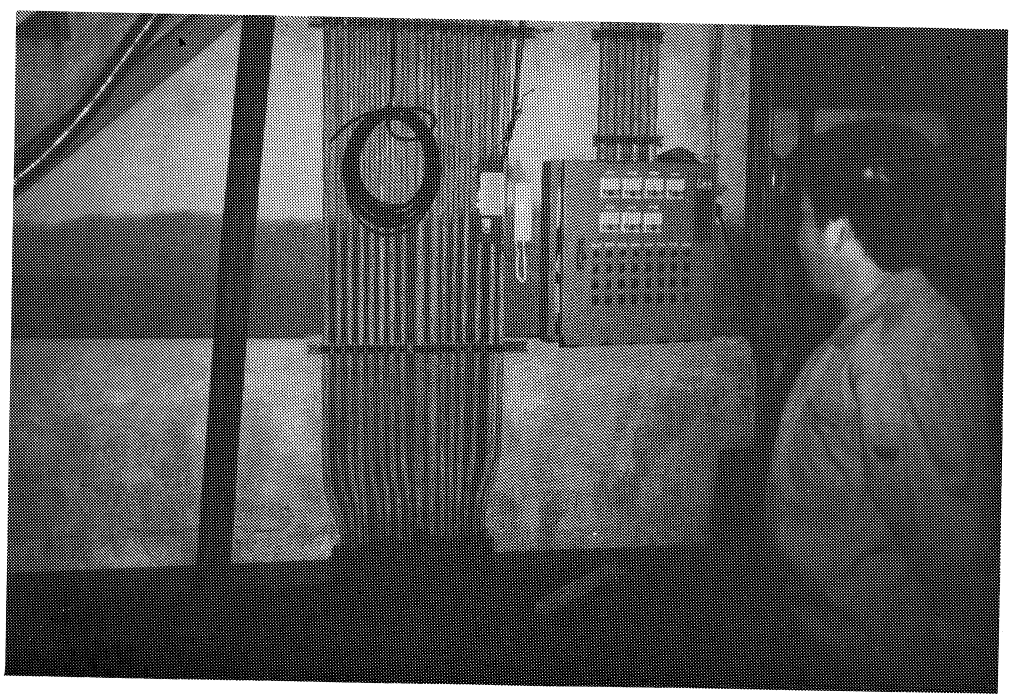


Figure 9-29: View of a basement room of the ASTP. Note the water line in both photographs showing the level to which the basement of the plant was flooded. Various electrical and mechanical equipment were flooded, making the plant inoperable for several weeks. The flood, which was caused indirectly by the tsunami, was due to inundation through the outflow piping. The tsunami forced water through the outflow piping into the basement. Protection against such backflow should be considered in the design of infrastructure facilities.

Figure 9-30: Okushiri-cho remote control switch building; this concrete shear wall building supports an approximately 40-m freestanding steel truss microwave tower.

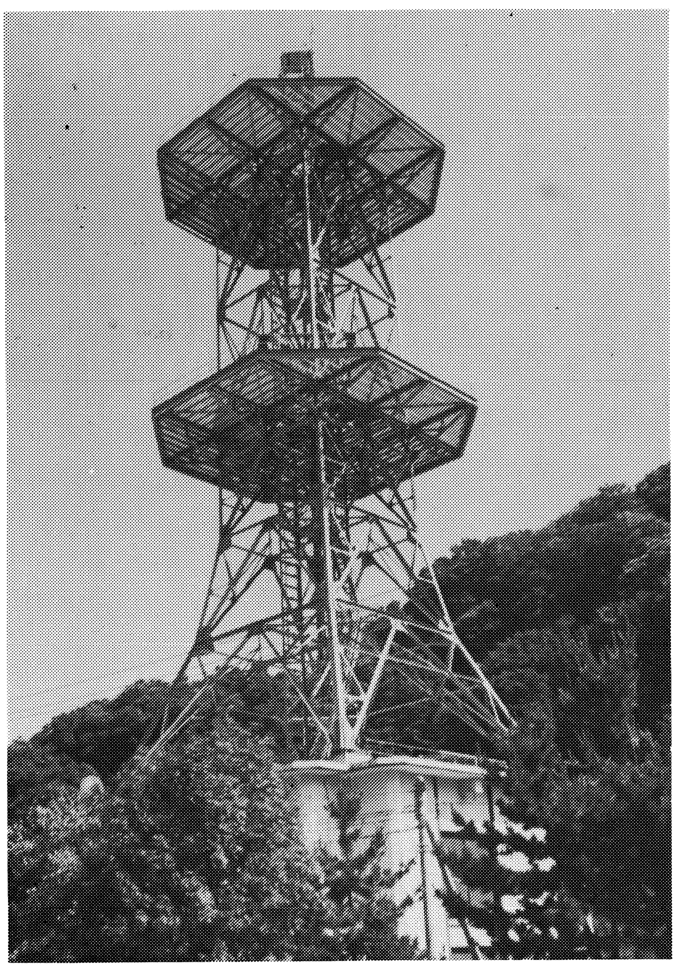
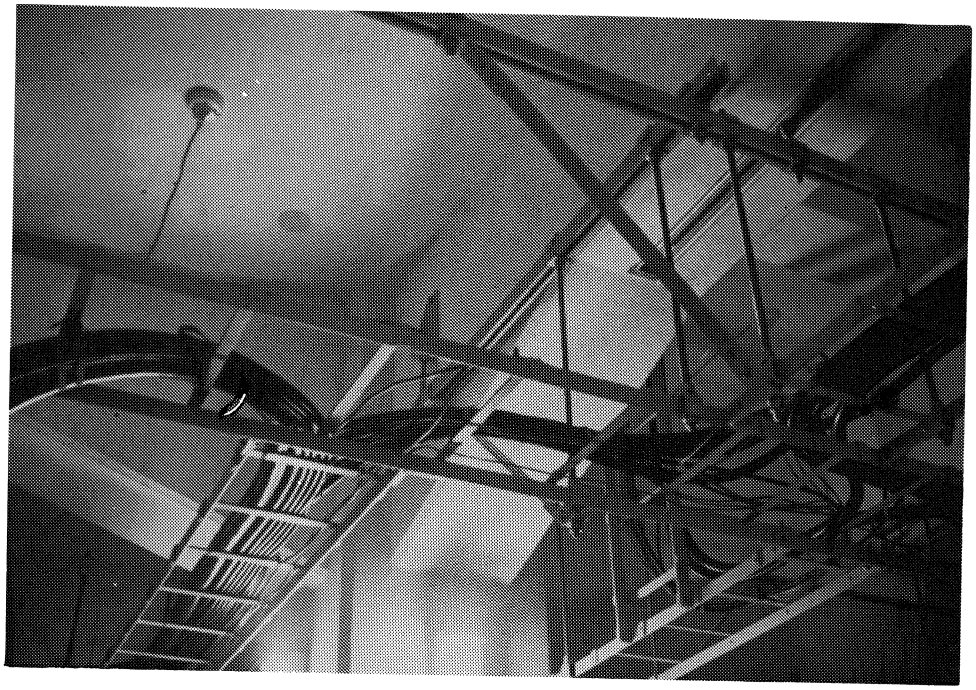


Figure 9-31: Okushiri-cho remote control switch building; close-up of the approximately 40-m freestanding steel truss microwave tower atop the building.



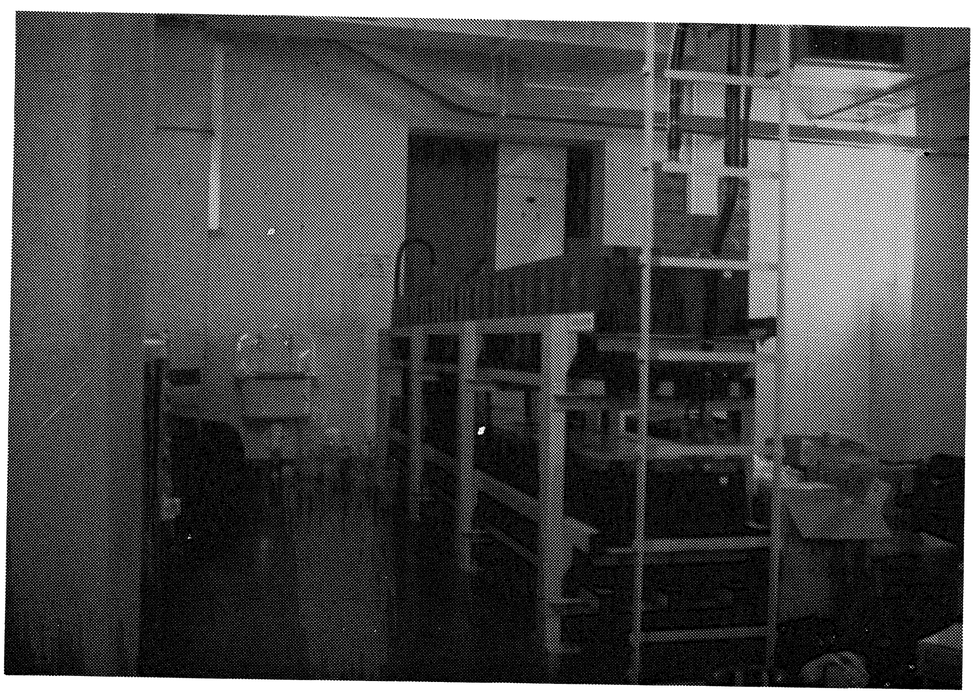


Figure 9-32: Okushiri-cho remote control switch building; the telecommunications equipment in the building was well-braced in both directions, to floor and ceiling. No damage was observed or reported.

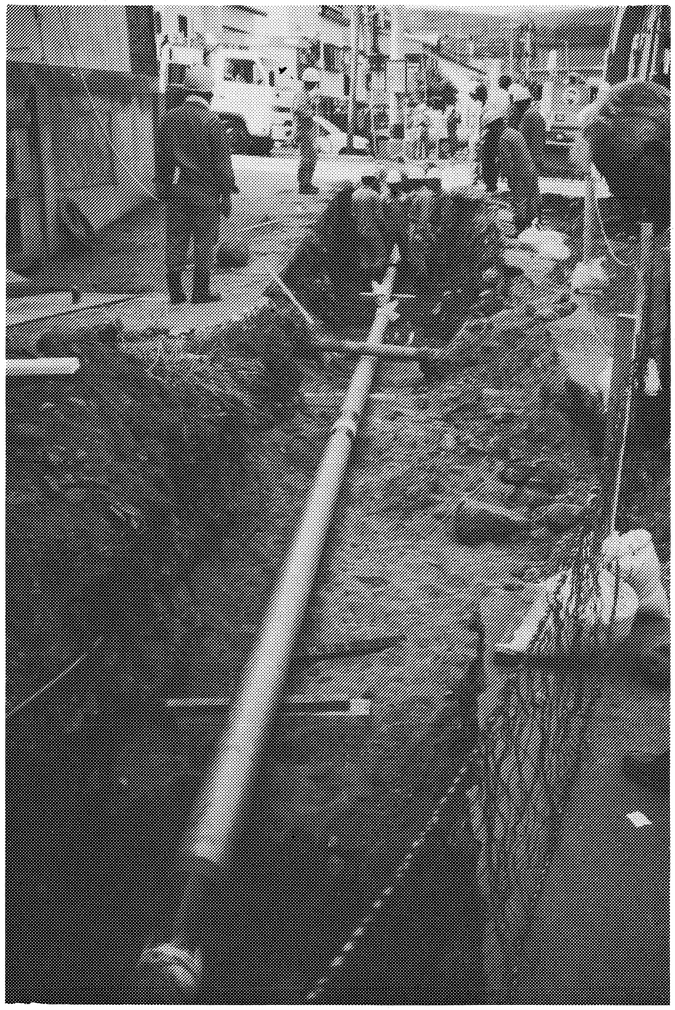


Figure 9-33: Ongoing repairs to a damaged 20-cm welded steel fuel line in the port area of Okushiri-cho. The pipe was probably ruptured by the extensive ground settlement that occurred in this area. The ground spreading was caused by the failure of one of several quay walls and bulkheads in the port.

Figure 9-34: Examples of typical damage from the ports of Setana (upper photograph) and Hakodate (lower photograph; photo courtesy of T. Leslie Youd), where quay walls displaced or tilted seaward by as much as 3 m. A peak horizontal ground acceleration of 0.12g was recorded nearby.

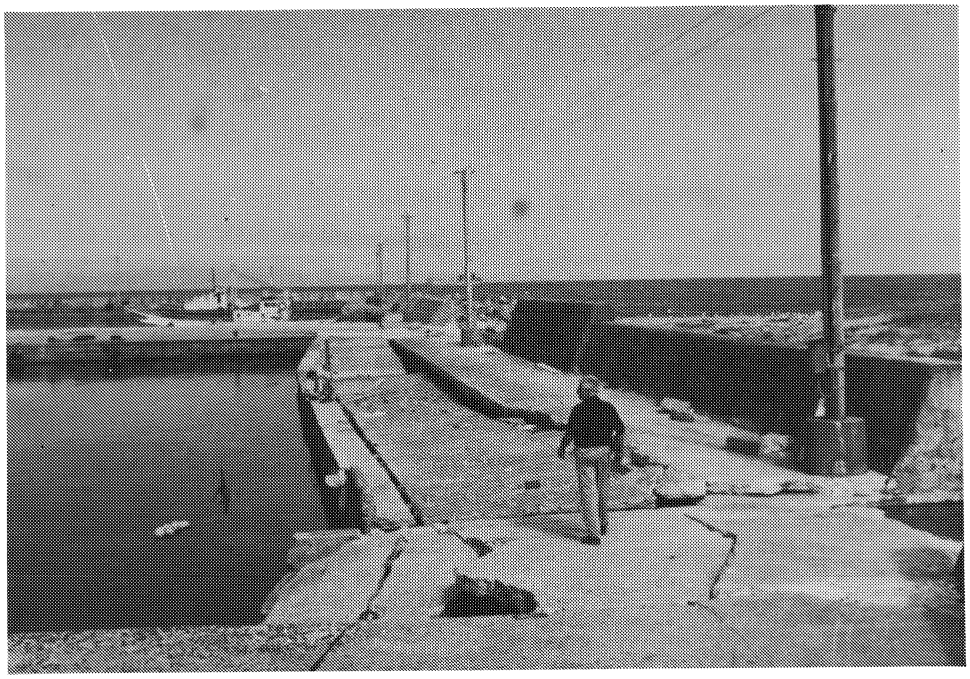
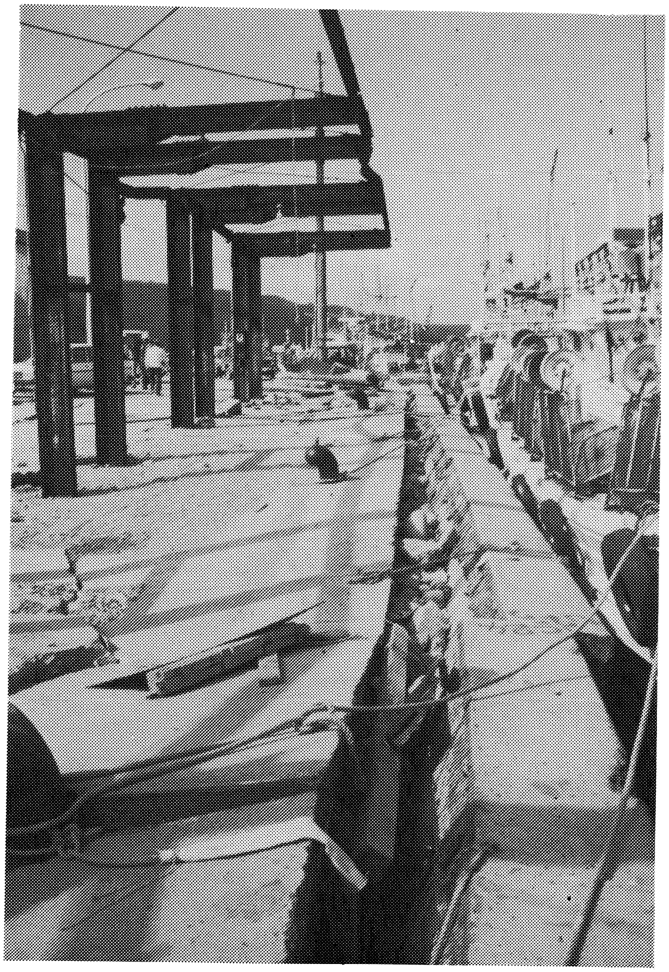


Figure 9-35: Typical damage from the earthquake to port facilities. These two examples are from Okushiri-cho Port.



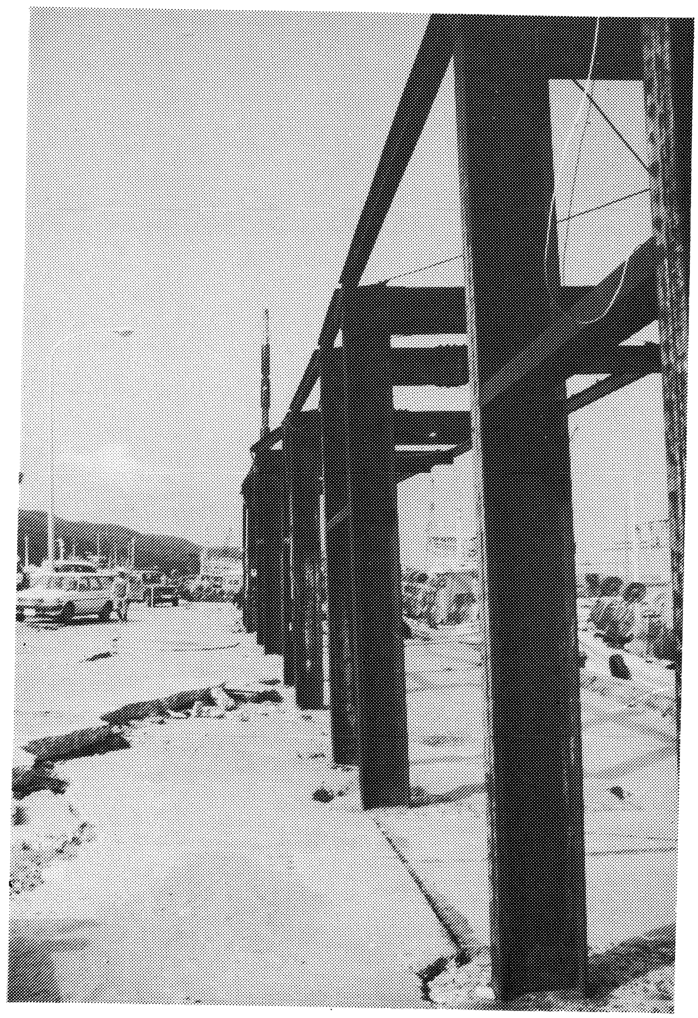
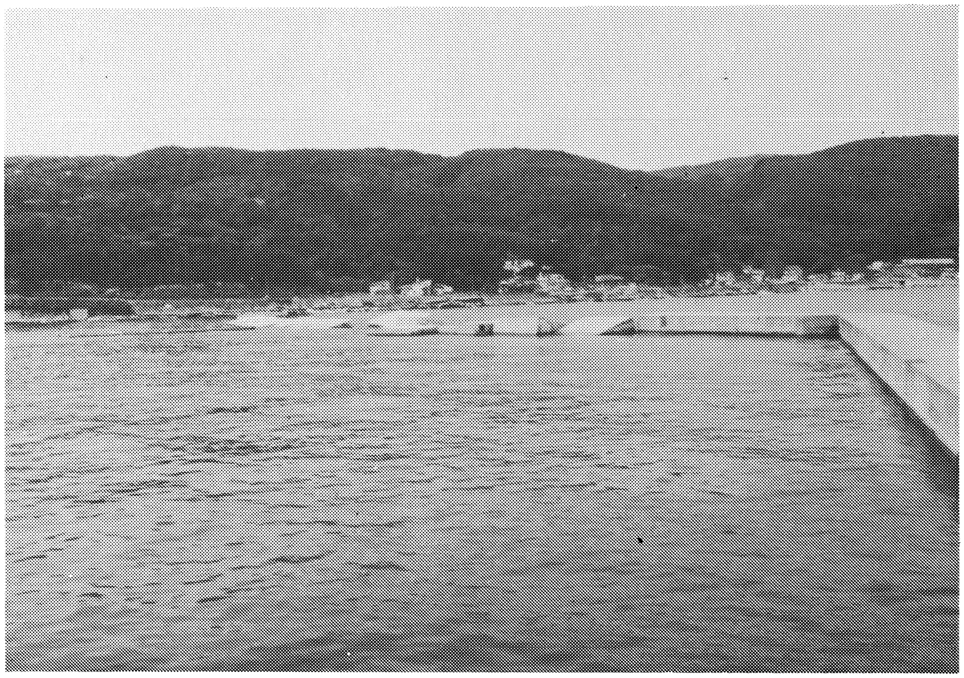


Figure 9-36: Damage to waterfront facilities at Okushiri-cho Port. The illustrated damage is due to soil failures from liquefaction, settlement, and lateral spreading of walls. Some of the damage is due to tsunami scour. Note that despite the severe damage to its foundations, the steel structure shown in both photographs has maintained its overall integrity, illustrating the large ductilities available in steel structures when properly designed and constructed.



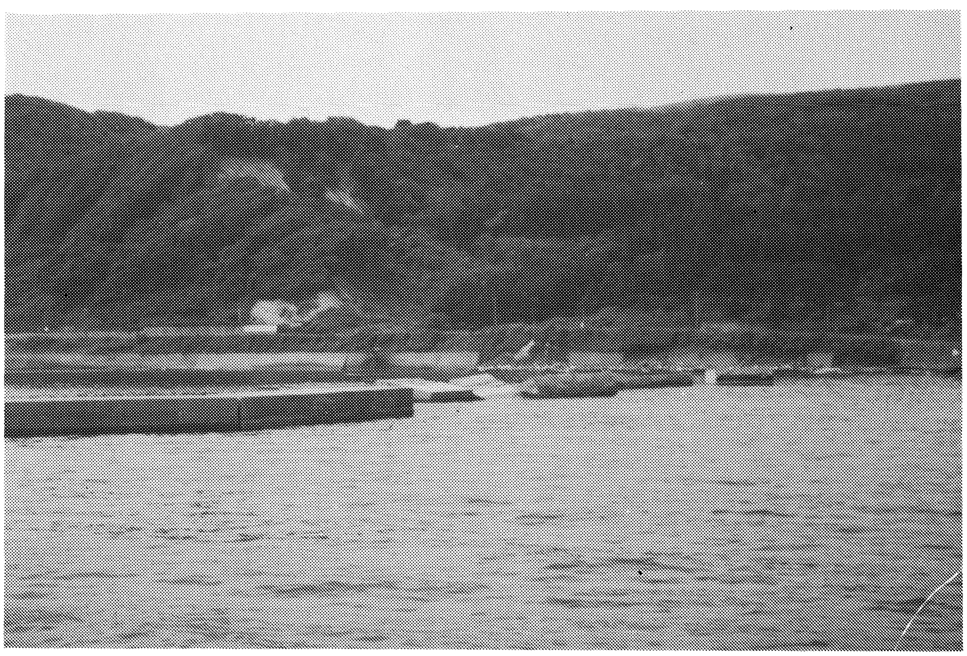


Figure 9-37: Damage to a breakwater at the Port of Okushiri-cho. These large concrete sections were probably displaced by lateral spreading of ocean-bottom deposits, although the tsunami may have caused the damage.

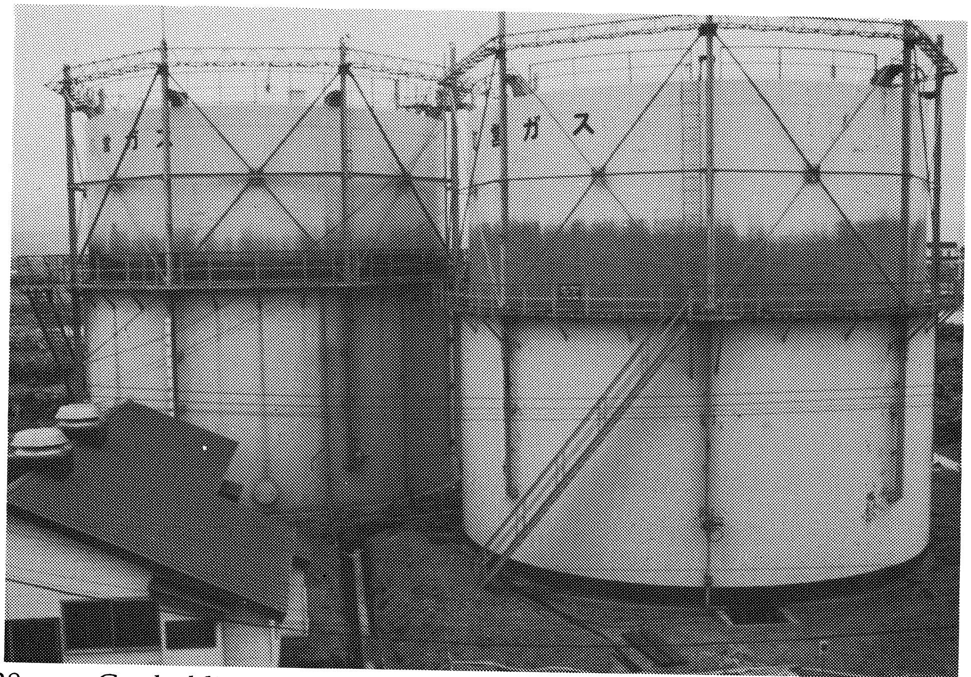


Figure 9-38: Gas holding tanks in the Oshamanbe area on soft soils. The tanks are not damaged, but the underground piping has been damaged by ground settlement, which can lead to total loss of the tank contents. Note the excavated piping. Similar damage was observed throughout the affected area.

Figure 9-39: Fuel oil tanks in the port of Okushiri-cho; the tank on the left buckled due to landslide impact (the same landslide which caused the collapse of the Hotel Yo Yo)--note that the tank on the right is undamaged.

SECTION 10
LIQUEFACTION AND ASSOCIATED GROUND FAILURES

Liquefaction of soil deposits caused much of the damage in the earthquake. The effects of liquefaction are discussed throughout this report in the various chapters on buildings, lifelines, etc.

Figures 10-1 through 10-9 illustrate damage at the Oshamanbe Elementary School, located just south of the town, in Hokkaido, on Highway 5, and about 80 km from the edge of the aftershock zone. It is a new complex of 2 one-story buildings--a classroom and offices building and a gymnasium--and sports fields. The structures were constructed on fill less than 2 m high over an area surrounded by rice paddies and drainage ditches. The structures include reinforced concrete frame and shear wall, wood- and steel-frame systems. They are supported on grade beams, which are supported on reinforced concrete piles.

The site suffered extensive liquefaction, which induced lateral spreading and extensive settlement. Figure 10-1 shows the effects of liquefaction to some of the sports fields. Settlement of up to about 1 m occurred around the buildings, as shown in Figures 10-3, 10-4, and 10-5, causing damage to all underground piping and conduit. Minor cracking was observed to the reinforced concrete shear walls at the back of the gymnasium building (Figure 10-6). Where it was possible to view the concrete piles that were exposed from settlement, severe shear damage was observed (Figure 10-7). Absolutely no damage was observed to the interior finishes of the buildings, indicating that overall they performed well, especially given the severe ground damage all around them.

Figures 10-8 through 10-13 show other examples of ground failures. Note the contrast, in Figure 10-10, between the damage to the well-founded Oshamanbe Elementary School and the lighter gas station buildings on shallow foundations without piles.

Figure 10-1: Oshamanbe Elementary School; damage to the sports fields from liquefaction, lateral spreading, and settlement.

Figure 10-2: Oshamanbe Elementary School; settlement of up to about 1 m and extensive liquefaction occurred. The school is built on top of a 2-m-high fill in a rice paddy area. The school is new. No structural damage other than shearing of piles just below the pile caps was observed. The buildings are a combination of wood frames, concrete frames with shear walls, and steel frames.

Figure 10-3: Oshamanbe Elementary School; settlement at the entrance of about 1 m.

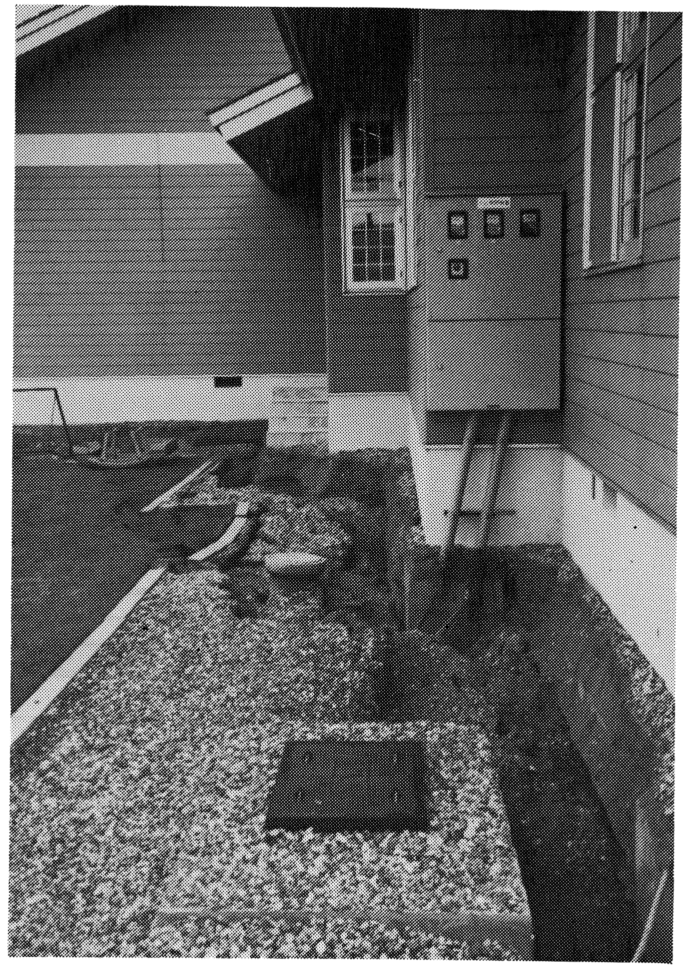


Figure 10-4: Oshamanbe Elementary School; settlement and damage to sewer, water, and power lines. Some of the piles at this location are badly damaged. The school damage is estimated at 10% to 20% of value.

Figure 10-5: Oshamanbe Elementary School--note that the settlement exposed the pile caps.

Figure 10-6: Oshamanbe Elementary School--note the minor cracking in spandrels near the column. Other minor cracking of shear walls was observed.

Figure 10-7: Oshamanbe Elementary School--sheared pile just below the cap.

Figure 10-8: Oshamanbe Elementary School--undamaged interior in the classroom building.

Figure 10-9: Oshamanbe Elementary School--the undamaged interior of the gymnasium.

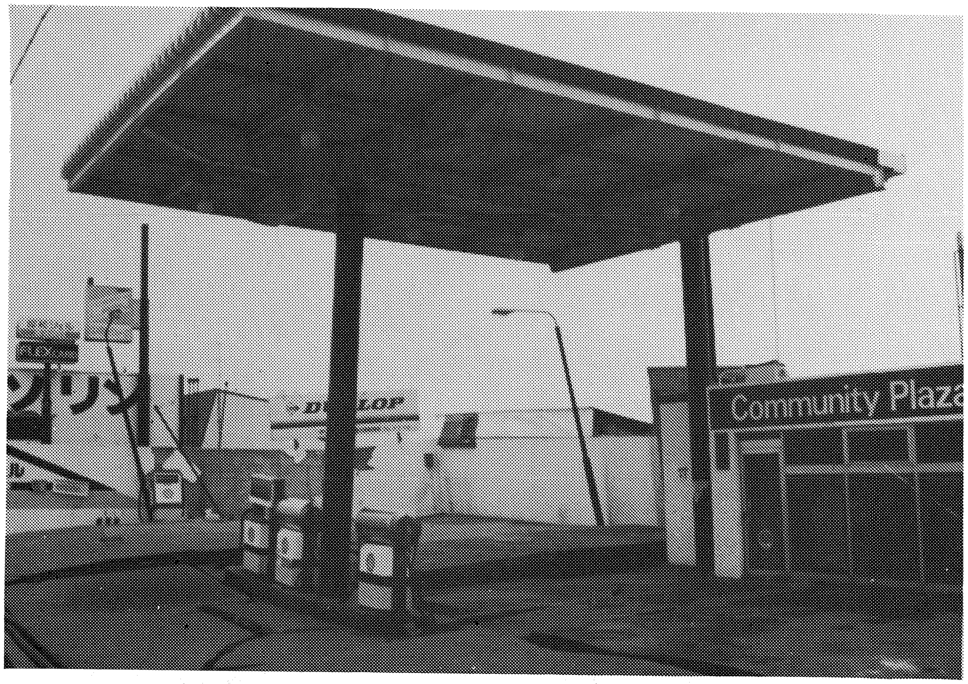


Figure 10-10: Substantial damage in Oshamanbe occurred to light buildings on shallow foundations due to liquefaction. This photo shows near-total damage to a gas station from liquefaction and settlement about 80 km from the edge of the aftershock area. Note how the tank(s) below are pushing up because of buoyancy. None of the glass is broken, indicating a low level of shaking. This is also a fill site on old farm land very near the shoreline. Much similar damage on poor soils was observed throughout the affected area.

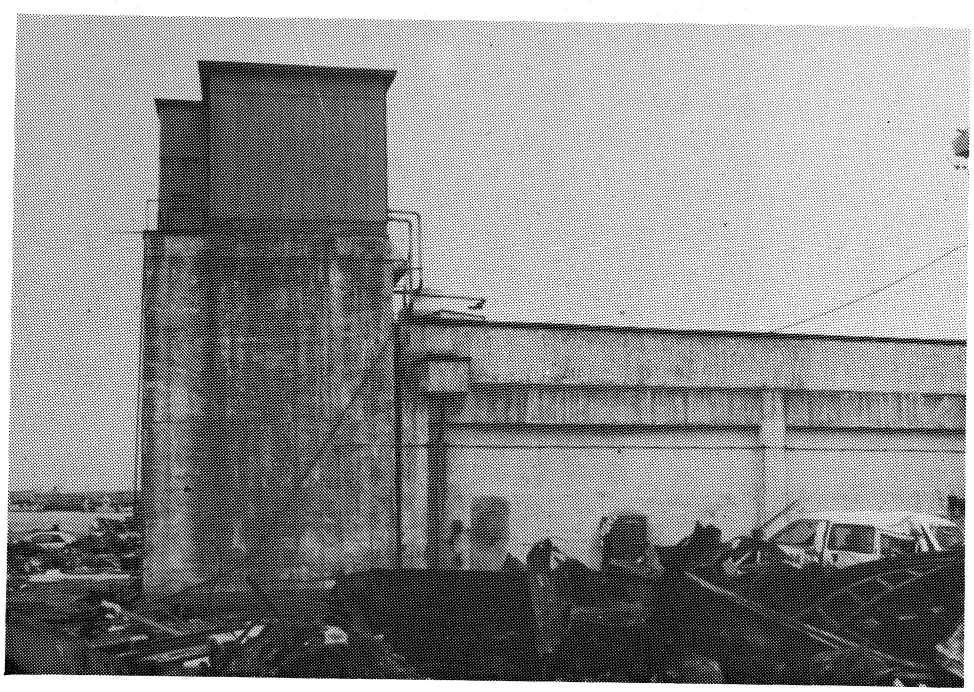


Figure 10-11: Differential settlement at these two reinforced concrete structures at the waterfront of the port of Aonae caused tilting of the taller structure on the left (and to the left). Note the gap between the higher and lower structures.

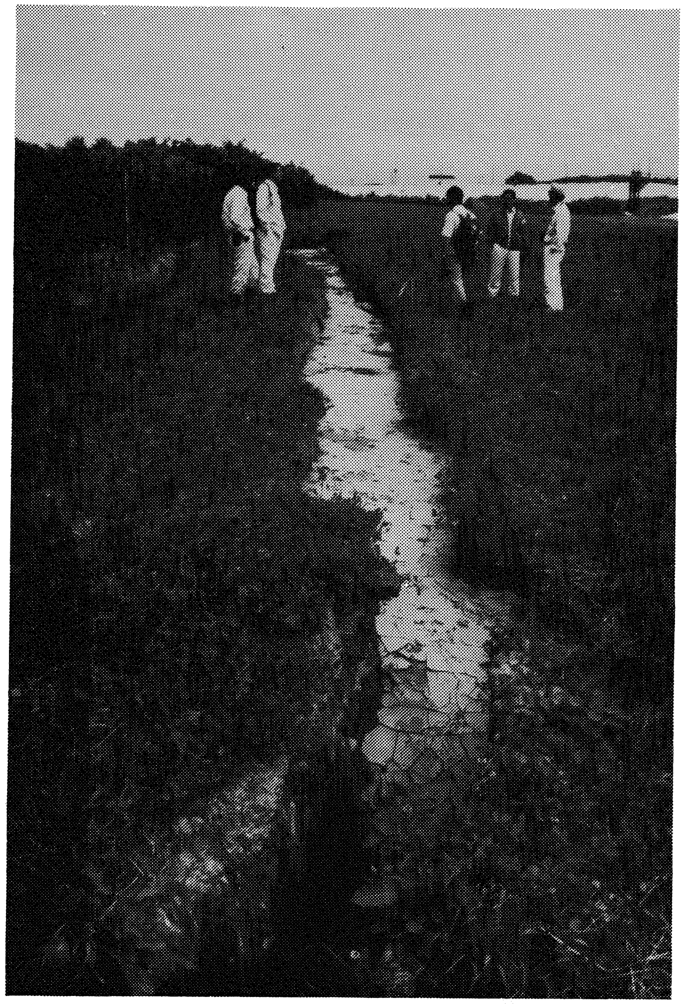


Figure 10-12: Lateral spreading of river deposits near Setana. The river itself is to the left. Note how the spreading fissure has been filled in with ejected sand from liquefaction.

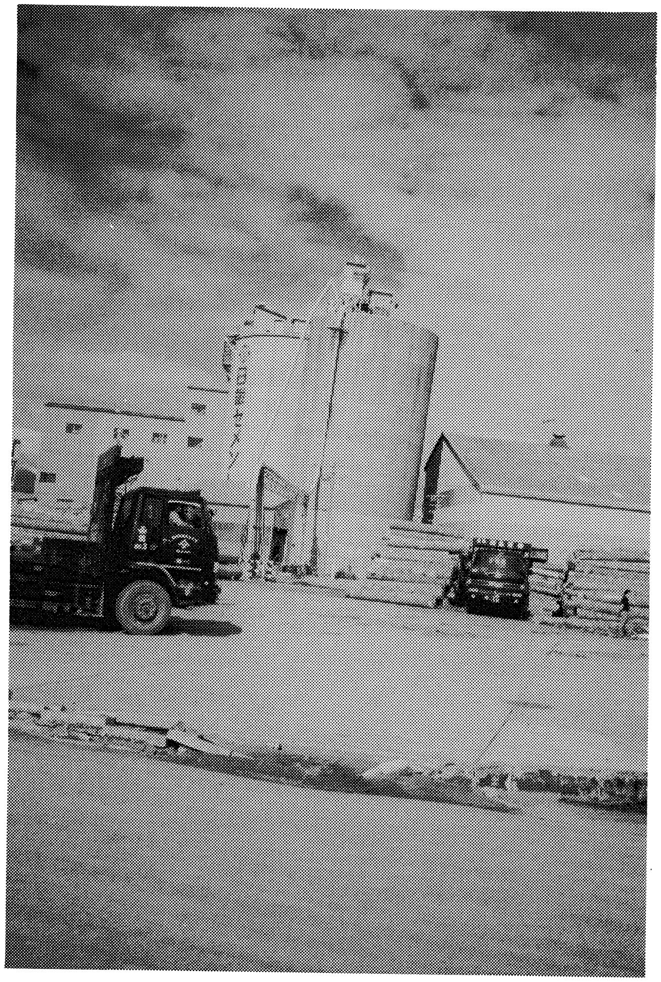


Figure 10-13: Liquefaction effects at the port of Hakodate--a tilted reinforced concrete silo and a buoyant manhole. Photographs courtesy of T. Leslie Youd.

SECTION 11
LANDSLIDES

Numerous landslides were observed throughout the entire affected region. Most were concentrated in the more strongly shaken areas, including Okushiri Island and the west coast of Hokkaido. In addition, numerous rockfalls were observed in the same areas.

Landslides caused extensive damage to roads and other infrastructure, as discussed elsewhere.

The largest single life loss from the earthquake other than from the tsunami, was caused by a landslide that buried the two-story Hotel Yo Yo (where 35 to 40 guests were killed) and several vehicles in Okushiri-cho. The slide occurred across the ferry landing in Okushiri-cho Port in steep terrain. The slide had a volume of about 800,000 m^2 and consisted of Pliocene tuff, tuffaceous sandstone, and conglomerate rock (References 1 and 2). The pre-earthquake slope was about 60^o parallel to the slide surface. The height of the slide was about 100 m, its width was about 170 m, and its thickness ranges from 20 to 40 m. That, and other large landslides, are illustrated in Figures 11-1 and 11-2. Other landslides and their effects are illustrated throughout the report.

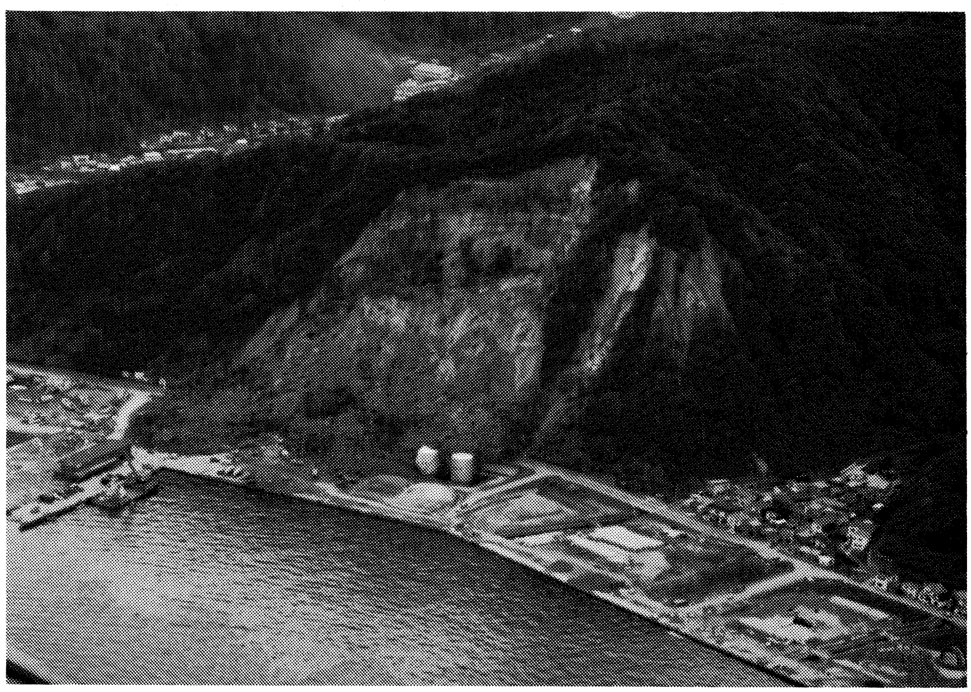


Figure 11-1: The port area of the town of Okushiri. Note the extensive tsunami damage. A large landslide about 100 m high and 170 m wide high buried the Hotel Yo Yo, killing 35 to 40 people and damaging the tanks (on the right side). This was the most destructive landslide of the many hundreds of landslides caused by the earthquake. Photographs by K. Kawashima.

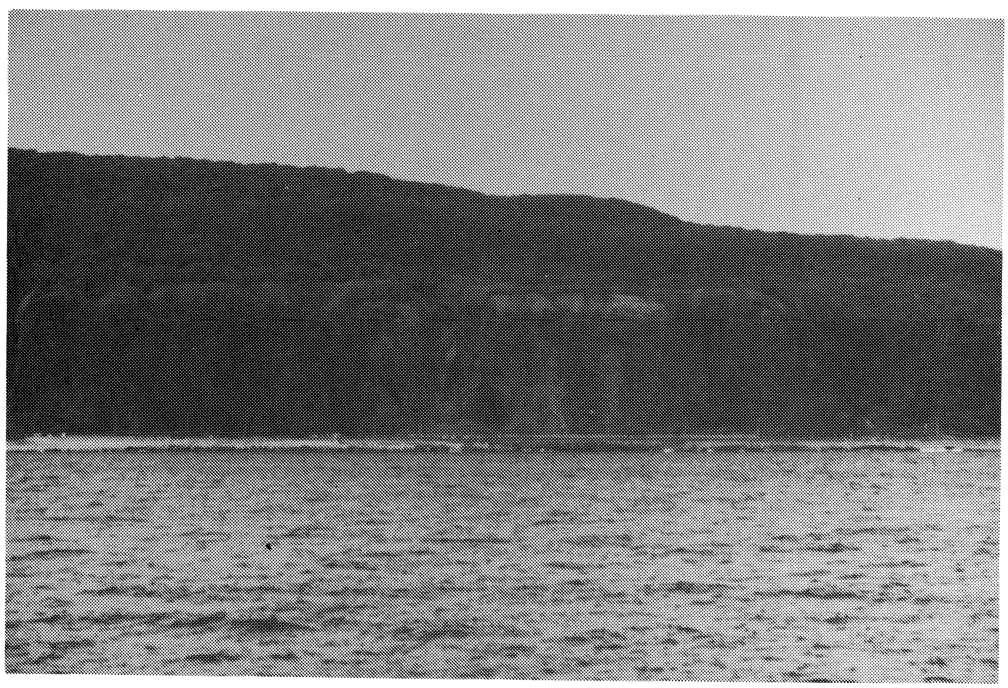


Figure 11-2: Landslides along the eastern coast of Okushiri Island. Similar and very large landslides were observed along the coastal bluffs of the Hokkaido coast south of Setana.

SECTION 12
CONCLUDING REMARKS

EFFECTS OF THE HOKKAIDO NANSEI-OKI EARTHQUAKE

The Hokkaido Nansei-oki Earthquake (offshore of southwestern Hokkaido Island, Japan) had a magnitude (M_W) of 7.8 and struck at 10:17 P.M., local time, on July 12, 1993. It affected an area of about 100 by 150 km in southwestern Hokkaido, east of Okushiri Island, and occurred at a depth of about 27 km in the Sea of Japan, north of Okushiri along a subduction zone that is speculated to be the boundary of the Eurasian and North American plates. The aftershock area around Okushiri extended over 170 km north to south and about 40 km east to west. As much as 150 km of faulting may have occurred along the causative fault zone. The highest recorded horizontal acceleration is reported to be 0.50g at Kuromatsunai, west-southwest of Sapporo and about 100 km from the eastern edge of the aftershock zone. The strongest ground motions probably occurred on Okushiri, where there were no instruments, but peak accelerations in excess of 0.40g have been estimated. The strongest aftershock ground motion to date was recorded at Otobe-cho, with a peak horizontal acceleration of 1.59g.

The earthquake affected a lightly populated part of the least populated major island of the Japanese archipelago. Ground shaking produced relatively light direct structural damage. However, extensive damage, as much as 110 km from the eastern edge of the aftershock zone, was due to ground failures, including liquefaction, lateral spreading, settlement, and landsliding. Large landslides occurred throughout the strongly shaken areas on Okushiri and Hokkaido.

The earthquake caused a large tsunami, which hit the coast of Okushiri less than 5 minutes after the earthquake and was the single largest agent of casualties and damage. That damage was concentrated on Okushiri and along the west coast of Hokkaido opposite the fault rupture. The settled areas along the coast of Okushiri were inundated by tsunami waves typically from 5 to 12 m high. The highest wave run-up along the southwest coast of Okushiri was about 30.5 m in a limited area. The tsunami caused extensive damage on the island and lesser but locally severe damage along the southwest coast of Hokkaido. Most of the populated areas hit by the tsunami were protected by tsunami walls (up to about 4.5 m high), which may have moderated the overall tsunami effects but were ineffective for the highest waves.

Most of the casualties in this earthquake were caused by the tsunami. As of July 24, the official death toll was 196, with about 50 people still missing. Most of the deaths were on Okushiri. Since the island is a tourist area, the number of missing might be higher than the estimate. As of July 19, the University of Tokyo's International Center of Disaster Mitigation Engineering reported that 540 houses were destroyed by tsunami or fire, 154 were significantly damaged, and 1,826 were partially damaged. Thirty-one public buildings were damaged, some severely; railways were disrupted at 124 locations; and highways were damaged in at least 365 locations. Serious damage occurred to schools, industrial structures, bridges, port facilities, and all other types of infrastructure.

OBSERVATIONS

The Hokkaido Nansei-oki Earthquake provides the opportunity for a number of important lessons and observations, relevant to mitigating of the effects of future earthquakes in other regions. These observations include:

- The area was recognized to be at high seismic risk, on an active plate boundary. Major efforts had been made toward mitigation, including improved building codes and construction of tsunami walls and fire cisterns. Despite these efforts, life loss and property damage was high--tsunami walls were inadequate to the task, and conflagration could not be prevented.

- Aboveground structures generally resisted shaking damage quite well, despite the apparently high levels of ground motion. This is encouraging, indicating that code and construction practices in Japan for the classes of structures tested are generally adequate to the task.

- Ground failures, due to liquefaction or landsliding, were widespread and a significant source of damage. In a more densely populated area, the liquefaction damage in particular would have been quite disruptive.

- The tsunami warning system functioned quickly and efficiently but was inadequate to the task in the epicentral area--that is, the tsunami arrived at Okushiri Island within minutes, prior to any reasonable time window for a warning system. On the other hand, in this near-field area, the shaking was sufficient warning. At greater distances, where shaking might not have been felt, the tsunami warning system functioned well and was adequate to the task.

- Despite the inadequacy of the tsunami warning system in the near field, the strong shaking was felt by all persons in the near field and immediately recognized as a warning for a possible tsunami. Residents knew this from the 1983 Nihonkai-chubu Earthquake, which had occurred farther away but still resulted in some tsunami damage on Okushiri. Most residents immediately ran for high ground and were saved. Despite this, some 200 persons perished. Without the prior knowledge derived from the 1983 event, many more might not have taken the possibility of a tsunami seriously, and the death toll might have been greater. In other areas, where there is no recent experience, education on tsunami effects (and how to react) is vitally necessary.

- The tsunami walls were inadequate, perhaps even exacerbating the problem in that they dammed waters once they were overtopped. Further efforts are required for tsunami run-up estimation and run-off gate design.

- The 1983 experience highlighted the tsunami vulnerability of the low-lying portion of Aonae. Given the immediate availability of the higher bluff areas, the dense development of the low-lying area blatantly ignored the potential for tsunami. A false sense of security may have been derived from the tsunami walls, constructed after the 1983 event. Existing patterns of land ownership make major changes in land use difficult, probably impossible. Further research is required for the problem of facilitating changes in land use when high-hazard areas are identified in areas of existing development.

- The occurrence of fires following the earthquake was to be expected, and is extremely difficult to prevent. While improved earthquake- and fire-resistive construction is important for mitigating this problem, improved response is the key for mitigation under present conditions. That only 9 of 38 members of the fire department volunteers responded was disappointing, although this may have been due to the others being at sea in their fishing boats. However, shortages in personnel were not the major problem in this fire--rather, lack of adequate access, and shortages in equipment and water supply were the main problems. Suppression of the fire occurred only when fire fighters were able to draft seawater and make a determined stand at a point of their own choosing. Improved response to fires following earthquake requires (i) detailed and specific planning based on realistic damage scenarios, (ii) provision for alternative water supplies, (iii) provision for immediate emergency availability of heavy construction equipment, such as front-end loaders and bulldozers.

- Lifelines generally functioned and responded well, due in part to the relatively moderate damage they sustained. The vulnerability of shoreside facilities to tsunami was highlighted, however, by the damage to the Okushiri Waste Treatment Plant (where tsunami run-up in the outfall pipe flooded the basement pump rooms).

- Homeless refugees were housed in the short term in schools, and then moved to temporary housing erected on available land. Some sites for the temporary housing were quite close to the shore and in areas that had been devastated by the tsunami. The vulnerability of these sites to another tsunami was a concern to these observers.

IMPLICATIONS OF THE HOKKAIDO NANSEI-OKI EARTHQUAKE

The Hokkaido Nansei-oki Earthquake is unique in recent history because of its effects. It combined, within a few hours, the triple hazards of strong earthquake shaking, destructive tsunami, and a large following fire. It is indeed fortunate that the large-magnitude event occurred in one of the least-populated regions of Japan.

On the small island of Okushiri, one can observe what can happen on a vastly larger scale to a modern metropolitan area. Tokyo in Japan or Seattle in the U.S. Pacific Northwest are two such cities that sit astride major subduction zones and near other active faults.

Tokyo Bay is ringed by heavy industrial, power, and petrochemical plants. Thousands of tanks storing toxic chemicals, various fuels, and other flammable fluids are interspersed throughout the vast complex. All of this is built on either fill or poor soils, both of which have a history of inadequate performance during strong shaking.

Some new technologies being employed are believed capable of controlling liquefaction and preventing serious damage in parts of Japan. This belief has allowed building construction in some possibly dangerous locations from a risk perspective. Until recently, the same confidence of protection existed about tsunami walls. That confidence is being questioned after the walls failed to protect Okushiri, however.

The soils around Tokyo Bay, from Yokohama to Chiba and beyond, could fail extensively in a major earthquake. Many large tanks in the area could fail as a result of such soil effects. A few ignitions would undoubtedly occur, and conflagrations might not be preventable.

The earthquake once again points out the hazard of fire following an earthquake. The ground motion at Okushiri was not strong enough to cause extensive structural damage. But a secondary earthquake effect--the tsunami--severely obstructed access to fight fires. Further, the presence of numerous and poorly anchored fuel tanks throughout Okushiri contributed to the fire spread. That condition exists throughout Japan, and unless corrected, will be a contributor to a major fire in a metropolitan area.

Past estimates of possible damage to the Tokyo area from an earthquake and its effects need to be reevaluated in light of the Hokkaido Nansei-oki Earthquake. The earthquake and fire risks remain high.

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