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INSIDE

The 1995 Hanshin-Awaji (Kobe), Japan, Earthquake

Thomas L. Holzer, *U.S. Geological Survey, 345 Middlefield Road, Menlo Park, CA 94025*

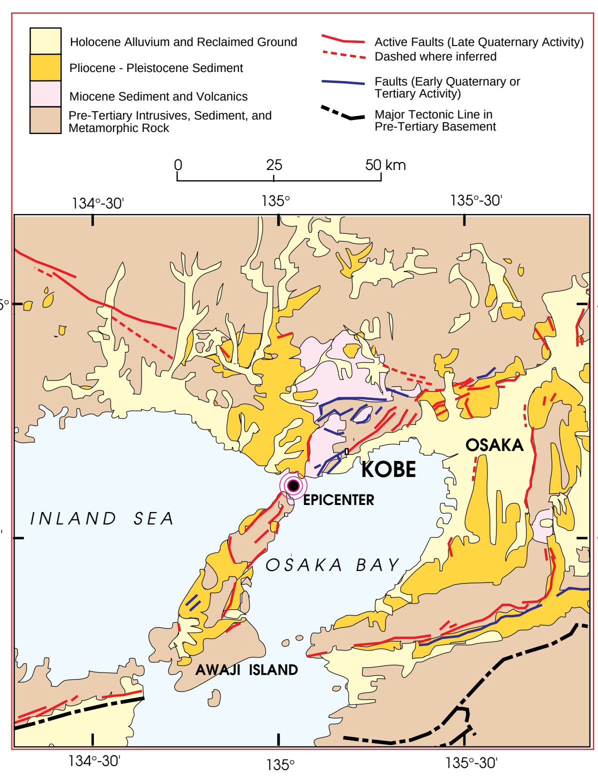

Figure 1. Neotectonic map of Osaka Bay region (generalized from Sangawa et al., 1983; Tsukuda et al., 1982; and Tsukuda et al., 1985).

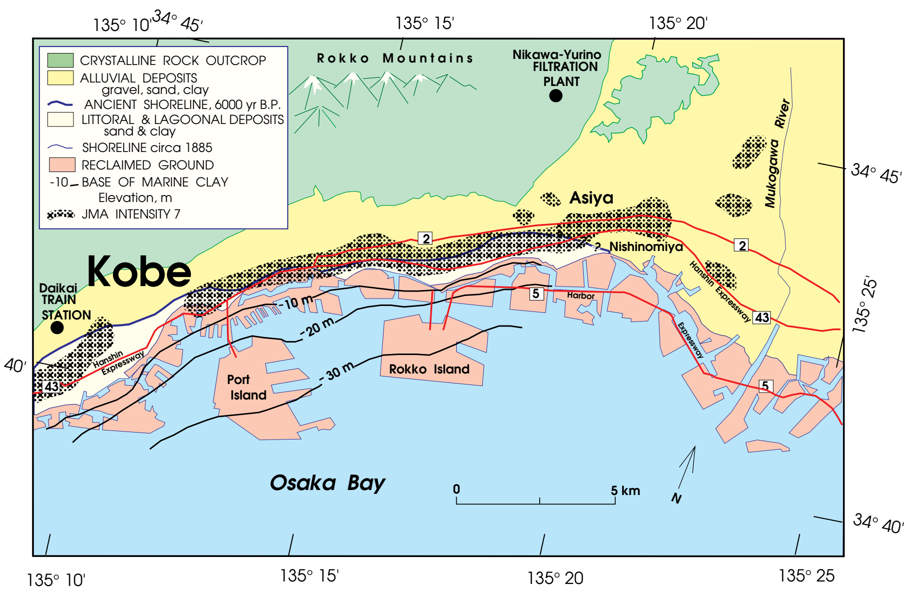

Figure 2. Generalized geologic map of Kobe (from Huzita and Kasama, 1983) and Japanese Meteorological Agency (JMA) intensity 7 area.

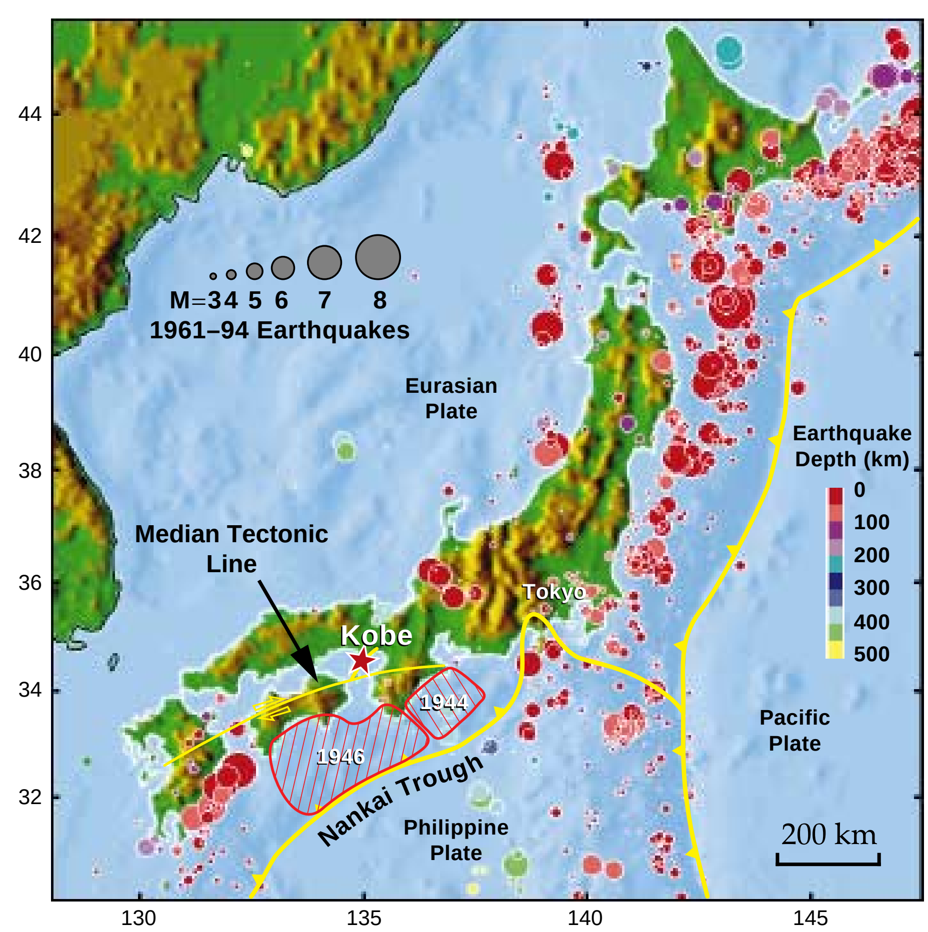

Figure 3. Japan, showing seismicity from 1961 to 1994, location of the 1995 Hanshin-Awaji earthquake, and projected rupture areas of largest historical earthquakes to shake Kobe, which were subduction-zone earthquakes in 1944 and 1946. (Figure prepared by Grant A. Marshall, U.S. Geological Survey.)

ABSTRACT

The January 17, 1995, earthquake that devastated Kobe, Japan, caused about $100 billion in property losses, making it the most expensive earthquake ever to strike an urban area. The earthquake killed 5378 people, damaged or destroyed about 152,000 buildings, and incinerated the equivalent of 70 U.S. city blocks. The earthquake confirms the credibility of predictions of major property losses when urban areas in the United States are subjected to local moderate earthquakes. It also provides an unusual opportunity to study the effects of near-source ground shaking on both the buildings and infrastructure of a modern city and to deduce implications for the United States. Damage to buildings, which accounted for about 60% of the total property loss, was greatest in buildings constructed under older building codes. The concentration of damage in older buildings highlights the need to address the seismic hazard from buildings that do not conform to current code. The infrastructure of Kobe, including expressways, railways, port facilities, and water, gas, electrical power, and sewer systems, also sustained major damage. The massive damage to infrastructure highlights the need to consider the seismic hazard to lifelines; catastrophic failure of one of these systems may undermine the functionality of a city. The lessons from Kobe for the earth sciences are similar to those from the 1994 Northridge and 1989 Loma Prieta, California, earthquakes. Areas subject to either near-source ground shaking or special site effects are at particular risk from earthquakes. Earthquakes become disasters when society is unprepared; society is more likely to prepare when earth scientists map and quantify earthquake hazards.

INTRODUCTION

The January 17, 1995, Hanshin-Awaji, Japan, earthquake, which severely damaged Kobe, a modern city with many engineered structures, is the most expensive earthquake ever to occur. Previous earthquakes such as the 1976 Tangshan, China, earthquake, which killed 650,000 people, have forcefully demonstrated the potential for great loss of life when buildings are not earthquake resistant. The 1995 Hanshin-Awaji earthquake confirms the credibility of predictions of major property losses when urban areas in the United States are subjected to near-source ground shaking. This confirmation should motivate additional efforts to mitigate the earthquake hazard in urban areas in the United States that are underlain by active faults; these areas include Los Angeles, Salt Lake City, San Francisco–Oakland, San Diego, and Seattle-Tacoma. This earthquake also provides a special opportunity to learn about the potential of near-source ground shaking and liquefaction to damage modern engineered structures and urban infrastructure.

Kobe presents interesting direct parallels with cities in the United States. For example, the geology of Oakland, California, which sits atop the highly active Hayward fault, is similar to that of Kobe. Both cities are built on young alluvial deposits and ground reclaimed from adjacent drowned estuaries. Both estuaries have thick accumulations of soft silt and clay. Thus, the earthquake in Kobe is a good analog for what may happen in Oakland. Salt Lake City presents a parallel in public perception of the hazard. Salt Lake City sits atop the Wasatch fault system, which has been documented by earth scientists to be capable of generating moderate earthquakes. As in Kobe, the fault has had only modest historical seismicity, and the public perception of and level of preparation for the earthquake hazard are not as high as in more seismically active areas.

The Earthquake

The Hanshin-Awaji earthquake (M_W = 6.9) occurred at 5:46 a.m. local time on January 17, 1995. The epicenter was located off the northeast tip of Awaji Island in Osaka Bay (Fig. 1). The earthquake ruptured bilaterally along a 35–50-km-long northeasterly trending zone; the northeastern part of the rupture zone passed beneath Kobe. The focal mechanism shows strike-slip motion on a nearly vertical fault. Surface faulting was observed only above the southwest end of the rupture zone, where a 9-km-long segment of the Nojima fault broke the land on the northwest side of Awaji Island. Surface faulting was primarily strike slip, with a maximum horizontal displacement of 1.7 m; locally, vertical offsets

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reached 1.0 m. Seismic profiles in Osaka Bay revealed scarps off the northeast end of Awaji Island with an aggregate length of 7 km. The offshore faults are offset about 5 km to the southeast of the Nojima fault.

Damage was concentrated in a narrow elongate zone (Fig. 2). The earthquake killed 5378 people, injured 33,189 people, damaged 152,297 buildings, and incinerated an area of 671,253 m^2, the equivalent of 70 U.S. city blocks (Asahi Evening News, 1995). Total property losses were about $100 billion.

GEOLOGIC SETTING

Japan is an island arc that has formed on the east boundary of the Eurasian tectonic plate (Fig. 3). The geologic history of Japan is dominated by subduction of the Philippine and Pacific plates beneath the Eurasian plate. In southwestern Japan, subduction occurs along the Nankai Trough. Although most of the seismic energy associated with plate convergence is released along the downgoing slab, Japan also faces a significant onshore earthquake hazard. About eight moderate or larger earthquakes occur per century onshore (Wesnousky et al., 1982).

Geologic mapping in Japan has revealed many onshore or nearshore faults that show evidence of Quaternary activity (Research Group for Active Faults in Japan, 1991). The Hanshin-Awaji earthquake of January 17, 1995, occurred on one of these mapped faults. Kobe is about 250 km northwest of the Nankai Trough and about 50 km north of the Median Tectonic Line (Fig. 3), a major geologic boundary that divides southwestern Japan into a northern "Inner Zone" and southern "Outer Zone." Basement rocks of the Inner Zone consist chiefly

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Slide Set Available on Kobe Earthquake Damage

Here is an excellent tool for educational use: a set of 35 mm color slides compiled by author Thomas L. Holzer, USGS, expanding on this article. These 30 slides, taken by several investigators, document geologic conditions and damage resulting from the January 17, 1995, M 6.9 Hanshin-Awaji earthquake that devastated Kobe, Japan. Views illustrate damage to buildings, transportation facilities, and lifelines. The set includes pictures of liquefaction and ground settling in areas of reclaimed ground, including the Port of Kobe, the third busiest port in the world. Maps show surficial geology, neotectonic setting, and liquefaction areas. Cross sections illustrate the Holocene history of Kobe. The set is supplied with a printed text describing the views.

Order slide set SLI001, *Kobe Earthquake Damage,* from the Geological Society of America, P.O. Box 9140, Boulder, CO 80301-9140, phone 800-472-1988 or (303) 447-2020. Orders may be faxed to GSA at 303-447-1133; please include complete credit card information. List price $47, postpaid by surface mail; GSA members may claim their discount. This is a limited, one-time offer. Orders must be received by September 15, 1995, and will be shipped about September 30.

About People

GSA Member **Alan V. Morgan,** University of Waterloo, Waterloo, Ontario, Canada, was awarded the 1995 John H. Moss Award for Excellence in College Teaching by the Eastern Section of the National Association of Geology Teachers. The 1994 NAGT Ralph Digman Award, for outstanding contributions to earth science education outside the formal classroom, went to Fellow **Yngvar W. Isachsen**, New York State Geological Survey.

The Illinois State Geological Survey has granted emeritus status to GSA Member **Philip C. Reed,** who retired April 30, in recognition of his distinguished service. Reed also received a Groundwater Science Award from the Illinois Groundwater Association this year. The Illinois Survey named Member **William W. Shilts,** formerly of the Geological Survey of Canada, as its new chief.

In Memoriam

Jack E. Harrison
Lakewood, Colorado
June 2, 1995

Wallace B. Howe
Rolla, Missouri

Lawrence S. Matteson
Bridgeport, West Virginia
December 8, 1994

Willis G. Meyer
Dallas, Texas

Alfred O. C. Nier
Minneapolis, Minnesota
May 16, 1994

Bradford D. Pearson
British Columbia, Canada

Peter O. Sandvik
Kiana, Alaska
May 24, 1995

C. Michael Scullin
Martinez, California
June 7, 1995

ANNOUNCEMENT

Travel Grant Program

30th IGC in Beijing, China • August 4–14, 1996

The Geological Society of America is accepting applications for the International Geological Congress (IGC) Travel Grant Program.

This program was established as a final act of the Organizing Committee for the U.S.-hosted 28th IGC held in Washington, D.C., in July 1989. Surplus funds available at the conclusion of the 28th IGC were transferred to the GSA Foundation with the stipulation that income from the fund be used to support the attendance of young geoscientists at future IGCs, until such time as the United States again hosts an IGC. Travel grants will consist of economy airfare to and from China.

To be eligible, an applicant must be a resident or citizen of the United States (includes students); must have a birth date after August 31, 1956; and must have an abstract for inclusion in the program of the 30th IGC.

Official application forms are available from the Grants Administrator, GSA Headquarters, 3300 Penrose Place, P.O. Box 9140, Boulder, CO 80301. Along with the form, applicants must include a copy of the abstract that was submitted to the 30th IGC. Applications must be supported by two letters from current or recent supervisors; students may use faculty members. **Qualifying applications and letters of support must be postmarked no later than September 15, 1995.** Applicants will be notified of results early in 1996. ■

GSA ON THE WEB

What's new on the GSA home page on the World Wide Web? If you haven't yet connected to the Web, the Universal Resource Locator (URL) is **http://www.aescon.com/geosociety/index.html.**

For current information on the 1995 Annual Meeting in New Orleans, go to **Meetings** and choose **1995 Annual Meeting.** This area contains a listing of Symposia and Theme Sessions and has information about Field Trips, Continuing Education, Exhibits, Travel, and Lodging.

If you want to know more about the GSA Employment Service or about becoming a GSA Campus Representative, check the **Membership** section, which also has information on nominating a member to fellowship and on obtaining forms for applying to become a GSA Member or Student Associate.

See the **Geoscience Calendar** section for a listing of meetings of general geological interest.

The **Publications** section has a monthly table of contents and abstracts of articles for the *GSA Bulletin* and *Geology.* Also in this section is a guide for authors preparing manuscripts for submission to GSA publications. *GSA Today* issues are posted here for downloading and viewing.

For Congressional Contact Information, see the **Administration** section. ■

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of Paleozoic and Mesozoic sedimentary rocks. In the Kobe region, these sedimentary rocks are intruded by large bodies of Late Cretaceous age granite and granodiorite; these intrusive rocks compose the mountainous region north of Kobe.

Downwarping within the Inner Zone during the Cenozoic created sedimentary basins bounded by the basement rocks. Kobe sits on the northwestern margin of one of these basins, the Osaka Basin. This area has subsided at a high rate throughout the Pliocene and Pleistocene and has accumulated a complexly interbedded sequence of Quaternary marine and alluvial deposits; maximum thickness of these deposits is more than 600 m.

Most of Kobe sits on a narrow 2–3-km-wide coastal plain. The landward, or northern, margin of the coastal plain is formed by the Rokko Mountains, and the shoreward margin by Osaka Bay. Surficial deposits of the coastal plain can be divided into two major groups, natural deposits and artificial landfills (Fig. 2). The natural deposits are of two types (Huzita and Kasama, 1983). The inner part of the Kobe Coastal Plain is underlain by an approximately 2-km-wide zone of alluvial deposits. Near the modern stream channels, most of the deposits are coarse grained, in many places containing gravel derived from the Rokko Mountains. These gravelly deposits range from 10 to 20 m in thickness. Interchannel areas are underlain by finer grained materials. The southern margin of the alluvial deposits is a prehistoric shoreline that approximately parallels the modern shoreline. This shoreline is marked by a 4-m-high erosional scarp that was cut at the end of the Jōmon marine transgression into Osaka Bay, about 6000 yr ago. An approximately 1-km-wide flat plain that is underlain by alternating layers of littoral sand and lagoonal clay lies bayward of this old shoreline. These sand and clay deposits, which are only a few meters thick, represent post-Jōmon deposition and progradation of the coastal plain.

More than 27 km^2 of land has been reclaimed from Osaka Bay along the Kobe shoreline. Artificial fill was derived from several large quarries in weathered granite and Cenozoic sediments east and west of Kobe. The first major reclamation effort filled 529 ha along the shoreline from 1953 to 1970. After these reclamation efforts, two large islands, Port and Rokko Islands, were created. Reclamation of Port Island started in 1966 and filled 826 ha. Rokko Island, which covers an area of 580 ha, was reclaimed from 1973 to 1992. Fill was dumped into standing water that had an average water depth of 12 m. No significant effort was made during reclamation to compact the sandy fill to increase its liquefaction resistance. Pre-earthquake standard penetration test resistance typically ranged from 5 to 10 blows/ft (Nakakita and Watanabe, 1977).

GROUND SHAKING

Ground shaking in the epicentral region of the earthquake was exceptionally well recorded (National Research Institute for Earth Science and Disaster Prevention, 1995). Recorded accelerations equaled or exceeded 0.5 *g* at ten sites. The maximum acceleration was 0.818 *g*, recorded on the north-south component of an accelerometer at the Kobe Oceanic and Meteorological Observatory. Ground velocities were greater than 100 cm/s. Near-source strong ground shaking lasted 10 to 15 s. The amplitude of shaking was unusually high in the period range from 0.25 to 2.0 s.

The attenuation of peak ground acceleration with distance from the source zone is consistent with the recently revised attenuation curves of Boore et al. (1994) (Fig. 4). Near-source values are lower than the near-source values recorded during the 1994 Northridge, California, earthquake, possibly reflecting the difference in source mechanisms. Ruptures on reverse faults, such as Northridge, seem to produce higher levels of ground shaking than do ruptures on strike-slip faults (Heaton and Wald, 1994). Preliminary comparison of the ground shaking at sites underlain by soft soils with that at nearby sites on either firmer soils or rock indicates that shaking was amplified by a factor of 2 at soft soil sites (Borcherdt, 1995). Amplification ratios are independent of the level of shaking, suggesting that site amplification was linear or independent of strain level (Borcherdt, 1995).

GROUND FAILURE

Much of the artificial fill in areas of reclaimed ground liquefied during the earthquake and expelled large volumes of both sand and water. About 17 km^2 of land area was covered by vented materials. Splatter marks on walls and other structures showed that water fountains reached heights of almost 2 m in a few places and typically reached 0.5 m.

Lateral spreading was widespread along the perimeters of the artificial fills and generally involved failure of

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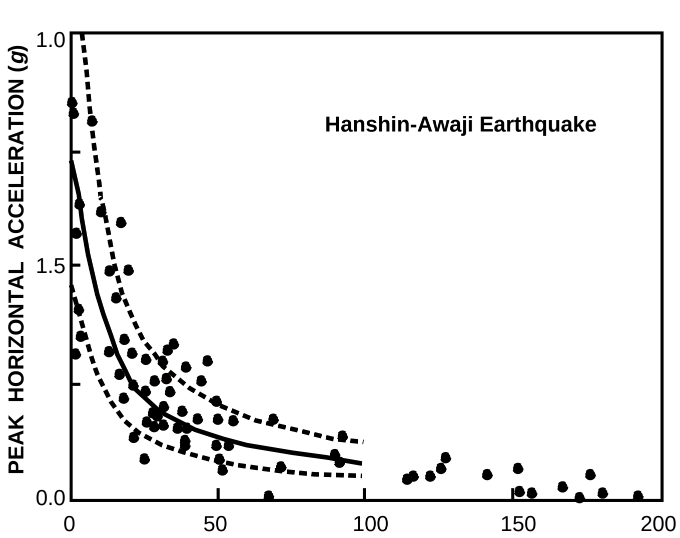

Figure 4. Observed peak horizontal acceleration vs. distance from the surface projection of the seismic rupture surface (modified from Borcherdt, 1995). Value plotted is the maximum of the two recorded orthogonal horizontal components. Attenuation curve is based on statistical correlations of ground-shaking recordings from earthquakes in western North America that were observed at sites with average shear-wave velocities of 180 to 360 m/s in the upper 30 m beneath the site (Boore et al., 1994). Solid curve shows median value; dashed curves are one standard deviation.

Figure 5. Differential ground settlement in artificial fill beneath the Harbor Expressway near Rokko Island. Postliquefaction consolidation caused ground to settle between bridge columns. Columns extend through liquefied zone. (Photograph by Carol S. Prentice, U.S. Geological Survey.)

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quay walls. Maximum permanent horizontal ground deformation from lateral spreading was about 2 m. Permanent horizontal ground deformation diminished rapidly in severity inland from the quay walls, although areas with ground cracks extended as much as 100 m inland from some walls.

Postliquefaction consolidation and expulsion of particulate matter caused regionally extensive settlements that ranged from 30 to 50 cm and locally exceeded 100 cm. Settlements were easy to detect and measure because many structures built on reclaimed ground are supported by piles or columns that extend through the liquefied zone (Fig. 5).

Despite the rugged terrain of the Rokko Mountains, only a few landslides were reported. Unpublished reconnaissance maps provided by the Geographical Survey of Japan, although they provide limited areal coverage of the mountain front near Kobe, showed only 12 landslides. Most of the landslides were on steep slopes inland from Nishinomiya. The largest and most damaging slope failure was next to the Nikawa-Yurino Filtration Plant (see Fig. 2 for location); this failure killed 34 people. Embankment failures also occurred along streams in the coastal plain.

EFFECTS ON BUILDINGS

Both nonengineered homes and engineered buildings were devastated. About 152,000 buildings and homes were destroyed or damaged. Approximately 60% of the total property loss derived from this destruction. Nearly 90% of the fatalities were caused by collapse of houses. The most comprehensive damage survey was by the Disaster Prevention Research Institute (DPRI), which inventoried damage in a 10 km² area of downtown Kobe. Much of the following information is from their report (Fujiwara et al., 1995).

Most of the destroyed homes were nonengineered wood-frame residences of traditional Japanese design that were built between the late 1940s and the 1970s. Single-family residential construction in Kobe is not regulated by a building code. Two principal styles of residential construction, Shinkabe and Okabe, were popular. These residences typically are either unbraced or lightly braced, one- and two-story, post-and-beam construction with heavy ceramic-tile roofs to resist the winds of typhoons. Most wood connections are by tenon-and-mortise rather than with nails. Resistance to horizontal shaking is further lowered by the absence of interior shear walls and, in cases of mixed use, by open storefronts on the first story. Many collapsed residences so thoroughly disintegrated that there was nothing to suggest that they had ever been more than piles of splintered wood and rubble (Fig. 6).

Many older reinforced concrete buildings also were severely damaged. The DPRI survey in downtown Kobe documented that 1558 reinforced concrete buildings were damaged, and 80 collapsed. A major revision of the building code in 1981, which significantly upgraded seismic resistance requirements, appears to have significantly lessened damage in newer buildings (Fig. 7). Many older reinforced-concrete buildings collapsed in midstory (Fig. 8). Various design problems contributed to this distinctive failure mode, including abrupt decreases with height in the horizontal stiffness of buildings, as well as structural discontinuities. Some discontinuities resulted from a uniquely Japanese approach to enhance the seismic resistance of buildings: encasement of a steel frame into a reinforced-concrete frame. For reasons of economy, steel frames were used only in the lower part of buildings. This is the first earthquake in which midstory collapses at the top of embedded steel frames were observed.

Damage to steel-frame buildings was also worse in pre-1981 buildings. The DPRI survey in downtown Kobe documented 977 damaged and 55 collapsed steel-frame buildings. Many of these buildings were built in the 1960s, when steel shortages and the high cost of structural steel in Japan prompted construction without much regard for seismic-shaking resistance; however, some new steel buildings were damaged. Although most of the damage had been from expected ductile deformation, brittle failures of some steel sections and welds were also observed.

Fires associated with the earthquake incinerated 6913 buildings in an aggregate area of 671,253 m². About 10% of the loss of life was attributed to fire. About two-thirds of the known ignitions were attributed to either leaking gas or electrical problems. Overturned kerosene heaters, candles, and bonfires that were lit after the earthquake to provide warmth caused the other ignitions.

EFFECTS ON INFRASTRUCTURE

In addition to the extensive damage to commercial and residential buildings, the infrastructure of Kobe, including highways, railways, port facilities, waterlines, sewage-treatment facilities, gas-supply lines, and electrical power supply system was badly damaged. The damage and the rate of recovery of the urban infrastructure are important aspects of the earthquake.

Some of the most spectacular images of damage involved the transportation system, both highways and railways. Kobe is serviced by two limited-access highways, the Hanshin and Harbor expressways, both of which are elevated structures. The Hanshin Expressway in Kobe, which was built in the 1960s, was the most heavily damaged; it includes a 600-m-long overturned section. Almost every column of this expressway, which rests on single columns along most of its length, was damaged. Columns of the expressway were short and stiff, causing them to undergo large dynamic forces. Steel reinforcing, particularly the ties that confine the concrete in columns, was inadequate (Comartin et al., 1995).

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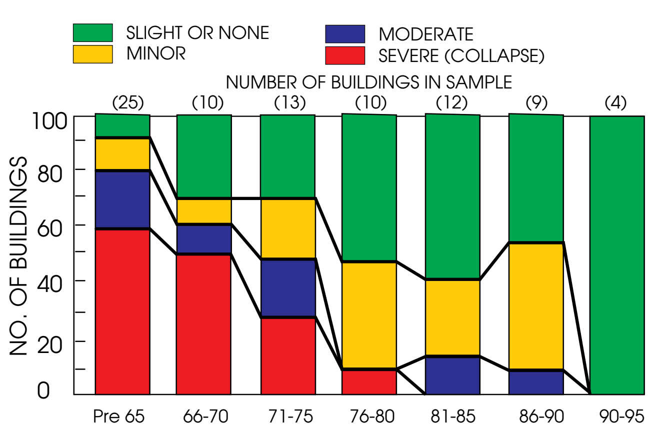

Figure 7. Correlation between damage level and year of construction of reinforced-concrete buildings (Fujiwara et al., 1995). Numbers in parentheses are the size of the sample.

Figure 6. Collapsed Japanese wood-frame home. (Photograph by Carol S. Prentice, U.S. Geological Survey.)

Figure 8. Collapsed sixth story in eight-story Kobe City Hall Annex, a reinforced-concrete building built in the 1960s. Behind it is the 16-story New City Hall, a 1980s steel-frame building that was not damaged and remained functional after the earthquake. (Photograph by Christopher Rojahn, Applied Technology Council.)

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Despite construction of the newer Harbor Expressway to modern seismic-design standards, many of its bridges slipped off their bearings, and one even collapsed (Fig. 9). Almost every expansion joint along the elevated Harbor Expressway was damaged. The heavy damage to the expressway may be partly explained by its location on reclaimed ground. Soil as it liquefied around the bridge columns was unable to resist the lateral rocking motions of the columns of the elevated roadway (Comartin et al., 1995).

Kobe also relies heavily on three major rail lines for ground transportation. As with the expressway system, most of these rail lines are elevated structures. Damage primarily derived from failure of columns that were built to older seismic-design standards.

The collapse of the underground Daikai Railroad Station in western Kobe (see Fig. 2 for location) is the first collapse of an engineered tunnel from seismic shaking ever reported. The station and adjacent tunnel were built in the 1960s by cut-and-cover techniques in stiff sandy silt. Reinforced-concrete columns in the station, which supported the roof of the station and 4.8 m of overlying soil, buckled, causing 1800 m^2 of land to settle in a 90-m-long elongate depression. Maximum settlement was 2.5 m. Collapse was localized above the 17-m-wide underground station and did not extend into the narrower 9-m-wide running tunnels at either end of the station.

Maritime transportation was also disrupted. The Port of Kobe was badly damaged, and no containerized cargo could be loaded or unloaded. Kobe is the largest foreign-trade port in Japan and the third busiest port in the world. The port contains 152 berths, with an aggregate wharf length of 27 km (Fairplay, 1994). It operates 400 dockside gantry cranes and derricks to load and unload cargo. More than 95% of the shipping berths were inoperable after the earthquake. Approximately 24 km of wharf was damaged.

Damage to quay walls, crane-rail systems, and dockside gantry cranes was caused by permanent ground displacement associated with lateral spreading at the margins of the fill (Fig. 10). Quay walls were typically displaced seaward about 1 to 2 m, and a 2–3-m-deep graben formed on the landward side of the wall. Damage to the cranes was caused by differential horizontal displacement between the seaward and landward crane rails. The seaward crane rail at Kobe typically rests on the quay walls, which are of caisson-type construction, and the landward crane rail rests on either a pile-supported wall or engineered fill. Horizontal displacement, which was greatest at the quay wall, pulled the two crane rails apart, distorting the steel moment frames of the cranes.

Approximately 650,000 customers of the Kobe City Waterworks Bureau lost water service. The disruption resulted from more than 4000 leaks in the main distribution lines and more than 20,000 leaks on private lots. Leakage was so massive that the volume of water in the distribution system dwindled from 338,455 to 94,908 m^3 in a single day. Of the 119 water-distribution reservoirs in the system, 57 completely drained within six hours, and 29 more eventually drained dry. A total of 21 of the distribution reservoirs are dual reservoirs with emergency shutoff valves on one of the reservoirs to ensure local sources of water in cases of disaster. Operation of these valves preserved 33,800 m^3 of water.

Figure 9. Nishinomiya Harbor Bridge where an approach span collapsed. Thomas D. O'Rourke of Cornell University stands astride ground crack caused by liquefaction-induced lateral spreading in bridge foundation.

Most of the pipeline breaks were in alluvial-soil areas and were not associated with permanent ground movements. Piping is primarily ductile iron. The piping system on Rokko Island, the newest area of fill, uses locking slip joints to accommodate permanent horizontal ground movement. No leaks in this system were observed.

Restoration of water service, despite outside assistance, was slow. It took 11 days to repair half the leaks, and only 80% of the leaks were repaired within a month. Repairs were hampered by damage to bureau offices. The bureau's headquarters was located on the collapsed sixth floor of the City Hall Annex (Fig. 8), and the two regional offices were either badly damaged or burned.

Sewage collection and treatment facilities were also damaged. The worst damage was to the sewage-treatment facility for Hagashi Nada, the eastern ward of Kobe, which was crippled by the earthquake. Damage forced discharge of chlorinated but otherwise untreated sewage into Osaka Bay. This sewage-treatment facility was built on reclaimed ground. Damage was caused principally by liquefaction-induced settlement and lateral spreading. Buildings and tanks of the facility are supported by piles that extend through the liquefied zone. Settling ranging from 0.5 to 1.0 m severed buried sewer lines where they were connected to the facility's buildings and tanks.

The Osaka Gas Company suspended service to 857,400 natural-gas customers in Kobe four hours after the earthquake after receiving many reports of leaking gas and when the scope of damage and fire hazard became clear. Most of the damage was to the low-pressure distribution system and occurred primarily at screw joints in this steel pipe system. Damage was extensive in both areas of liquefaction and areas without permanent ground deformation. Only about 90 repairs were necessary in the medium-pressure lines, primarily in hilly areas where repair crews reported ground cracking and in liquefaction areas. The two liquified natural-gas terminals and the high-pressure piping system were undamaged. Total losses were approximately $1.9 billion.

Restoration of gas service became a major challenge for Kobe because many residents depend on it for heating and cooking. A month after the earthquake, service had been restored to only about one-third of the gas customers. Restoration was hampered by the numerous leaks in the low-pressure system and inflow of water and soil into the gas pipes. Traffic congestion and road-surface damage also interfered with repair operations.

About 1 million customers were without electrical power immediately after the earthquake. The blackout resulted primarily from shaking damage to 58 substations and 38 transmission lines (77 to 275 kV). Service was also disrupted by damage to about 900 power poles. Six power generation plants were damaged. Damage to power plants, most of which were located on reclaimed ground, resulted from both shaking and permanent ground deformation. Kansai Electric Power Co. estimated its losses at $2.3 billion, of which approximately 10% was attributed to liquefaction.

Restoration of electrical power was rapid. By one and three days after the earthquake, power was restored to 600,000 and 890,000 customers, respectively. Restoration was completed within a week, although some repairs were only temporary.

CONCLUSIONS

The 1995 Hanshin-Awaji earthquake confirms that even moderate events can cause major property losses when they occur directly within a modern urban area. Although the engineering design practice and construction in Kobe may differ in detail from those in areas of high seismic hazard in the United States, the concentration of damage in structures built to older building codes should be a particular cause for concern in the United States. Each new earthquake provides an opportunity to learn and to improve the seismic provisions of our building codes, but new codes are not retroactive. This situation permits buildings to remain in service that are not resistant to collapse. Kobe confirms that nonconforming older buildings are a substantial part of the earthquake hazard in the urban environment. If we are to reduce earthquake risk in our cities, we must address the problem of nonconforming buildings.

The 1995 earthquake also highlights the need to consider standards for each part of the infrastructure of a city. Urban infrastructure generally is subject to a lifeline-specific rather than a general standard, including specification of the design earthquake or ground shaking. The disabling of the Port of Kobe and the severe disruption to transportation, water, sewer, gas, and power systems demonstrate the need to ensure the integrity of the whole infrastructure. The chain of postearthquake functionality of a city may well rest on its weakest link.

Earthquakes present a challenging geologic hazard because their mitigation raises a complex range of issues that extends well beyond the purview of the earth sciences. In broad outline, however, the lessons from Kobe for the earth sciences are similar to those from the 1994 Northridge and 1989 Loma Prieta, California, earthquakes. Areas that either have a potential for near-source ground shaking or are susceptible to special site effects are at particular risk in earthquakes (Holzer, 1994). Society is more inclined to mitigate earthquake hazards when the geoscientists are able to specify the degree of hazard.

Figure 10. Damage to Maya Wharf caused by liquefaction-induced lateral spreading. The quay wall moved outward, causing formation of a graben. The seaward rail for gantry cranes is located on the quay wall, and the landward rail is located on a pile-supported wall behind a graben.

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