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by

S.W. Swan and S.K. Harris

Technical Report NCEER-93-0017

September 30, 1993

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NOTICE

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ABSTRACT

A magnitude 8.0 earthquake occurred 30 kilometers off the southern coast of the pacific island of Guam, on Sunday, August 8, 1993. Moderate damage to structures and lifelines occurred throughout the island. Fortunately injuries were generally minor and there were no fatalities.

Nearly all building structures on the island are constructed of reinforced concrete or masonry. High-rise hotels suffered the greatest effects from the earthquake. Of some two dozen high-rise structures, two or three suffered structural damage severe enough to justify demolition.

Effects to lifelines on the island ranged from minor in communications systems, to moderate in electric power, water and transportation systems, and severe in the commercial port facility.

The earthquake is expected to have a long term impact on the island's economy by diminished flow of material through the port, and reduced tourism.

ACKNOWLEDGEMENT

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INTRODUCTION

At 6:34 p.m. local time on Sunday, August 8, 1993, a magnitude 8.0 earthquake (USGS) occurred off the southern coast of the Pacific Island of Guam. This is the largest seismic event to affect United States territory since the great Alaskan Earthquake of 1964. Damage to structures and lifelines occurred throughout the island. Fortunately injuries were generally minor and there were no fatalities.

There were no instances of catastrophic collapse in building structures, although a partial collapse did occur in one concrete frame high-rise. Damage to most structures could be characterized as minor to moderate. A few buildings are expected to be a total loss. Lifeline damage ranged from minor to roads, bridges, and telecommunications, to major effects on electric power, water, and the island's single commercial port. Local government authorities initially estimated direct damage to commercial structures at about $100 million. This figure appeared somewhat low, and did not include the significant effects of business interruption. General effects throughout the island could be characterized as Modified Mercalli Intensity VII to VIII (MMI).

The island appears to have been spared disastrous effects due to the depth of the earthquake, with the hypocenter estimated at about 60 kilometers beneath the ocean floor.

SECTION 2
THE ISLAND OF GUAM

Guam lies near the southern end of the chain of Marianas Islands that bound the subduction zone of the Marianas Trench. The trench is formed by the Pacific plate slipping westward beneath the Philippine plate. The vulcanism resulting from the subducted crust melting beneath the eastern edge of the Philippine plate formed the islands some 40 million years ago.

The island of Guam encompasses about 600 square kilometers, with a length of about 50 km. and a width of about 12 km. at its narrow center. The mountainous southern half of the island consists of a thin layer of soil over volcanic rock, with a few alluvial bands along the coast. The northern half is almost entirely a limestone plateau. A limestone reef surrounds much of the coastline, creating shallow wading pools with the surf breaking several hundred meters from the beach. Most of the developed areas of the island rest on firm soil or rock. An exception is the port area west of the primary city of Agana, which is a combination of alluvium and artificial fill.

The island contains a population of about 130,000, including some 20,000 military personnel serving on the five Navy and Air Force bases. The northern tip of the island is Anderson Air Base, a large service center for aircraft based in the Pacific. Agana on the north central coast is the main city and government center. West of Agana is the commercial port and primary naval base. To the north and east are adjacent commercial areas, including the resorts of Agana and Tumon Bay.

The entire island of Guam was a secured military reservation until 1962. The civilian population was generally limited to the native Chamarro people who have occupied the island for at least 3,000 years. Guam was opened for outside immigration in the 1960s, resulting in an influx population both from Asia and from the mainland United states.

Most of the current population is concentrated on the heavily developed northern half of the island, the relatively flat limestone plateau. The mountainous southern half is sparsely populated, but served by a well-maintained system of two-lane highways and concrete bridges. Commercial and residential development on Guam looks essentially the same as anywhere else in the United States, except for the tropical setting.

Guam has essentially no heavy industry. Following World War II the island became a major military center in the Pacific, which was the primary basis of its economy through the 1970s. In the 1980s the island's tourism potential began to be seriously developed. Tumon and Tamuning Bays now have some two dozen beach-front high-rise hotels that serve an increasing trade from Japan. It appears that tourism is replacing the U.S. military as the primary source of income to the island's economy.

SECTION 3
SEISMICITY

The August 8, 1993 earthquake was the largest and most damaging to strike the island in living memory. However the island lies near the end of a zone of high seismicity corresponding to the tectonic plate interface that extends south from Japan. Great earthquakes, of magnitude on the order of 8.0, damaged the few structures on the island in 1849, 1902, and 1909. More recently, a magnitude 7.1 event occurred north of the island in 1975, a magnitude 5.2 event on the island in 1978, and a magnitude 6.3 event northeast of the island in 1983. These earthquakes were sufficiently distant or of such moderate magnitude to cause only minor damage. The 20th century has for the most part been a period of quiet seismicity for the island.

Determination of the source of the August 8 earthquake is difficult, since strong motion overloaded the island's seismometers. Seismometers that did record the event are distant from the source, in Japan, or Hawaii, for example. Furthermore, the earthquake's deep sea location means that there is little knowledge of the type of rock through which the seismic waves propagate, complicating estimates of wave velocity, and subsequently the point origin of the waves.

Estimates of the epicentral location initially placed it north of Guam toward the neighboring island of Rota. Further study indicated that the fault movement was in the Marianas trench about 50 km to the south of Guam (Figure 3-1). In this region the trench curves toward the southwest beneath the Marianas Island chain. The westward movement of the Pacific plate relative to the Philippine plate combines strike-slip sliding with subduction compression. Based on a moment-tensor solution of long distance seismic waves by the USGS, the August 8 earthquake appears to have been a shallow-dipping subduction thrust toward the northwest, combined with a limited amount of strike-slip movement along the trench. The orientation of the fault plane is more-or-less normal to Guam, so that the rupture did not approach the island. The fault plane was estimated to be centered some 60 km beneath the ocean floor. This relatively deep source (compared to California earthquakes for example) reduced the intensity of shaking on the island.

There were reportedly three Kinemetrics SMA-1 strong motion accelerographs at different locations on the island, maintained by the U.S. Navy. Unfortunately, no service had been performed on the instruments for several years; both batteries and recording film were exhausted. Subsequently there were no measurements of ground motion. There was some

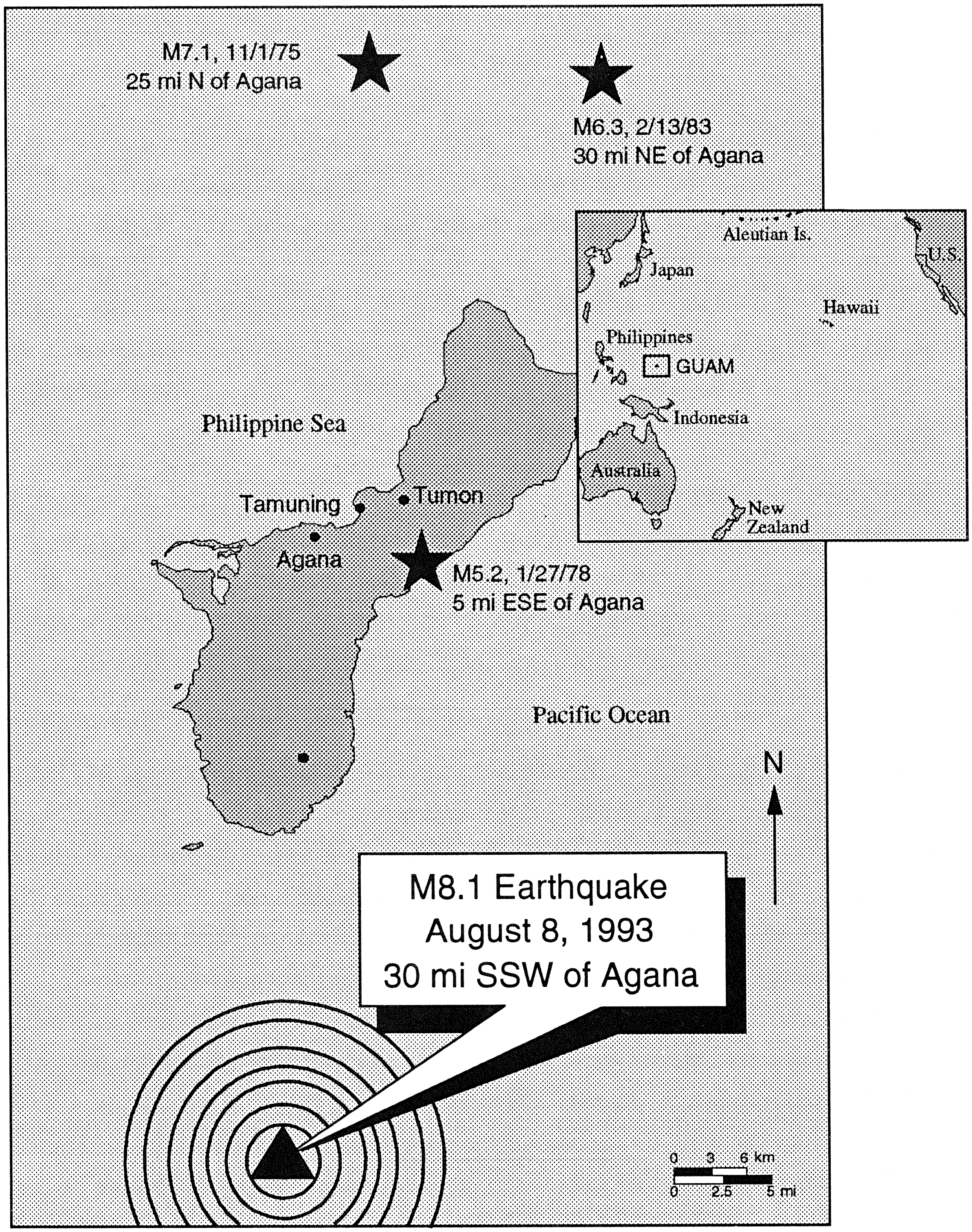


Figure 3-1: The map shows the best-estimate location of the August 8 epicenter relative to the island of Guam. Locations are also shown for other earthquakes occurring near the island within the last 20 years.

evidence of the level of ground acceleration at certain sites. Massive rigid objects, such as electrical transformers, shifted on their concrete pads, indicating that peak acceleration must have exceeded static friction. This would imply peak acceleration of at least 0.30g. Since the degree of damage to structures was observed to vary in different areas of the island, it is safe to assume that the intensity of motion also varied considerably. As an average, it is reasonable to estimate the peak amplitude of ground motion on Guam as 0.20g to 0.30g. People's accounts of the earthquake indicated that strong motion lasted on the order of 60 seconds.

SECTION 4
GEOLOGIC EFFECTS

Nearly all of Guam's surface would be described as firm soil or rock (Figure 4-1). Permanent ground displacement from the earthquake, in the form of settlement or spreading, was therefore rare. The largest region of soft soil bounds Apra Harbor, location of the commercial port and the U.S. Navy port on the west side of the island. The harbor area is a combination of coral reef surrounded by natural alluvium and artificial fill.

The isolated instances of liquefaction observed in the earthquake occurred in the harbor area. Sand boils were observed at various locations. Settlement and spreading created large fissures running for several hundred meters in sections of the Navy base (Figure 4-2). Buried water lines and electrical conduit were fractured by the soil displacement. Liquefaction-induced spreading split the enlisted personnel's shoreside recreation center on the Navy base, collapsing about half of the wood-frame structure. Although the center was full at the time of the earthquake, people were able to leave before the building began to disintegrate.

The heavily developed tourist area near Tumon Bay was spared liquefaction effects because of their foundation on the coral reef that bounds much of the island's shoreline.

Rock slides occurred at many locations on the steep cliffs that rise inland from the shoreline along the northern half of the island. Most rock slides were small enough to be nondamaging, although parked cars were crushed by a dislodged boulder rolling through an auto sale slot near Agana.

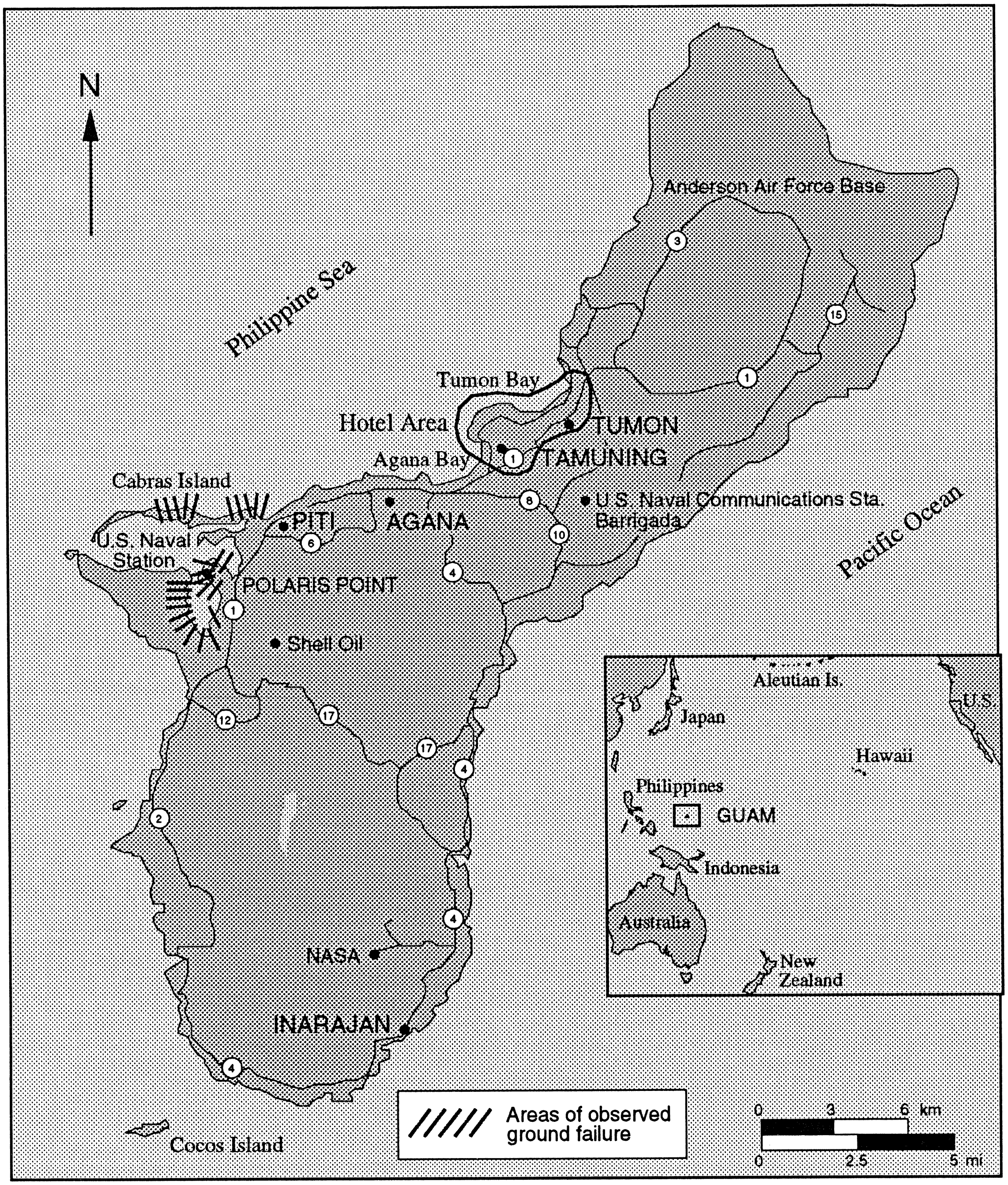


FIGURE2.DRW 71031-01 9/21/93

Figure 4-1: Most of Guam is relatively firm soil or rock, with the exception of the port area of the western shore. The most intense ground shaking appeared to occur near the port, including areas of soil liquefaction. The tourist hotel district around Tumon Bay, sited on the coral reef, appears to have experienced moderate ground shaking.

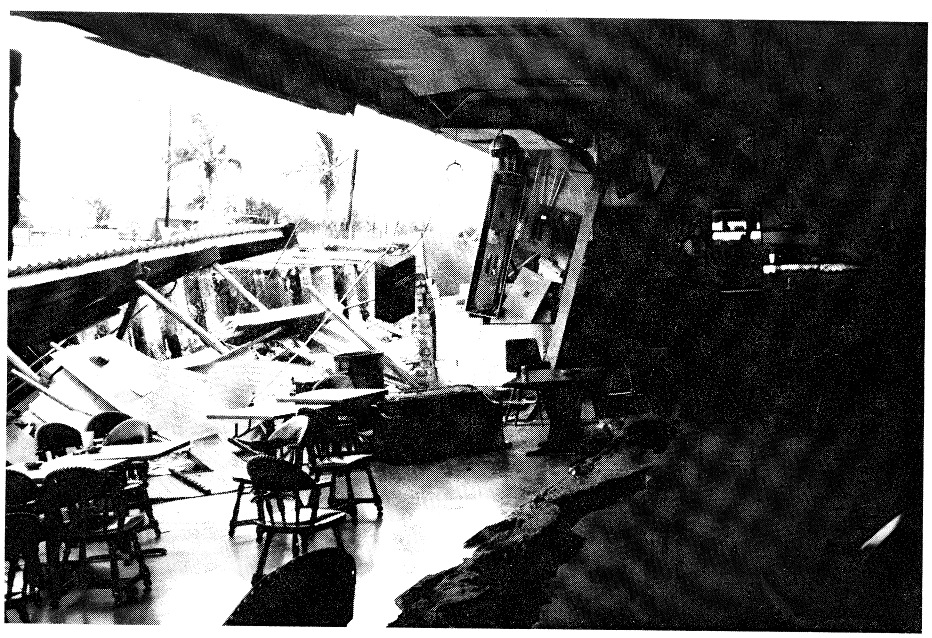


Figure 4-2: Liquefaction in the soft alluvium and fill beneath the Navy port area created fissures running several hundred meters (top photo). The enlisted personnel's shoreline club partially collapsed due to liquefaction-induced spreading beneath the structure (bottom photo).

SECTION 5
EFFECTS ON STRUCTURES

Nearly all building structures on the island are constructed of reinforced concrete or concrete-block masonry. The high-rise hotels along the northern coastline are principally concrete shear wall buildings, or concrete frames with reinforced masonry in-fill. Typical commercial buildings are low-rise structures, most often of concrete-block masonry, or cast-in-place concrete construction. Homes also are typically concrete or concrete-block masonry structures.

Light steel-frame and wood-frame structures are not generally practical on the island because of the high winds generated by the frequent typhoons. In addition, the warm, humid environment invites corrosion of steel and rotting of wood.

The *Uniform Building Code* (UBC) is the building standard for the island. From a seismicstandpoint, the island is classified as UBC Zone 3 (Z = 0.3g), the same as Seattle or Salt Lake City. For comparison, San Francisco and Los Angeles are in Zone 4 (Z = 0.4g). Materials of construction and member detailing are restricted equally in Zones 3 and 4. However, the required design loading in Zone 3 is 75% of that in Zone 4. Buildings in Guam are also designed to resist typhoon-level wind gusts of 70 m/s (155 mph). In many instances, this additional requirement provides substantially greater lateral strength than would be required for seismic resistance alone. The severe wind-design requirement appears to have contributed significantly to the relatively good seismic performance of structures observed.

5.1 Residential and Small Commercial Buildings

Homes on the island are generally one- or two-story concrete or concrete-block structures, usually with precast concrete slab roofs. Most of these structures appeared to survive the earthquake without damage. There were exceptions, such as the U.S. Navy base near the port area, where approximately 40 housing units were reported to have been evacuated.

Wood-frame homes are rare due to their relatively poor performance in typhoons. The few wood-frame homes observed were typically mounted two or three feet above the ground on concrete-block pedestals, presumably as a precaution against infestation and wood rot. Remarkably no instances were encountered of homes toppling from their pedestals, a frequent occurrence in past earthquakes in tropical locations.

With rare exceptions, low-rise commercial buildings also showed little obvious evidence of earthquake damage when viewed from the street. Closer examination, however, revealed at least superficial effects in many cases. Many concrete-block or cast-in-place concrete buildings were found to have some degree of cracking and spalling in walls or framing, exposing reinforcement in the more extreme cases. Cracking or working at wall joints or at locations where block in-fill adjoined concrete structural members was also common, as was spalling at column-beam connections. However, the large majority of low-rise buildings escaped serious damage. Shattered plate glass windows were found to be rare, indicative perhaps of the inherent stiffness of concrete and masonry structures designed to resist typhoons.

5.2 School Buildings

There are about three dozen schools on the Island, serving the elementary and secondary grade levels. The structures are typically one- and two-story concrete frame buildings, with concrete-block in-fill and concrete slab roofs. Several schools were damaged to varying degrees. A government-sponsored inspection following the earthquake determined that portions of three schools, constructed between 1965 and 1986, were structurally unsafe.

Engineering inspections of schools revealed poor construction practices in some instances. It was reported that a 1990 study of 34 schools had concluded that nine of the schools were potentially unsafe, including those that were significantly damaged in the earthquake. Bond issues for construction of new or replacement schools are being developed.

The most severely damaged school was Inarajan High School, at the southern end of the island (Figure 5-1). The school consists of several adjoining two- and three-story concrete-frame buildings with masonry in-fill, and was constructed in 1973. One wing with partial-height in-fill walls suffered severe cracking and spalling of concrete columns. This is an example of the "short column effect", where the presence of the partial-height in-fill walls shortens the effective height of the columns, forcing them to fail in shear. It appeared that at least one wing of Inarajan High School would have to be demolished.

5.3 Major Commercial Buildings

The high-rise hotels and condominium complexes adjacent to Tumon and Tamuning Bays comprise most of the tall building stock on Guam. There are approximately 20 of these high-rise buildings, nearly all constructed after 1970. Most of these range from about 10 to 20 stories in height. Lateral force-resisting systems include concrete shear walls and concrete frames with

Figure 5-1: One wing of Inarajan High School suffered shattered concrete due to the short column effect, where shear loads from half-height masonry in-fill were transferred into the columns.

concrete-block masonry in-fill. The buildings feature a variety of architectural designs, most of which include long, narrow wings with rooms on one or both sides of a common corridor.

These large buildings suffered the greatest effects from the earthquake. Essentially all of the major hotel and condominium buildings suffered some level of damage, in the form of cracking and spalling in concrete block in-fill as well as concrete walls, beams and columns. However, only a few appeared to suffer structural damage severe enough to justify demolition. Several others are known to have damage estimated at between 10 and 20 percent of their replacement costs. Virtually all of the hotels were closed for two or more days due to loss of power and water, and to permit damage evaluation. The only known high-rise steel structure appeared to have suffered little or no damage, although it was unoccupied at the time of the earthquake.

5.4 Concrete Frame Structures with In-fill

Two of the most serious instances of damage involved concrete-frame structures with concrete-masonry in-fill. In both cases, due to architectural and functional reasons, the in-fill was discontinued in lower stories, leaving the concrete frames to resist the imposed seismic demands alone. This created dynamic irregularities in the buildings, including soft-stories and torsion. Both of these buildings were of fairly recent design, but did not appear to include any special detailing in soft story columns to ensure the required ductility.

Perhaps the most dramatic effects were suffered by the Royal Palm Resort complex, a twelve-story structure that was open only 18 days prior to the earthquake (Figure 5-2). In the rear wing (adjacent to the beach) several columns in the second story collapsed, causing the wing to tilt substantially. The floors above the damaged level contained guest rooms, while the floors below appeared to contain mostly open common areas. Consequently, most of the in-fill shear walls above appear to have been discontinued below the third floor, creating the soft story. Other damage visible from the exterior included moderate shear cracking of in-fill walls and working of joints between in-fill and concrete elements. Following the collapse, guests were temporarily trapped in the damaged wing. Remarkably there were no serious injuries. It appeared that the rear wing of the building could not be repaired and would have to be demolished.

The four-story, five-year-old Grand Hotel was also severely damaged (Figure 5-3). In-fill walls enclosed most of the ground floor along the sides and rear of the building, while the front was mostly open, with large storefront windows between columns. The lack of shear resistance across the front created a soft first story, combined with a tendency for structural torsion. While the upper three stories of the building appeared essentially intact, the second floor shifted nine

Figure 5-2: A partial collapse occurred in the seaward wing of the Royal Palms Condominiums. A discontinuity in masonry in-fill at the second floor concentrated shear on the corner columns.

Figure 5-3: The Grand Hotel near Tumon Bay suffered the most extensive damage of low-rise structures on the island. A soft first story effect shattered columns at the base of the building and shifted the upper three floors nine inches relative to the ground.

inches relative to the foundation, shattering concrete in the ground floor columns. Some of the columns lost their ability to resist gravity loads, leaving portions of the building supported by the in-fill masonry walls. The building was subsequently slated for demolition.

5.5 Cast-in-Place Concrete Structures

Some dramatic examples of severe but repairable damage occurred in cast-in-place concrete buildings. In many cases, damage was due to discontinuous elements. However, improper detailing and construction also contributed substantially to the damage observed. Often, the heavily damaged cast-in-place concrete structures were of early-1970s vintage.

The 12-story Tropicana Hotel was significantly damaged. It consists of a narrow nine-story tower atop a broader three-story base and was built circa 1971. Many of the lateral load-resisting walls extend only through the upper floors, and are discontinued at the second or third story. There are, however, other shear walls at the lower levels, so the building does not appear to have significantly soft lower stories. Much of the damage appeared to be due to the concentration of loads at discontinuities. The most severe example of such damage occurred on the second floor, where a major shear wall was discontinued. Because of the discontinuity and changes in wall geometry above, the second story wall developed an extreme shear stress concentration. This resulted in the wall cracking and spalling the full story height, extending into the floor slabs above and below. Other damage observed in the Tropicana included damage to columns under discontinuous walls, cracking in link beams between shear walls, and severe cracking of masonry walls and concrete stairs in the rear stair tower. In spite of the damage, the Tropicana remained open for business and is expected to repaired.

The Alupang Cove condominium complex in Tamuning also suffered serious, although repairable, degree of damage (Figure 5-4). The building consists of two eight-story wings that join at an angle. The most visible damage occurred along a breezeway in the northern wing. In this area, concrete columns and masonry screen walls were severely damaged, leading to a partial loss of vertical support for the breezeway. These elements do not appear to have been intended to resist lateral loads, but were damaged because of the building's flexibility in its longitudinal direction. Shear cracking occurred in concrete spandrels at their interface with a major concrete shear wall at the eastern end of the breezeway. Other damage observed appeared to be due to improper detailing. Major pounding damage to a bearing wall was observed at the ground floor between the main structure and the abutting one-story mechanical building. In the southern wing, concrete spalled from floor slabs at their attachment to a major shear wall,

The Alupang Cove Condominium Complex suffered effects typical of mid-to high-rise buildings in the tourist area.

Figure 5-4: Shattered columns, shear cracking at spandrels, and pounding damage at the interface of the one-story mechanical building (at left) are seen along the front fact of the Alupang Cove.

exposing the slabs' embedded prestressing tendons. Repair of the prestressed slabs presents a problem since the exposed tendons cannot be retensioned.

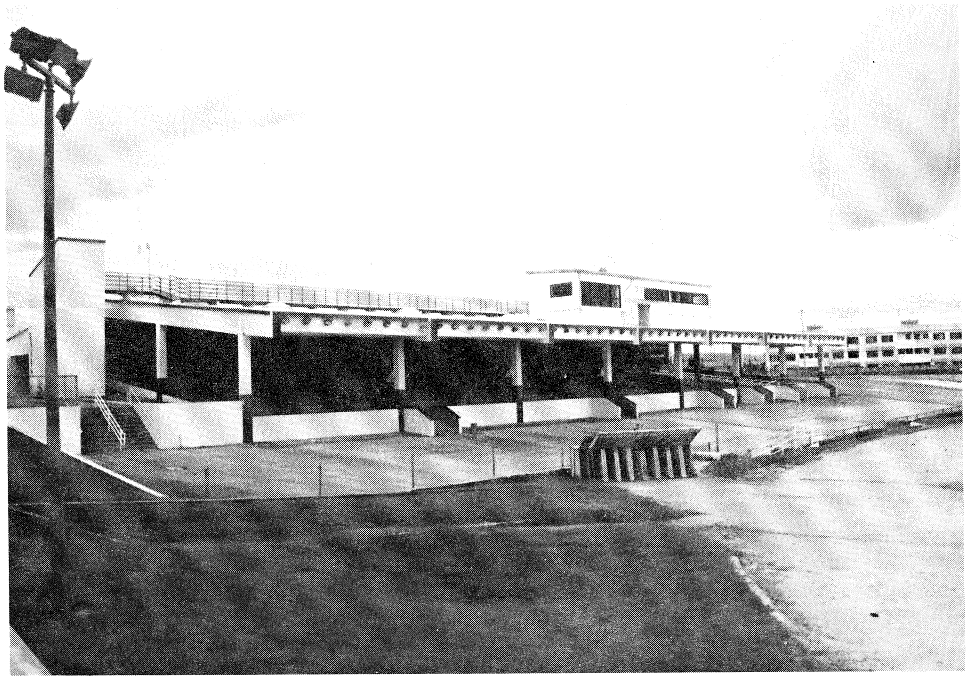
The grandstand roof structure of the Greyhound Racetrack near Tamuning was severely damaged (Figure 5-5). The structure consists of a large main roof, supported only by concrete columns, and a second lower roof, supported on one side by the main-roof columns and on all other sides by concrete shear walls. There is a concrete-block screen wall in the vertical space between the two roofs. The screen wall apparently failed as it attempted to transfer seismic forces from the main roof to the lower roof. At this point the only remaining lateral load path between the two structures was through the large roof beams supporting the lower roof. These beams developed dramatic inclined cracks, apparently due to torsion induced by the shear transfer.

Concrete canopies, consisting of heavy slabs supported by concrete columns, are common on the island. Frequent damage to the supporting columns was observed, apparently due to improper detailing of highly stressed top connections. The most notable instance of such damage was the collapse of the canopy at the entrance to the Reef Hotel on Tumon Bay (Figure 5-6). The canopy's four concrete columns failed catastrophically, dropping the slab onto two parked taxis beneath. Fortunately, the drivers were out of the cars at the time of the earthquake. The concrete columns completely shattered and their longitudinal reinforcing buckled. The minimal horizontal ties appeared to be ineffective in providing confinement. Although there were no other instances of life-threatening collapse of canopies, minor to moderate damage of canopy columns was observed throughout the island.

5.6 Precast Concrete Structures

Structures with precast concrete shear walls were also damaged, in some cases severely. As is often the case with precast elements, damage was concentrated in the connections, which generally do not possess the strength to develop the full capacity of the element or the ductility required to sustain large deformations.

The mid-rise portion of the Hilton Hotel is a seven-story shear-wall structure that was developed in the early 1970s. It is constructed of vertical load-bearing, precast concrete wall panels and cast-in-place slabs. Inter-panel connections consist of panel reinforcing welded to embedded steel plates. Extensive damage occurred in the lower stories including crushing and spalling of concrete at the corner connections of wall panels, crushing of concrete panels at the floor slabs, and shattering of spandrels. Reinforcing steel and panel connectors were exposed due to damage



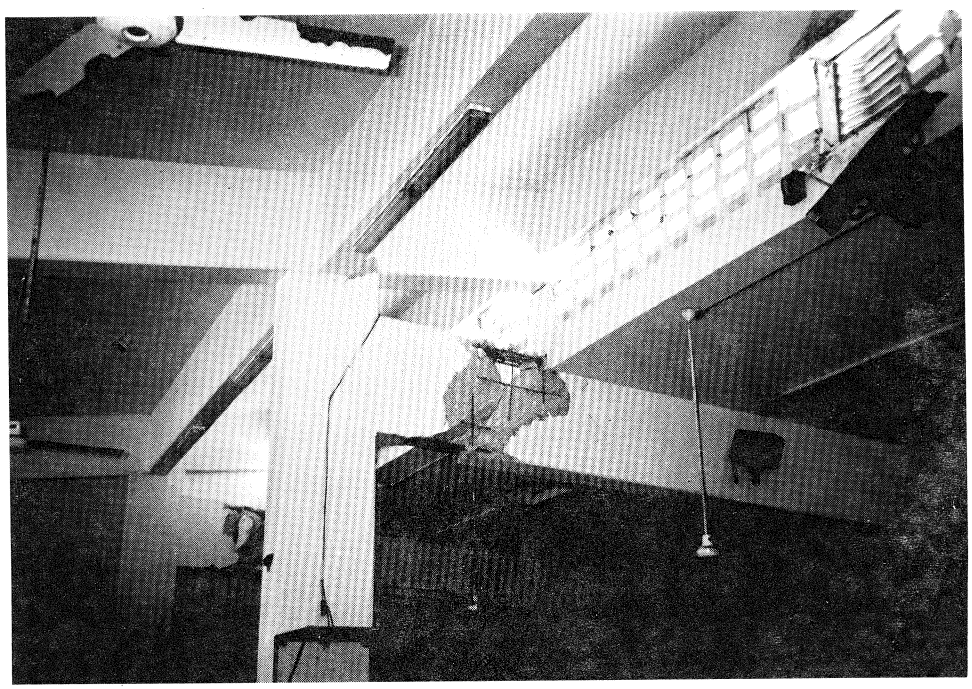


Figure 5-5: The Greyhound Racetrack consists of two concrete canopies offset vertically at the center of the structure. The concrete beams spanning between the two canopies were shattered by the different response motions of the two halves of the structure.

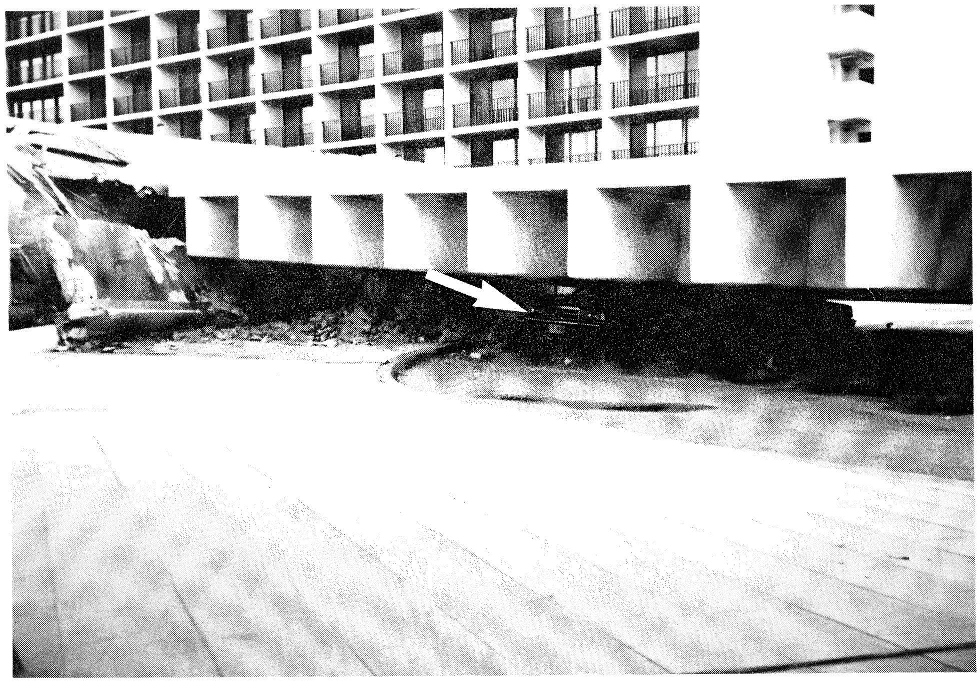


Figure 5-6: The most severe instance of concrete canopy damage occurred at the Reef Hotel, where crushing of concrete columns dropped a heavy slab onto taxis parked near the entrance.

in some sections. These connections were required to carry the large overturning forces generated by the shear walls, which were not provided with thickened, specially reinforced boundary elements. Eccentricities in the connections contributed to premature spalling of concrete and buckling of reinforcing. The slender panels appear to have been unable to withstand the extreme axial strains imposed by the combination of gravity and seismic loads. Concentration of high stresses around the discrete precast connections also resulted in localized severe damage. Interestingly, an adjacent wing of similar design, but constructed utilizing cast-in-place walls had minimal damage, indicating the extent to which connection behavior contributed to the observed damage. The Hilton was closed following the earthquake pending repairs; the damaged wing was under consideration for demolition.

Guam Memorial Hospital also suffered damage to precast concrete elements. Shear wall panels in the emergency room area exhibited spalling at connections. Unlike the panels at the Hilton, however, these elements were set between cast-in-place columns and do not bear vertical loads. The connections consisted of short, headed studs, welded to steel plates at the panel edges. Damage observed consisted mainly of local shear cracking and spalling at and near the connections. The hospital remained in operation following the earthquake.

5.7 Poor Construction Quality

Poor quality of construction appeared to contribute significantly to damage in many cases. In reinforced concrete elements, poorly consolidated areas (rock pockets) were observed, although not frequently. Problems relative to reinforcement were much more commonly observed. These included improperly spaced ties, improperly located longitudinal bars, insufficient or excessive cover, and often severely corroded reinforcing. Also, electrical conduit and junction boxes were often observed within damaged structural elements.

The coral-based aggregates used in the local concrete may have exacerbated damage in some cases. These aggregates appear to have low tensile strength, as is observed in light-weight concrete, which is generally weaker in shear than normal-weight concrete.

Concrete-block masonry, especially when used as in-fill, was often found to be improperly constructed. Most problems observed were with respect to grouting. Grout was often found to be poorly consolidated or to contain foreign material, such as dirt or paper. In upper courses, immediately below concrete elements, poorly placed grout or a complete lack of grout was commonly observed. This contributed to damage in concrete elements adjacent to the block as well as to out-of-plane displacement of the tops of in-fill walls. Improperly placed reinforcing and poor tooling of mortar were also observed.

SECTION 6
EFFECTS ON LIFELINES

Lifelines serving the island include the electric power system, with shared operation by the government's Guam Power Authority, and the U.S. Navy. Guam is equipped with an island-wide wastewater system, and a potable water system supplied primarily from wells. There is no central gas system; fuel for cooking is supplied from on-site propane tanks. The Guam Telephone Authority operates local phone service. Long distance service is provided by AT&T or MCI. The island has no rail system. All transportation is over the well-maintained two-lane highways. Concrete bridges span the several rivers that drain the mountainous southern half of the island. The island is served by one commercial airport, and one commercial seaport. The airbases of course have their own landing fields. The Navy maintains its docking facility adjacent to the commercial port.

6.1 Electric Power

Power is produced on the island by a combination of oil-fired steam plants, diesel generators, and gas turbine generators. The total generating capacity of the island is about 280 megawatts (MW), of which two-thirds is provided by three steam plants. The remaining generation is provided by diesels and gas turbines, located at various substation sites.

Bulk power is transmitted throughout the island at 115 and 34.5 kilovolts (kV), with local distribution at 13.8 kV. Power poles are heavy reinforced concrete columns designed to withstand typhoon loads (Figure 6-1). The distribution system is designed to limit power outages from high winds. Most cables are relatively taut between poles to minimize sway and subsequent line contact. Pole-mounted transformers are bolted in place to preclude detachment.

The earthquake totally blacked out power on the island. Within a few hours a few of the gas turbine and diesel generators were able to restart and reenergize a portion of the 34.5 kV system. Most of the island remained without power for two days, until the steam plants could be repressurized and brought back on line. By Thursday, the fourth day following the earthquake, electrical service had been restored to most of Guam.

The transmission and distribution system experienced minor damage. Power Authority engineers estimated two or three dozen broken porcelain insulators supporting transmission cable on power poles. There were a few instances where cables detached and fell to the ground in the transmission or distribution system. The 115 and 34.5 kV substations suffered a few

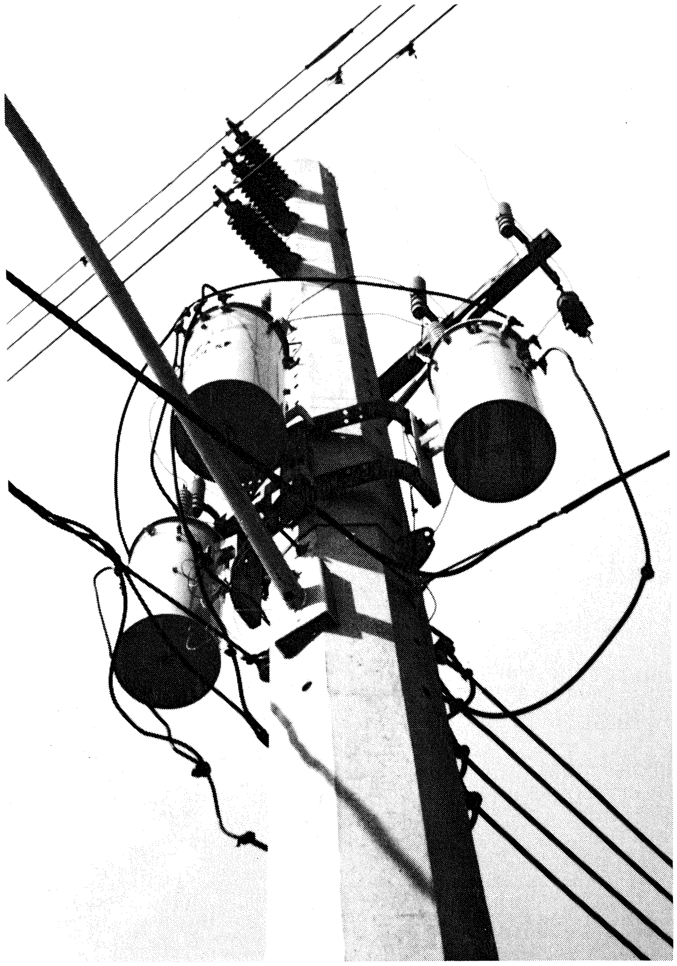


Figure 6-1: Wind loads on Guam result in power and transmission poles of heavy reinforced concrete (top photo). A small portion of poles suffered broken ceramic insulators. Broken insulators are collected on pallets in the Power Authority's service yard (bottom photo).

isolated instances of broken porcelain or detached conductors (Figure 6-1). There was no damage in the major switchyard equipment such as transformers or circuit breakers. Several large substation transformers were noted to have shifted on their base pads, as much as 16 inches at one station. There were no instances of damage to power poles or transmission towers.

Damage in all generating plants was minor except for the Navy-operated steam plant located in the port area (Figure 6-2). Settlement of soil fill created vertical offsets of up to four feet near the plant's salt water intake channel, fracturing the buried circulating water lines to the condensers. Two of four generating units were operating at the time of the earthquake. The plant's DC power supply was lost when batteries toppled from their racks. Simultaneous loss of DC and AC operating power meant that the spinning turbines coasted down without lube oil pressure, possibly resulting bearing damage. Additional damage in the plant included an overturned station service transformer, an overturned motor control center, and leaks in various piping systems. The turbine buildings were not accessible for a week following the earthquake due to airborne asbestos dislodged from thermal insulation.

Repairs were completed to one of the larger units at the Navy steam plant, and it was brought back on line about four weeks after the earthquake. This provided some relief to the island's electrical system. The Navy plant represents about 20% of Guam's generating capacity. With the plant off line, the remaining generating capacity could barely meet demand.

6.2 Water and Wastewater

The government's Public Utility Agency of Guam (PUAG) operates potable water and wastewater systems. The primary raw water source is a system of 94 wells spread throughout the island. Raw water is drawn from typical depths of about 400 feet through motor-driven deep well turbine pumps. Most well water is of sufficient quality that chlorination at the wellhead is the only necessary treatment. Potable water is stored in ground-mounted welded steel tanks near population centers around the island.

In addition to the system of wells, there is one recently-constructed water treatment plant serving the southeastern section of island. The treatment plant pumps raw water from the nearby Telafofo River, and treats it by a combination of chlorination and flocculation.

The heavily developed northern half of the island is served by a central wastewater system, including a total of five sewage treatment plants. At the treatment plants, wastewater is chlorinated and routed through settling basins prior to discharge offshore.

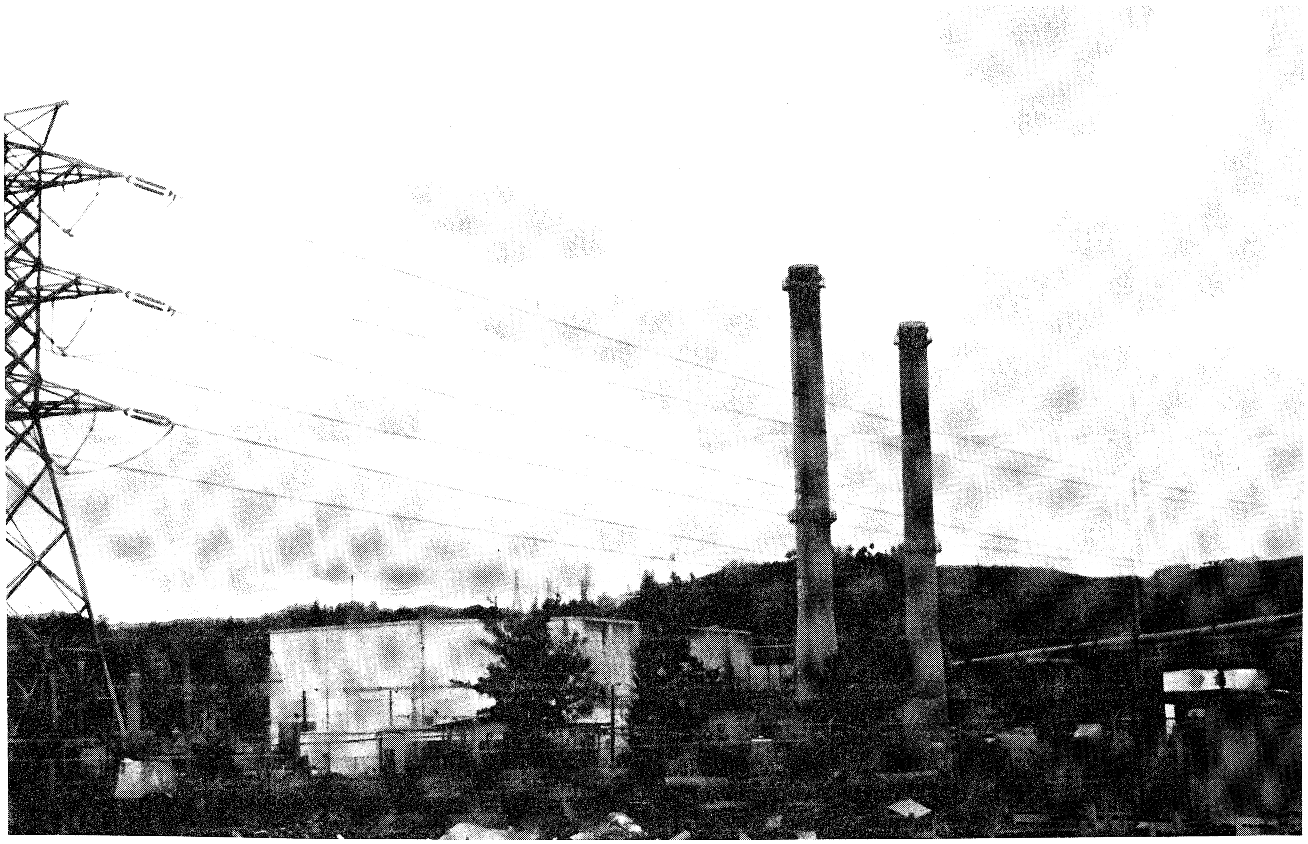
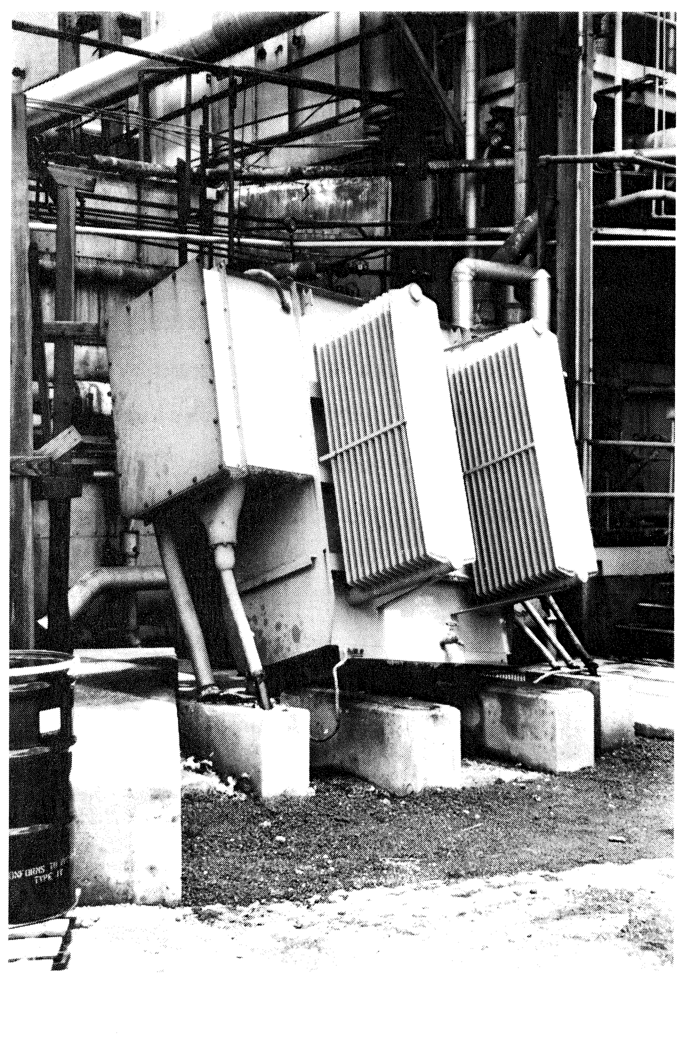


Figure 6-2: Overturned power supply equipment, such as batteries, motor control centers, and the station service transformer (at right), cut off both DC and AC power to two operating units at the Navy's Piti Steam Plant. Damage to the plant severely reduces the island's generating capacity.



Underground lines for both the water and wastewater systems include clay pipe, cast iron, ductile iron, asbestos cement, steel, and PVC, with line sizes from 6 to 24-inch diameter. The island-wide potable water system includes about 500 miles of buried piping.

Because the water system depends on electric power to pump from the wells, the two to three day power blackout following the earthquake also impeded water service. The water system is reported to have only about an hour's storage capacity in the steel tank reservoir if the well pumps are not running. A few of the wells have emergency generators so that a limited number of pumps could supply water to critical facilities such as the main hospital.

The PUAG water and wastewater system management indicated that all wells, pumps, storage tanks, and treatment plants survived the earthquake without significant damage (Figure 6-3). Restoration of service however was limited by damage in the buried piping systems.

As of Saturday, the sixth day after the earthquake, over 100 breaks had been reported in water mains. Nevertheless, most of system remained pressurized in the heavily populated areas surrounding Agana. Most of the pipe failures appeared to be leaks rather than ruptures. There were, however, instances of total loss of flow in water mains. Within the firm limestone site of Anderson Airbase, for example, a six-inch water line fractured and offset 12 inches.

Pressure in the potable water could be maintained by allowing loss through small leaks and closing valves to isolate heavily damaged sections. This resulted in loss of water pressure to isolated sections of Agana and neighboring towns. Many of the villages in the remote southern half of the island were without water due to isolation of the long runs of water main supplying the area.

There were no immediate earthquake-induced blockages in sewage lines. However, since the system is unpressurized, sewage line breaks would generally not be immediately apparent.

There was no clear trend in the pipe failures as a function of pipe material or size. The generally firm soil or rock surrounding the buried pipe apparently limited damage. Pas experience would indicated that the average failure rate of less than one break per system mile would be considered low for an earthquake of this size.

Figure 6-3: The Public Utility Agency of Guam (PUAG) reported no damage to their welded steel storage reservoirs or the Ugum Water Treatment Plant (above). Over 100 breaks occurred in the island's 500 miles of buried water mains. Repairs are underway to a broken main near Agana at right.

6.3 Telephone

The Guam Telephone Authority (GTA) provides local phone service to the island. The phone system is new, with installation of buried fiber-optic cable nearing completion. The telephone switching system is apparently all digital. There are three main switching stations on the island.

Based on brief discussions with management at the Agana Switching Station, there was no significant damage to the phone system's DC power supply anywhere in the system. The loss of AC power was made up by emergency diesels at the switching stations. Phone service on the island "became busy" but did not overload.

6.4 Roads and Bridges

The island's system of two-lane paved highways experienced local slumping or spreading in pavement at a few locations, typically on hillsides (Figure 6-4). Rock slides dumped debris on roads. It was not necessary however to close any roads due to damage.

There was no major damage to any of the island's concrete beam bridges. Several bridges were closed for about a day due to settlement at the abutments and minor cracking in the concrete. Bridges were reopened following inspection and repaving the approaches to compensate for abutment settlement.

6.5 Port

The most serious earthquake effect to the island was loss of operation in the container handling section of the port facility. Spreading of fill adjacent to the three container handling gantry cranes misaligned the rails over more than half of the travel span for the cranes (Figure 6-5). Travel distance for the gantry cranes is severely limited, limiting the number of large container ships the port could serve. All bulk material in and out of the island flows through this port.

Repairs to the port would involve recompacting the fill in the area of soil spreading, and replacing the rails and pile foundations beneath. In the meantime, service to container ships in the commercial port would be sharply curtailed. The older section of the port, which was relatively undamaged, could still offload non-container cargo from smaller vessels. This, however, seriously reduces the flow of material into the island. Shortages in certain commodities were starting to be seen within a week of the earthquake.

Figure 6-4: Soil failure in the form of slumping or spreading damaged roadways in certain locations on the island. Concrete beam bridges suffered minor cracking and slumping at abutments. Water mains attached to the sides of bridges tended to fail due to differential movement at the interface of abutments (arrow, below)

Figure 6-5: Perhaps the most serious effect from the earthquake was due to spreading of fill beneath the crane rails in the container handling section of the commercial port. Offset of the rails severely limits the travel distance of the gantry cranes, curtailing off-loading of container ships, the primary source of supply to the island.

SECTION 7
CONCLUSIONS

In spite of the proximity of the large magnitude earthquake to the island, the overall level of damage could be described as moderate. There were obvious exceptions, such as the liquefied areas of the port, and the partial collapse of certain buildings. However, life for most of the island's inhabitants returned more-or-less to normal within a week.

People's descriptions, combined with observations of effects, indicated that motion was of long duration (about one minute), but probably of moderate amplitude. It is likely that peak ground accelerations ranged from 0.20g to 0.30g around the island. The depth of the fault rupture obviously absorbed much of the earthquake's energy before it reached the surface. Effects from the earthquake therefore might be comparable to a shallow event of similar magnitude, occurring 200 to 300 kilometers from a population center.

Structures on the island are nominally designed in accordance with modern American standards. However, both attention to structural detail and construction quality appeared lax in many structures. While most smaller buildings appear to have escaped the earthquake without significant damage, many of the major buildings suffered some level of damage, ranging from cracking and spalling to near collapse. Due to the remote location of the island, many designs are performed in the continental United States or Japan. This probably results in limited surveillance of the construction process by the design professionals, contributing to poor construction quality.

The poor performance of hotel buildings appeared to be partially attributable to irregular structural configurations. This graphically illustrates that overall lateral strength does not itself ensure adequate building behavior. Rather, superior earthquake performance can best be achieved by providing continuous systems, regular configurations, toughness through proper detailing, structural redundancy, and proper construction inspection.

These latter issues comprise the principal difference between design approaches to wind and earthquake loading. Wind-resistant designs are primarily concerned with a structure's strength and serviceability. Earthquake-resistant designs are also concerned with strength, but must also consider the ductility of the structural system. Structures are intended to remain elastic (essentially without structural damage) under design wind loads, which are close to the most severe expected. Real earthquake loads, however, are much higher than design earthquake loads. Structures are not expected to remain elastic in worst-case earthquake loading. Structural damage is expected, but catastrophic damage and collapse are not. These are prevented by ductility in design. It is therefore possible for a structure to possess sufficient strength to resist high winds, but to be severely damaged in a major earthquake.

Many regions of the U.S. are in the process of adopting earthquake resistive design standards for the first time. An important lesson from this earthquake is that adoption of reliable codes does no by itself ensure good performance, until the design professionals, construction industry, and building officials are trained to design and construct structures as appropriate quality. Further, the total economic loss of one wing of the 12-story luxury hotel which had been opened only 18 days graphically demonstrates the importance of investing design effort in structural integrity as well as architectural features.

There was a wide variation in effects to the island's lifelines. Guam's system of highways and bridges experienced minor damage, and only brief closures. The telephone system appeared to be unaffected by the earthquake.

Electric power service was lost to the island for two to three days due to moderate damage in the transmission and distribution system, followed by delays in restarting generation plants. Damage to the navy's steam plant, which represents about 20% of the island's generating capacity, created a severe shortage of power generation compared to demand. As all other generating units could not be kept on line at all times, local blackouts (sometimes planned, sometimes not) became a chronic problem after the earthquake.

Water service was first interrupted by lack of power for pump stations, then by the discovery of breaks in buried water mains. Nevertheless, water pressure to most of the developed area of the island was restored within a week of the earthquake. The reliability of the water supply might be partially attributed to the large number of individual sources. Guam's water comes from a system of some 94 wells and local purification stations scattered throughout the island. This creates a highly redundant interconnected system of water supply lines that is relatively tolerant of individual breaks. One of the longer term problems for the water supply may actually result from chronic blackouts of the electric service. The island's water system requires the well pumps to work almost continuously to recharge the steel tank reservoirs. A power outage to a large area may therefore result in a loss in water pressure within about an hour.

Liquefaction-induced soil failure beneath the container handling area of the commercial port may incur the most serious effect from the earthquake. Nearly all material into Guam flows through the single port, most of it through the modern container handling sections. Curtailment of container handling capability appeared to be creating spot shortages within a few days of the earthquake. This problem may persist for months.

Finally, the earthquake's effect on the important tourist business will have the ultimate impact on the island's economy. Most of the hotels in the tourist area resumed operation as soon as power and water service were restored. A few were closed as a precaution due to structural damage. News of the earthquake may have caused a significant portion of vacationers to change plans to visit the island, in spite of the actual moderate level of damage. Limitations in power and water reliability, combined with spot shortages of consumer goods, could ultimately damage the reputation of an otherwise ideal vacation resort.

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