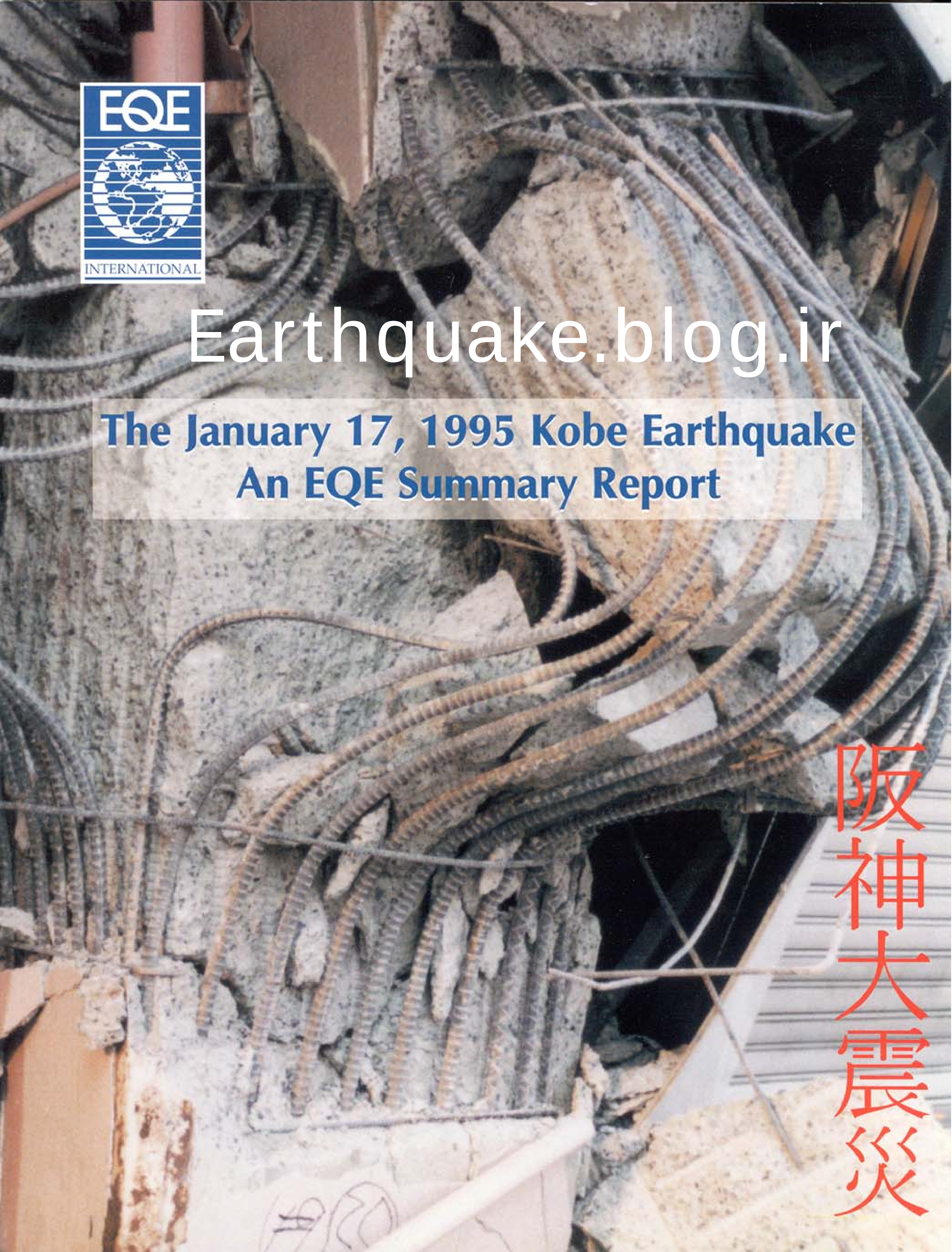


EQE INTERNATIONAL

The January 17, 1995 Kobe Earthquake
An EQE Summary Report

阪神大震災

THE JANUARY 17, 1995 KOBE EARTHQUAKE

An EQE Summary Report

April 1995

阪神大震災

Earthquake.blog.ir

This report summarizes the effects of the Kobe Earthquake, one of the costliest natural disasters in history. Immediately after the main shock, an earthquake reconnaissance team from EQE went to the affected region to evaluate the effects of the earthquake and to assess the extent and causes of damage to structures and infrastructure before critical evidence was removed.

The information presented in this summary report was collected over the two months following the earthquake. The statements and conclusions made are based strictly on our preliminary findings and assessments. Additional information and detailed investigation in the ensuing months may change some of our conclusions.

CONTENTS

阪神大震災

Kanji on the cover reads “The Great Hanshin Earthquake Disaster,” the popular name for this earthquake in Japan. The official name for the earthquake as given by the Japan Meteorological Agency is “The Hyogo-ken Nambu Earthquake.”

ACKNOWLEDGMENTS

Mr. Umeta of the Ashiya Fire Department; Dr. K. Ishida from the Central Research Institute of Electric Power Industry (CRIEPI); Mr. K. Beppu and Mr. K. Koizumi of the Daily Yomiuri Newspaper; Dr. Robert Kassawara from the Electrical Power Research Institute (EPRI); Mr. C.Y. Chang of Geomatrix Consultants; Felix Treibmann from Gerling-Konzern; Dr. Hitomi O. Murakami and Ms. Chiaki Watanabe, from the Department of Architectural Engineering, Hokkaido University; Mr. Mikage and Mr. Takinami of the Japan Rail Corporation; Mr. R. Norita, Mr. N. Fujii, Mr. M. Hirose, and Mr. Y. Mino from Kansai Electric's headquarters; Mr. T. Yamanaka from Kansai Electric's New York Office; Mr. S. Ouchi at the Port Island Incinerator Plant, Kobe City Environment Bureau; Mr. S. Tanioka at Rokko Island Slag Center, Kobe City Development Bureau; Mr. K. Tochio from the Port Island Sewage Disposal Plant, Kobe City Sewage Department; Lieutenant H. Nakachi from the Kobe Fire Department; Mr. S. Ohta from Kobe Newspaper; Professor S. Takada of Kobe University; Mr. Morita and Mr. M. Matsushita of the Kobe Water Department; Professor K. Toki, Professor H. Iemura, Professor Igarashi, Professor T. Sato, and Professor Sugito of Kyoto University; Dr. Haruo Hayashi and Dr. Hiroyuki Kameda, from the Disaster Prevention Research Institute, Kyoto University; Dr. K. Kawashima of the Public Works Research Institute; Dr. M. Izumi and Dr. H. Katukura from Izumi Research Institute, Shimizu Corporation; Mr. M. Takeda from the Power/Energy Division, Shimizu Corporation; Professor T. Katayama and Professor F. Yamakazi of the University of Tokyo; Dr. M. Kimura from Tokyu Construction Co.; Dr. Y. Ogawa of the UN Centre for Regional Development; Professor M. Hamada of Waseda University; Paul Sommerville from Woodward-Clyde Consultants; Professor S. Murikami of Yokohama University; Mr. T. Kumagi, Zurich International Company.

The "Earth Science Aspects" of this report was written in large part by Geomatrix Consultants, and we wish to extend a special thanks to them for their assistance.

EQE INVESTIGATION TEAM: John Alderman, John Beardall, Dr. Kenneth Campbell, Robert Campbell, Dr. Stephanie Chang, Craig Cole, Kent David, James Goltz, Bill Gordon, Ming Lee, David O'Sullivan, Thomas Roche, Dr. Charles Scawthorn, Richard Tiong, Peter Yanev

RESEARCH & PUBLICATION: Linda Decker, Patrick Ellis, Kelly Fleming, Anna Giaconia, Ronald Hamburger, David McCormick, Dr. Michael Rojansky, Scott Schleifer, John Smallwood-Garcia

Foreword

As individuals, many of us at EQE have worked intermittently in Japan since the 1970s, and have had continuous contact with many of our Japanese peers over that time. As a company, we have worked in Japan and for Japanese clients since 1983 and have investigated several destructive earthquakes there.

At the time of the earthquake, four of our senior staff members were in Japan, including Dr. Charles Scawthorn, who received his Ph.D. from Kyoto University. Two more EQE engineers were en route to Japan to evaluate the industrial facilities of a U.S. multinational corporation. Once we realized the importance of what had happened in Kobe, we quickly dispatched seven more investigators. The team consisted of structural and mechanical engineers, a fire protection engineer, a sociologist, an economist, and an insurance company executive. Four members of the team are fluent in Japanese.

A number of our multinational clients were affected by the earthquake, so we were able to gain a detailed understanding of the earthquake's effects and its impact on their operations, in addition to studying buildings, industry, ports, the supporting infrastructure, and emergency response and recovery efforts. We are currently working extensively in Kobe and throughout Japan, and continue to learn from the disaster. By the end of March 1995 we sent more than 25 employees to Japan to evaluate damage, to work on projects, and study the effects of the earthquake.

We wish to express our appreciation to our colleagues in Japan—Japanese, North Americans, and Europeans—who assisted us in the midst of their own response to the disaster; to Geomatrix, Inc., for their contribution on the earth science aspects of this report; and to the dedicated EQE employees who investigated this earthquake, researched and wrote this report, and produced this publication.

Finally, and most importantly, we wish to extend our sympathy to the victims of this earthquake. To those of us in the earthquake engineering profession, the deaths and other tragic consequences of every earthquake are particularly hard to accept because we know many of the deaths and injuries could have been avoided. It is our sincere hope and belief that by studying the causes of damage from earthquakes and publishing these reports future earthquakes will result in fewer tragedies.


2F
カフェ・ド・パリ
2F
いろはにほへと
B1

EXECUTIVE SUMMARY

On the first anniversary of the moment magnitude (M_W) 6.7 1994 Northridge Earthquake, Kobe, Japan was struck by an M_W6.9 earthquake. Both earthquakes struck in the pre-dawn hours, both ruptured beneath densely populated areas, and both caused horrible damage. Yet in Kobe there were many more deaths, financial losses dwarfed those in Northridge, and the amount of destroyed building stock and infrastructure was far worse in Kobe than in Northridge.

The reasons for these differences are many, but it would be incorrect to issue a blanket condemnation of current Japanese seismic engineering practice. While engineered structures did fail due to design flaws, they were predominantly older structures built before the current Japanese building code became effective; or they frequently failed due to problems revealed to be deficiencies in California design practices by the Northridge Earthquake. Japanese seismic engineering expertise has justifiably been considered among the best in the world, and a careful examination of the damage in Kobe does not change that conclusion.

Despite differences in design and construction practices, the same general principles frequently came into play: highway collapses were often primarily due to insufficient lateral ties in the concrete columns, nonductile concrete frame buildings did much worse than ductile design, shear walls typically helped to lessen catastrophic damage, and soft soils resulted in greater damage to the structures constructed on them.

The most important lesson in both earthquakes is that the knowledge to significantly improve structures to resist earthquake damage and thereby avoid most of the deaths and financial losses exists; what is lacking is a consistent willingness to marshall the resources necessary to put that knowledge to work on the scale necessary to prevent disasters. It is an odd paradox, for time and time again it is demonstrated that it usually costs less to prepare for earthquakes in advance than to repair the damage afterwards.

Differences in Kobe and Northridge

While there are more similarities than differences in structural performance in the Kobe and Northridge earthquakes, there are important differences that explain why the Kobe Earthquake was so much more damaging. Some of the lessons from these differences apply only to Japan, others apply to all areas of the world at risk from earthquakes.

The vast majority of deaths in Kobe occurred in the collapse of housing built using traditional Japanese methods. Traditional Japanese housing construction is based on a post-and-beam method with little lateral resistance. Exacerbating the problem is the practice of using thick mud and heavy tile for roofing, resulting in a structure with a very heavy roof and little resistance to the horizontal forces of earthquakes. U.S.-style frame housing with light-weight roofs is now coming into use in Japan and newer housing constructed using these methods had little or no damage from the earthquake.

Another significant difference between the Kobe area and the Northridge area is the quality of the soils. Because of a severe shortage of available land, much of modern urban Japan, including Tokyo, is built on the worst soil possible for earthquakes. Much of the newer construction in Kobe, particularly larger buildings, is built on very soft, recent alluvial soil and on recently constructed near-shore islands. Most of the serious damage to larger commercial and industrial buildings and infrastructure occurred in areas of soft soils and reclaimed land. The worst industrial damage occurred at or near the waterfront due to ground failures-liquefaction, lateral spreading, and settlement.

The Port of Kobe was an extreme example of the problems associated with poor soils in areas prone to earthquakes. The port is built almost entirely on fill. The engineering profession has tried hard to develop methods for strengthening filled areas to resist failures during earthquakes, but most of these methods have been put into practice without the benefit of being adequately tested in strong earthquakes. The results were decidedly mixed, but the failures costly—most retaining walls along the port failed, and the related ground settlement pulled buildings and other structures apart.

Buildings

The large commercial and industrial buildings in the Kobe area, particularly those built with steel or concrete framing, are similar to buildings of the same vintage in California. The Japanese building code had a major revision for concrete-frame buildings and a more limited revision for steel-frame buildings in 1981. The *Uniform Building Code*, as used in California, had major changes in 1973, 1975, and several times since then. The current Japanese code requires that buildings in Japan be designed for somewhat higher force levels than does the *Uniform Building Code*. Both areas require design for much higher forces than most other earthquake regions of the world.

Typically, pre-1981 concrete-frame buildings performed very poorly in Kobe, with many collapses. Post-1981 buildings performed much better—some were extensively damaged, but most had light damage. The buildings that fared best, and those without significant damage, had extensive concrete shear walls.

As in other earthquakes, large commercial and industrial steel-frame buildings performed better than any other type. However, major damage and a few collapses were observed. Pre-1981 steel buildings had most of the serious known damage. Certain innovative types of steel buildings, including high-rises, had very serious damage, and collapses might have occurred if the duration of the earthquake had been a few seconds longer.

Building owners usually do not understand that the earthquake provisions of even the strictest building codes do not necessarily have reasonable performance criteria for larger and stronger earthquakes. The current regulations, including those for all of California, are typically written with the expectation that in a strong earthquake a building will be severely damaged—in fact, it is assumed the building may need to be torn down, but it should not collapse. In California, higher performance criteria are mandated for certain types of structures—schools, hospitals, police and emergency response buildings, and certain power facilities. An informed building owner can choose to use these higher criteria, and thus avoid having their high-value, heavily occupied commercial building designed, in effect, to the same earthquake performance level as a low-value farm building.

Transportation

A number of major expressways, rail lines, and bridges, some of very modern design, were severely damaged. There are no significant new lessons from the collapse and damage of the older unretrofitted bridges and elevated structures. The structural and foundation details that typically caused damage to the expressways and rail lines have been observed in numerous earthquakes, and the damage was predictable. Some of the upgrade details observed in older retrofitted structures, such as steel column jacketing, are now widely used in California for strengthening. The apparent good performance of these details in Kobe is important to ongoing U.S. programs and needs to be studied in detail.

Many bridges and bridge approaches were severely damaged. The performance of large new bridges, including cable-tied arch, braced arch, and cable-stayed bridges, should be studied extensively because this is the strongest earthquake to affect such bridges.

The Port of Kobe, much of which was new, was devastated by widespread and severe liquefaction and/or permanent ground deformation, which destroyed more than 90% of the port's 187 berths and damaged or destroyed most large cranes. Shipping will be disrupted for many months, and some shipping business will probably never return to Kobe, resulting in significant losses to the local economy.

Other Infrastructure

The electrical and telecommunications systems in Kobe and surrounding areas performed as expected based on experience from previous earthquakes. Long term power outages were isolated to the most heavily damaged areas. Facilities near the epicenter sustained damage while resiliency of the systems prevented widespread service interruption. Most of the major transmission lines skirt the heavily damaged region of Kobe—the results may have been substantially different if the epicenter was located closer to the 500 kV transmission system. There were substantial financial losses to the electrical utilities, however, because expensive specialized equipment must be replaced and the distribution network must essentially be rebuilt within heavily damaged areas of Kobe.

During the earthquake, Kobe's water system sustained approximately 2,000 breaks. Generally, ground or building failure was the cause of the severe damage to Kobe's water systems. The resulting lack of water contributed significantly to the fire problem and will be a major hardship on the population for several months. The gas system had major damage, generally caused by ground or building failure, which also contributed significantly to the fire problem.

Fire

More than 150 fires occurred in Kobe and surrounding areas in the hours after the earthquake. These resulted in several large fires, and fire fighters were for the most part unable to combat them because of streets being blocked by collapsed buildings and building debris, traffic congestion, and severe water system damage. Calm wind conditions prevented conflagrations. The United States and Japan have both sustained the largest peacetime urban conflagrations in this century's history—because of earthquakes. Fire following earthquake is a potential major agent of damage, and needs to be recognized as such by planners.

Conclusion

The Kobe Earthquake dramatically illustrates the damage that can result when a strong earthquake strikes a modern industrialized area. It should not, however, be taken as an indication of what should be considered inevitable. While every major earthquake teaches new lessons to the engineering profession, the lessons are now increasingly refinements to knowledge already put into practice in many new structures. In Kobe and in Northridge, those structures with current seismic design details survived strong earthquakes with little damage and thereby validated current seismic design philosophies.

Significant seismic engineering challenges still need to be met, but the most critical challenge now is to society. The means to lessen the disastrous effects of strong earthquakes now exist and it is the responsibility of business and government leaders to put those means to work to save lives, and preserve financial and economic prosperity.


ROKKO
&CD RENTA
ロコメイト
ビデオCD

INTRODUCTION

An entire city block destroyed by fire, Chuo Ward.

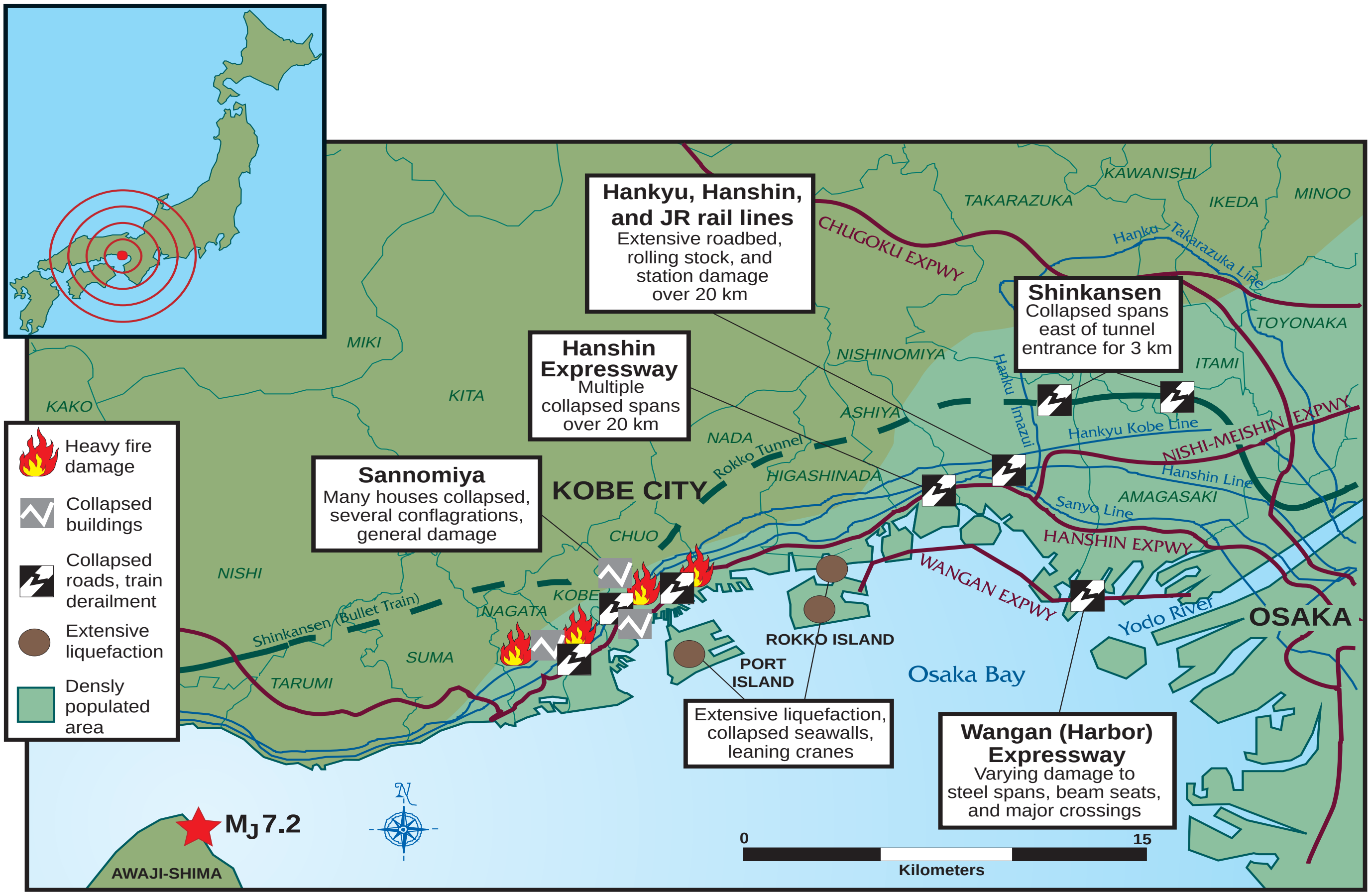
On Tuesday, January 17, at 5:46 A.M. local time, an earthquake of magnitude 7.2 (M_j)[1] struck the region of Kobe and Osaka in south-central Japan. This region is Japan's second-most populated and industrialized area, after Tokyo, with a total population of about 10 million. The shock occurred at a shallow depth on a fault running from Awaji Island through the city of Kobe, which in itself has a population of about 1.5 million. Strong ground shaking lasted for about 20 seconds and caused severe damage over a large area.

Nearly 5,500 deaths have been confirmed, with the number of injured people reaching about 35,000. Nearly 180,000 buildings were badly damaged or destroyed, and officials estimate that more than 300,000 people were homeless on the night of the earthquake.

The life loss caused by the earthquake was the worst in Japan since the 1923 Great Kanto Earthquake, when about 140,000 people were killed, mostly by the post-earthquake conflagration. The economic loss from the 1995 earthquake may be the largest ever caused by a natural disaster in modern times. The direct damage caused by the shaking is estimated at over ¥13 trillion (about U.S.$147 billion). This does not include indirect economic effects from loss of life, business interruption, and loss of production.

Damage was recorded over a 100-kilometer radius from the epicenter, including the cities of Kobe, Osaka, and Kyoto, but Kobe and its immediate region were the areas most severely affected. Damage was particularly severe in central Kobe, in an area roughly 5 kilometers by 20 kilometers parallel to the Port of Kobe. This coastal area is composed primarily of soft alluvial soils and artificial fills. Severe damage extended well northeast and east of Kobe into the outskirts of Osaka and its port.

1. Based on the Japan Meteorological Agency (JMA) magnitude scale, roughly equivalent to a moment magnitude (M_w) of 6.9.



Top: Map of the Kobe area.

Bottom: One of hundreds of collapsed buildings throughout central Kobe.

Opposite, top: Collapsed portion of the Hanshin Expressway.

Opposite, bottom: Search party investigating a collapsed residential wood-frame building, Nada Ward.

Our experience with many past earthquakes in developed, industrial areas is that the media, particularly television, can present an exaggerated image of the damage by concentrating on the few spectacular collapses that occurred. The actual damage in Kobe and the surrounding region, however, was much worse than the media could convey, because it is very difficult to show more than local damage at one time. For example, images of the main, 550-meter-long collapsed section of Kobe's elevated Hanshin Expressway were ever-present throughout the media, but that collapse was only a small fraction of the losses to the area's highway system.

Central Kobe, according to many older residents and our investigators, presented the image of a war zone, with a large percentage of both commercial and residential buildings destroyed.

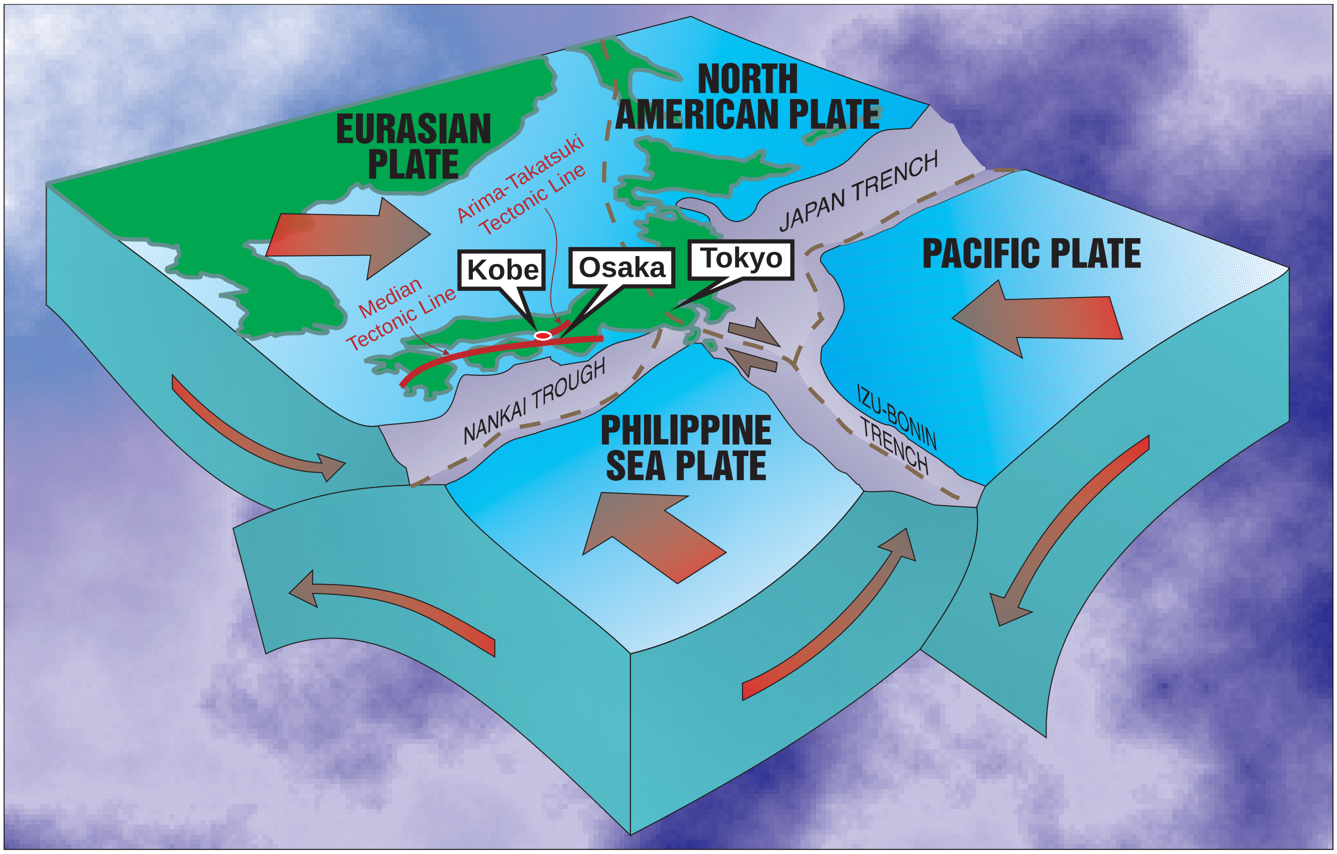
All of this happened in about 20 seconds.

Top left: Self-defense troops performing a search and rescue operation at a collapse site.

Top right: Many streets were blocked by collapsed buildings, hindering emergency response.

Bottom: This man is hauling water. Nine days after the earthquake, 367,000 households were still without water.

EARTH SCIENCE ASPECTS



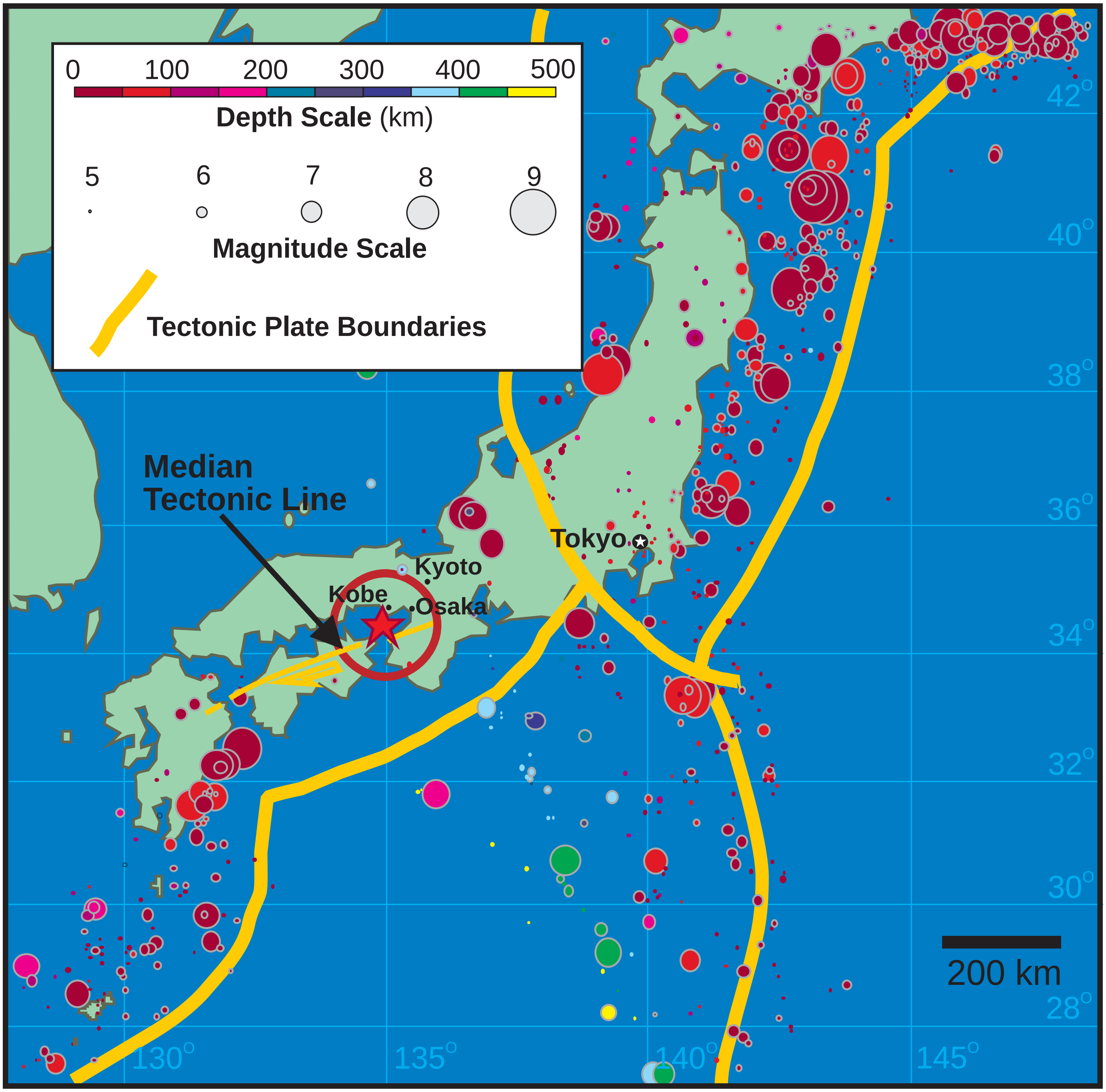
The causative plate action.

Southwestern Japan is located on the southeastern margin of the Eurasian Plate, where the Philippine Sea Plate is being thrust (subducted) beneath the Eurasian Plate in a northwest direction along the Nankai Trough. A portion of this relative plate motion is taken up by right-lateral strike-slip faulting along a major east-northeast-trending fault known as the *Median Tectonic Line* (MTL), located immediately south of Awaji Island and Osaka Bay.

The main shock occurred along a northwest-trending branch of the MTL called the *Arima-Takatsuki Tectonic Line* (ATTL). This fault system, like the MTL, has a predominantly right-lateral strike-slip sense of displacement. Historically, this region has seen somewhat lesser seismicity than in the Tokyo area and some other parts of Japan, but has had magnitude 7 or greater events in historical times (e.g., in 1596). In 1916, a magnitude 6.1 earthquake occurred at almost the same epicentral location as the 1995 event.

In the Kobe area, cretaceous granites are overlain by a relatively thick Plio-Pleistocene sedimentary unit called the *Osaka group*, which consists of alluvium interbedded with marine clays. Relatively thin terrace deposits and recent alluvium overlie the Osaka group. Fill material has been placed along much of the waterfront and comprises human-made islands, such as Port and Rokko islands.

Preliminary reports from the Japanese Earthquake Research Institute indicate that the hypocenter of the M_j7.2 (equivalent to M_w6.9) main shock occurred at a depth of approximately 15 to 20 kilometers. The main shock's focal mechanism indicates predominantly strike-slip movement along a plane that dips 80° to 90° to the southwest. The aftershock sequence (and, by inference, the faulting below the surface) is approximately 60 kilometers long, extending from the northern part of Awaji Island along the Nojima Fault to northeast of Kobe along the Rokko Fault zone.



Japanese earthquakes, 1961-1994.

Relative Seismicity of Japan

Immediately following the earthquake, much speculation in the media attempted to place in perspective the seismicity of Japan, particularly with respect to California. Various Japanese sources also professed surprise that the earthquake occurred in the Kobe area, which had not been struck by a truly devastating earthquake since 1596.

All of Japan lies in one of the most seismically active regions of the world, with all heavily populated areas subject to strong earthquakes. The island nation is surrounded by major offshore faults and is crisscrossed by many active faults, one of which, the Nojima Fault, ruptured in this event. The last similar earthquake to cause severe damage and comparable life loss was the 1948 M7.0 Fukui Earthquake, which was located near the city of Fukui, some 175 kilometers to the northeast of Kobe. Since 1948, Japan has been relatively fortunate because none of the 12 earthquakes greater than M6.9 during this period were centered in a densely populated area or very close to a major urban area.

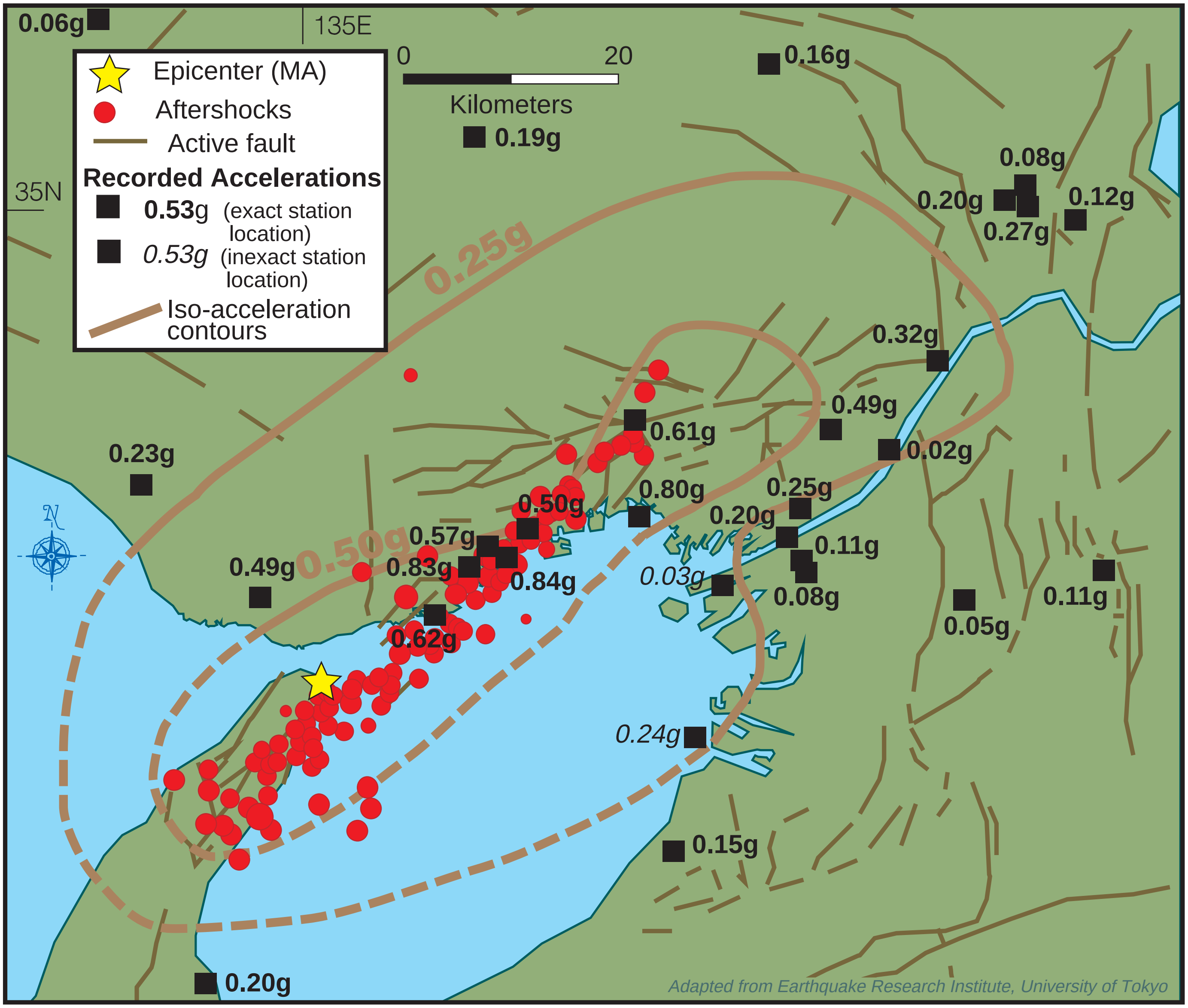
California, with a land area approximately equal to that of Japan but with a population of approximately 25% of Japan's (31 million versus 125 million), has recently been more seismically active, with three recent earthquakes of magnitude 6.5 or greater centered in heavily populated areas—the M7.1, 1989 Loma Prieta (San Francisco Bay Area); the M6.7, 1994 Northridge (Los Angeles); and the M6.6, 1971 San Fernando (Los Angeles area) earthquakes. The recent Northridge event was centered in the heavily populated, by California standards, San Fernando Valley.

In comparing the relative seismicity of Japan with California and the rest of the world, it is important to limit the types of events considered to those that are potentially damaging. Very deep events (i.e., deeper than 60 kilometers) are typically nondamaging. Therefore, the comparison shown below is based on shallow events, less than 60 kilometers deep, for corrected magnitude (M_s) equal to or greater than 7.0. The data are for the period of 1900 to 1989 (90 years) (Reference 1). For California (and western Nevada), the data are based on Reference 2 and are directly comparable to the world data for events with magnitudes equal to or greater than 6.0.

The number of shallow and potentially damaging earthquakes (M5 to M8.9) in Japan is about a factor of 6 to 7 greater than in the California region. Japanese earthquakes represent about 6% to 7% of the world's potentially damaging shallow earthquakes.

RELATIVE SEISMICITY OF JAPAN

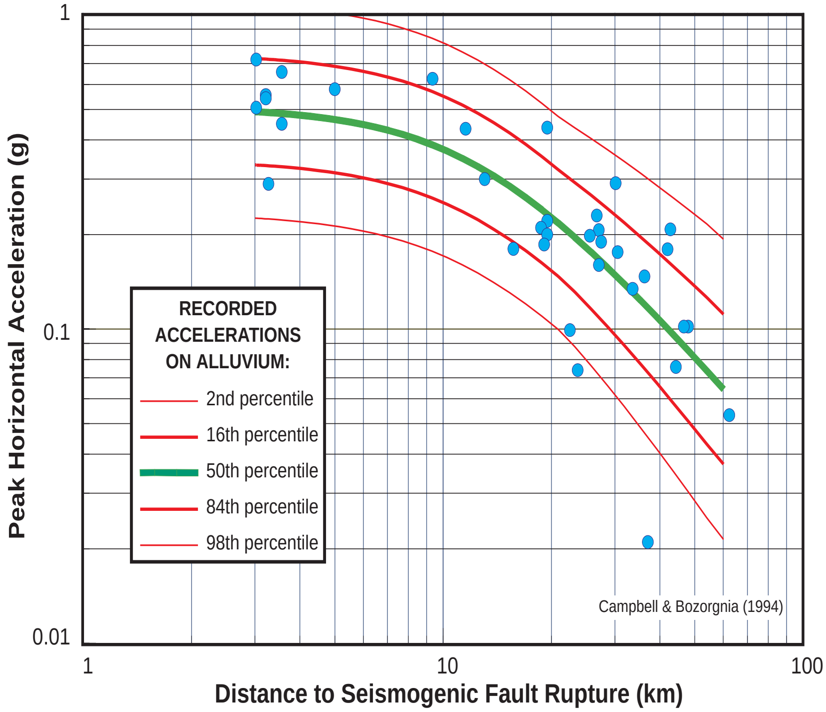
RICHTER MAGNITUDE	AVERAGE NO. OF SHALLOW EARTHQUAKES IN 90 YEARS: WORLD	CALIFORNIA AND W. NEVADA	JAPAN
8.0 - 8.9	45	1	4
7.0 - 7.9	775	7	45
6.0 - 6.9	7,100	75	450
5.0 - 5.9	70,000	730	4,500



Ground motion map.

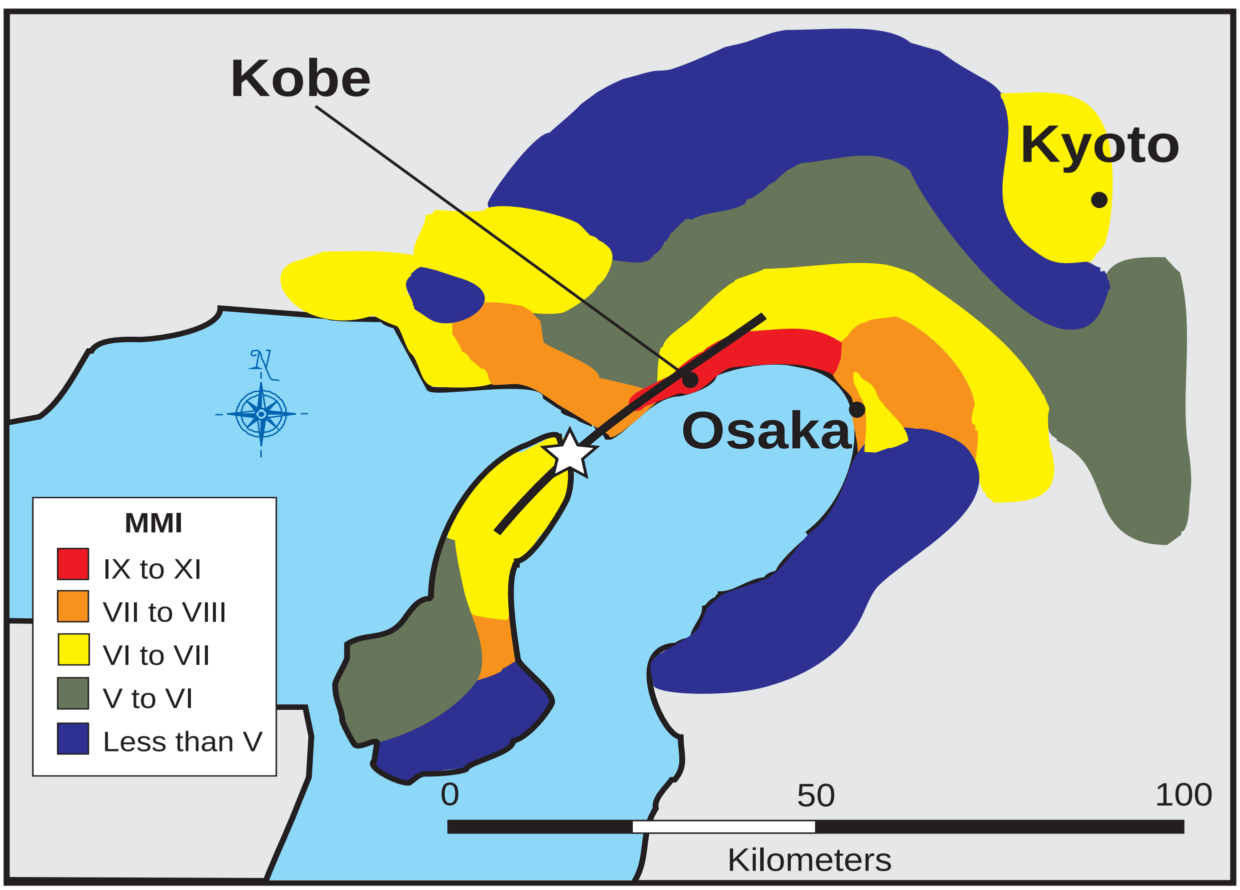
An approximately 9-kilometer-long surface fault rupture was identified along the Nojima Fault, which is on the northwestern coast of Awaji Island and southwest of Kobe. The fault strikes N40°W, dips steeply to the southeast, and has a predominantly right-lateral strike-slip sense of displacement consistent with the mechanism of the main shock and the trend of the aftershocks. Geomatrix Consultants (a geotechnical firm) measured local displacements at two locations along the northern part of the fault from the recent earthquake: Vertical displacements were 1.2 meters, and right-lateral displacements were 1.5 meters. These displacements are in good agreement with measurements by others, who reported maximum vertical displacements of about 1.2 meters and right-lateral displacements of 2.1 meters. Past surface-faulting events, which are probably similar to the most recent event, were evidenced by the 6- to 7-meter-high fault scarp along the fault. Given a long-term slip rate of 1 millimeter per year for the ATTL, as listed in "Active Faults in Japan: Sheet Maps and Inventory by the Research Group of Active Faults," and an average displacement of about 1 to 1.5 meters, as suggested from observed displacement on the Nojima Fault, it appears that an earthquake roughly the size of the Kobe shock occurs on average once every 1,000 to 1,500 years along this portion of the ATTL.

It is unknown whether the surface fault rupture extended to the northeast across the Akashi Strait and onland to connect with



Top: Comparison of Kobe Earthquake strong ground motion data with predictions from Campbell and Bozorgnia (1994) indicates that the Kobe strong motion was typical.

Bottom: Generalized Modified Mercalli Intensity (MMI) map for the January 17 event.



faults in the Kobe-Nishinomiya area. Equivocal evidence of surface faulting has been described in this area and apparently is consistent with the aftershock sequence, which is approximately 60 kilometers long and extends northeast of Kobe. Based on empirical data of earthquake magnitude versus surface fault length, a 9-kilometer-long surface rupture should yield only an M_w6.2 earthquake, whereas a 60-kilometer-long rupture should yield an M_w7.1 earthquake, which is more consistent with the observed magnitude for this earthquake.

A shaking intensity of up to 7 on the JMA intensity scale [equivalent to X to XI on the Modified Mercalli Intensity (MMI) scale] has been assigned to the coastal strip extending from the Suma Ward to Nishi-nomiya and in the Ichinomiya area on Awaji Island; JMA 5 (MMI VII to VIII) to Iwakuni, Hikone, Kyoto, and Toyooka; and JMA 4 (MMI VI) to Nara, Okayama, Osaka, Takamatsu, Shikoku, and Wakayama. The distribution of maximum horizontal ground accelerations and velocities recorded in the Kansai area is shown on page 8. This figure was modified from a map provided by the Earthquake Research Institute, University of Tokyo. The map has been augmented with additional acceleration and velocity recordings reported by the Committee of Earthquake Observation and Research in the Kansai Area. The maximum horizontal accelerations are those reported by several different agencies and represent either the maximum of the two peak horizontal accelerations or the vectoral combination of the two horizontal components. A maximum acceleration of 0.84g (g equals 981 cm/s/s) was reported in central Kobe, and several recordings in the range of 0.5g to 0.8g were reported in the heavily damaged Kobe-Ashiya-Nishinomiya area.

Parking lot on reclaimed land near Ashiya. Sand covering the lot is evidence of large-scale liquefaction and sand ejection.

A preliminary estimate of the 250 cm/s/s (0.25g) and 500 cm/s/s (0.51g) iso-acceleration contours is overlain on the map on page 8. The contours show a distinct bulge toward the northeast, indicating that ground motions were higher northeast of the epicenter in the direction of rupture propagation principally because of source directivity (i.e., focusing). The 250 cm/s/s contour does not extend as far as Osaka, which is consistent with the lower intensity (JMA 4) reported for this area. It is interesting to note that the maximum accelerations in the Kyoto area are similar to those in the Osaka area, even though the former was reported to have a JMA intensity of 1 unit higher.

A comparison of the recorded maximum accelerations with predictions for an M_w6.9 strike-slip earthquake (page 9) indicates that the accelerations recorded during the earthquake are generally consistent with, though possibly slightly higher than, those recorded worldwide during other major strike-slip earthquakes of similar magnitude. The maximum accelerations are also similar on average to those recorded during the 1994 M_w6.7 Northridge, California, Earthquake. This comparison, along with other structural and geotechnical information that is available, would seem to suggest that the greater damage and the larger numbers of deaths, casualties, and homeless sustained during the Kobe Earthquake were likely caused by the aggregated effects of an extremely dense population, an older building stock, and the predominance of poor soils in the strongly shaken area.

Failed quay wall in Nishinomiya. Lateral spreading and settlement of fill material have pushed the wall to the right. Note the backhoe for scale.

Liquefaction and Other Ground Failures

The earthquake caused extensive ground failures, which affected buildings, underground infrastructure, the port, highways, all types of other facilities on soft or filled ground, and recovery efforts.

Ground failures occurred primarily because of *liquefaction*, the result of loose, water-saturated sand being shaken during an earthquake and assuming a semiliquid state. The areas affected by liquefaction were more heavily developed than any other earthquake-stricken region to date. Therefore, the lessons are valuable and will enhance our knowledge of liquefaction for both natural soils and reclaimed lands with high water tables.

The affected areas were located primarily along the coastline and the numerous watercourses in the general area of Kobe and the valleys between Kobe and Osaka. Widespread liquefaction, over many square kilometers, occurred around Kobe, Ashiya, Nishinomiya, Amagasaki, Osaka, Sakai, Izumiotsu, Kishiwada, and other areas around Osaka Bay. Massive liquefaction and lateral spreading took place in areas of reclaimed land and on the many artificial islands in the city of Kobe and Nishinomiya. Ejected sand from liquefaction covered much of the islands and interfered with rescue and recovery operations.

Similar effects were observed throughout the Kobe mainland along the coast, including parts of downtown. Typically, as in downtown Kobe, settlement and liquefaction of less than 50 centimeters were observed. That increased to as much as 3 meters along the coastline. The settlement caused severe damage to underground utilities, severing all services (gas, water, sewage) to large parts of the mainland and to all reclaimed islands, including the largest islands—Rokko and Port. A month after the earthquake, these services had largely been restored to Rokko and Port islands.

The most obvious and destructive liquefaction and related lateral spreading of soils

Human-made island in Nishinomiya showing evidence of large-scale liquefaction, settlement, and lateral spreading.

and settlement occurred along the dozens of kilometers of seawalls along the port. Lateral spreading on the order of 3 (or more) meters and vertical settlement of 2 to 3 meters were observed along the seawalls of numerous islands, including Port and Rokko islands, and throughout the Port of Kobe. The largest settlements, and worst damage, seemed to be associated with the older reclaimed lands, such as the older parts of the port. The newer, engineered fills performed somewhat better than did the old fills, but with less than adequate results.

Numerous buildings on reclaimed land tilted because of ground settlement. These were primarily older, heavy concrete, industrial buildings, probably on mat foundations. The majority of industrial and other buildings on fill were supported on piles (most of these were lighter steel buildings). Most pile-supported buildings appeared to perform well; many multistory or large pile-supported buildings in areas where extensive liquefaction (and limited lateral spreading) occurred had little or no damage. Typically, the sidewalks of such buildings would settle 50 centimeters or more, but there would be no apparent damage to the buildings themselves. The same was generally true for newer highway structures supported on piles. However, the strong shaking may have exceeded the capacity of many pile foundations supporting elevated expressway and bridge piers, causing tilting or lateral movements (observed to be as much as 2 meters) of the piers. This often contributed to damage or collapse of the superstructures.

References

1. Pacheco, J. F., and L. R. Sykes. 1992. "Seismic Moment Catalog of Large Shallow Earthquakes, 1900 to 1989." *Bulletin of the Seismological Society of America,* Vol. 82: 1306-1349.

2. Ellsworth, W. L. 1990. "Earthquake History, 1769 - 1989." In *The San Andreas Fault System, California.* R. E. Wallace, ed. U.S. Geological Survey Professional Paper 1515: 153-187.

BUILDINGS

This collapsed concrete building in Kobe completely blocked the street.

The number of buildings destroyed by the earthquake exceeds 100,000, or approximately one in five buildings in the strongly shaken area. An additional 80,000 buildings were badly damaged. The large numbers of damaged traditional-style Japanese residences and small, traditional commercial buildings of three stories or less account for a great deal of the damage. In sections where these buildings were concentrated in the outlying areas of Kobe, entire blocks of collapsed buildings were common. Several thousand buildings were also destroyed by the fires following the earthquake.

Mid-rise commercial buildings, generally 6 to 12 stories high, make up a substantial portion of the buildings in the Kobe business district. The highest concentration of damaged mid-rise buildings was observed in the Sannomiya area of Kobe's central business district. In this area, most of the commercial buildings had some structural damage, and a large number of buildings collapsed on virtually every block. Most collapses were toward the north, which was evidently the result of a long-period velocity pulse perpendicular to the fault. This effect has also been observed in other earthquakes. Failures of major commercial and residential buildings were noted as far away as Ashiya, Nishinomiya, and Takarazuka. In general, many newer structures performed quite well and withstood the earthquake with little or no damage.

In the heavily damaged central sections of downtown Kobe, approximately 60% of the buildings had significant structural damage, and about 20% completely or partially collapsed. One survey of a 120,000-square-meter area in downtown Kobe (the Sannomiya area) found that 21 out of 116 buildings, or

Top left: Badly damaged concrete shear wall building.

Top right: Ground settlement in central Kobe.

Bottom: Mid-height collapse of a mixed-use building (built circa 1977) in Nishinomiya. This type of collapse was very common in this earthquake.

The ruins of the Ginza after the 1923 Great Kanto (Tokyo) Earthquake and fire.

18%, were visibly destroyed. Another report indicated that 22% of office buildings in a portion of the Kobe city center were unusable, while an additional 66% may need more than six months for complete restoration. City inspectors declared approximately 50% of the multifamily dwellings in Kobe as unsafe to enter or unfit for habitation, leaving more than 300,000 people homeless.

Age of construction, soil and foundation condition, proximity to the fault, and type of structural system were major determining factors in the performance of structures. Damage was worst in the areas bordering the port or streams and rivers—where soils were either poorly consolidated alluvial deposits or fill—and tended to be relatively minor in the foothills of Rokko Mountain, where either soils are very shallow or there are rock outcroppings. Loose and soft soils amplify ground motions in comparison to bedrock, especially ground motions within a certain frequency range. The duration of shaking also tends to be longer on such soils.

Structural damage directly resulting from soil failures was observed for smaller buildings without pile-supported foundations, but it did not appear to be the dominant problem for mid- and high-rise structures supported on piles that extended into dense soils or rock. Although hidden damage may be discovered at a later date, the performance of piles appeared to be good as long as substantial lateral soil displacement did not occur.

A survey of 24 commercial buildings being demolished in the central Sannomiya area of Kobe two months after the earthquake found the following breakdown of building types: 70% were frame type, 20% were shear wall type, and 10% were braced frame type. The breakdown of the frame-type structures included 50% nonductile concrete frame, 35% steel reinforced concrete (SRC) frame, 10% moment-resisting steel frame, and 5% steel frame with masonry infill. Of the shear wall buildings being demolished, 75% were concrete and one was unreinforced masonry. Several of the buildings being demolished were of multiple construction types.

Building Code

The first building code in Japan was introduced in 1926 after the 1923 Great Kanto Earthquake and ensuing fire devastated

Buildings in central Kobe (Chuo Ward). In the foreground is the complete collapse of a two- or three-story traditional Japanese wood-frame building with a heavy tile roof. On the right is a six- or seven-story office building of 1960s' or 1970s' vintage. This reinforced concrete building is a typical example of a mid-height story collapse. The high rise to the left is a post-1981 office building that has no apparent damage. Ground settlement in the vicinity of these buildings was between 30 and 60 centimeters.

Concrete-frame structure with a mid-story collapse (Flower Road, Kobe).

Tokyo. The regulations have been reviewed and amended several times over the years as the result of damage during subsequent strong-motion earthquakes. Bridge codes and codes for civil-engineering-type structures (e.g., quay walls) have undergone similar changes over the years.

Since the 1926 code, Japan's seismic codes have typically been as advanced as any in the world. Japanese engineers upgraded their standards after the 1968 Tokachi-oki Earthquake in northern Japan and California's 1971 San Fernando Earthquake. In the early 1980s, laws and orders concerning seismic design methods for buildings were extensively revised. The current Japanese seismic provisions are specified in the Building Standard Law Enforcement Order by the Ministry of Construction (1981), and in the Standards for Seismic Civil Engineering Construction in Japan (1980). During the period between 1971 and 1980, some lessons learned in previous earthquakes were included in the design of major buildings, even though the requirements were not yet codified.

In the last several years, U.S. and Japanese professionals have been working together to understand seismic performance and to upgrade codes. Direct comparison of the codes for the two countries is difficult because of their different formats; however, comparative studies have suggested that newer Japanese mid- and high-rise buildings are comparable to or somewhat stronger than their counterparts in the United States.

The current design philosophy in Japan is to keep seismic stresses within the elastic (non-damaging) range for earthquakes that can be expected to occur once or twice (moderate earthquakes) during a building's life span, and to prevent collapse for larger, less frequent earthquakes. This means that for a moderate earthquake, the building is expected to have little or no damage. A similar philosophy is used in the United States, although, in general, more damage is considered acceptable for moderate-sized earthquakes.

Buildings are divided into four general types in the current Japanese code. In general, the guideline is: the larger the building, the more engineering and attention to quality of the seismic-force-resisting system required.

- *Small buildings*

  - For small, one- or two-story wood buildings and one-story buildings of other construction types, prescriptive construction requirements apply, and no explicit design is required. A similar practice is applied to wood-frame houses in the United States.

- *Buildings less than approximately 30 meters high*

  - For buildings with a regular configuration, prescriptive requirements apply. Additionally, a comparison of calculated and permissible stresses for the loads associated with a moderate earthquake (0.2g peak ground acceleration) must be made.

- Irregularly shaped buildings are checked using the same requirements as for regular buildings. In addition, calculated drift (horizontal deflections) must be compared with allowable drifts, and the engineer must either (1) limit configurational irregularities, and meet minimum member size and detailing requirements that vary with construction material type, or (2) check the ultimate strength at each floor level versus the demands for a severe earthquake (1.0g peak ground acceleration). The demands for a severe earthquake are amplified for structures with large configurational irregularities, and reductions in demand are made to account for the ductility of the construction type. Note: Many Japanese buildings are quite irregular in their configurations when compared to U.S. buildings, which makes them much more difficult to design for earthquakes.

Steel buildings less than 13 meters high can be checked as regular buildings if the assumed moderate earthquake forces are amplified by 50%, and if the connections for the braces and the frames are designed to be stronger than the braces, columns, and beams.

Concrete buildings less than 20 meters high can be checked as regular buildings if they have a minimum combined shear wall and column area at each story. (For larger buildings, the minimum combined areas must be checked for each story in each direction.)

- *Buildings between the approximate heights of 30 and 60 meters*

  - These buildings are treated in the same manner as are irregular buildings under 30 meters high, except that an ultimate strength check at each floor level for a severe earthquake is required.

- *Buildings more than approximately 60 meters high*

  - These buildings require special permission from the Ministry of Construction, and a dynamic (computer) analysis must be performed for the severe earthquake scenario. In practice, these buildings are subjected to nonlinear analysis techniques. Peer review is also required.

Undamaged reinforced concrete school in the Rokkomichi area. The building was used as a refuge center in the weeks following the earthquake.

Modern parking garage in central Kobe (Chuo Ward). The building was undamaged. The structural system includes steel moment-resisting frames and concrete shear walls.

It appears that, in general, buildings (other than smaller buildings) constructed using the above provisions of the current code performed well in the earthquake and protected life safety. However, a number of newer buildings, including high rises, were severely damaged and more damage may be uncovered as buildings are carefully evaluated. Structures that did poorly included older houses and smaller commercial buildings (both concrete and steel), and mid-rise concrete structures designed and constructed prior to the early 1980s using the same nonductile details that had been employed in high-seismic U.S. regions up until the early 1970s.

Reinforced Concrete-frame Buildings

Many of the mid-rise structures in Kobe were reinforced concrete-frame buildings of two types: The older ones were of nonductile concrete frame and the newer ones were of SRC frame.

Dozens of reinforced concrete commercial buildings partially or completely collapsed at one or more floor levels. Typically, the buildings were 6 to 12 stories tall, and the failure often occurred within the middle third of the building height. One possible contributing factor was that the period of the strong ground motion pulses may have been in a range that generally coincided with higher vibration modes for these buildings. This would have tended to amplify stresses in the middle portion of the buildings.

Another possible factor was that there were changes in building strength or stiffness at these levels. For example, if shear walls or the steel columns encased in concrete that extend up from the foundation discontinue at a floor level, the strength and/or stiffness of the structure above that floor may be significantly less than at the floor below.

The pre-1981 code required that a concrete-frame building exceeding six stories in height have SRC construction for the lower six stories as a minimum, although those buildings for which EQE engineers reviewed drawings always used SRC throughout the building height. The older code also specified design lateral loading that is more uniform over the height of the building, instead of having amplified forces near the top and reduced forces at the bottom, as is currently the practice in

Kobe City Hall, Sannomiya District. In the foreground is the old City Hall with a mid-story collapse. Behind it is the new City Hall, which exhibits signs of only minor damage.

Japan and the United States. The older code's practice results in weaker upper stories.

Instances of concrete structures with collapses or failures in the bottom (ground) floor were also fairly common. These failures typically resulted from soft or weak stories created by the need for garages and the desire to have numerous large open windows for storefronts at the bottom floor. The high land costs and general congestion in Japan exacerbate this problem. Very narrow multistory buildings with open storefronts are very common. Irregular distribution of shear walls or concrete frames resulted in substantial torsion, causing the structure to twist as well as sway due to earthquake loading.

The damage mode most commonly observed was a brittle shear failure of concrete column elements, leading to a pancake collapse of the floor level above. The brittle failures resulted from inadequate reinforcing details. In general, damaged columns were observed to have lateral reinforcing (referred to as *ties*) with relatively large spacings. These ties typically had hooks at their ends that were bent only 90°. Consequently, when the earthquake struck and the concrete cover outside the ties spalled or fell off, ties opened up and could not provide the confinement to the central concrete core. Complete failure quickly followed. Many of the

Top: Mid-height collapse of a concrete-frame building.

Bottom: Soft story collapse of a restaurant in Kobe.

Below: Severely damaged reinforced concrete building with shear walls at Sannomiya Station, central Kobe. The building consists of a relatively simple (structurally and architecturally) upper portion on top of a complex lower portion. Inset: Detail of the shear wall damage at the setback level.

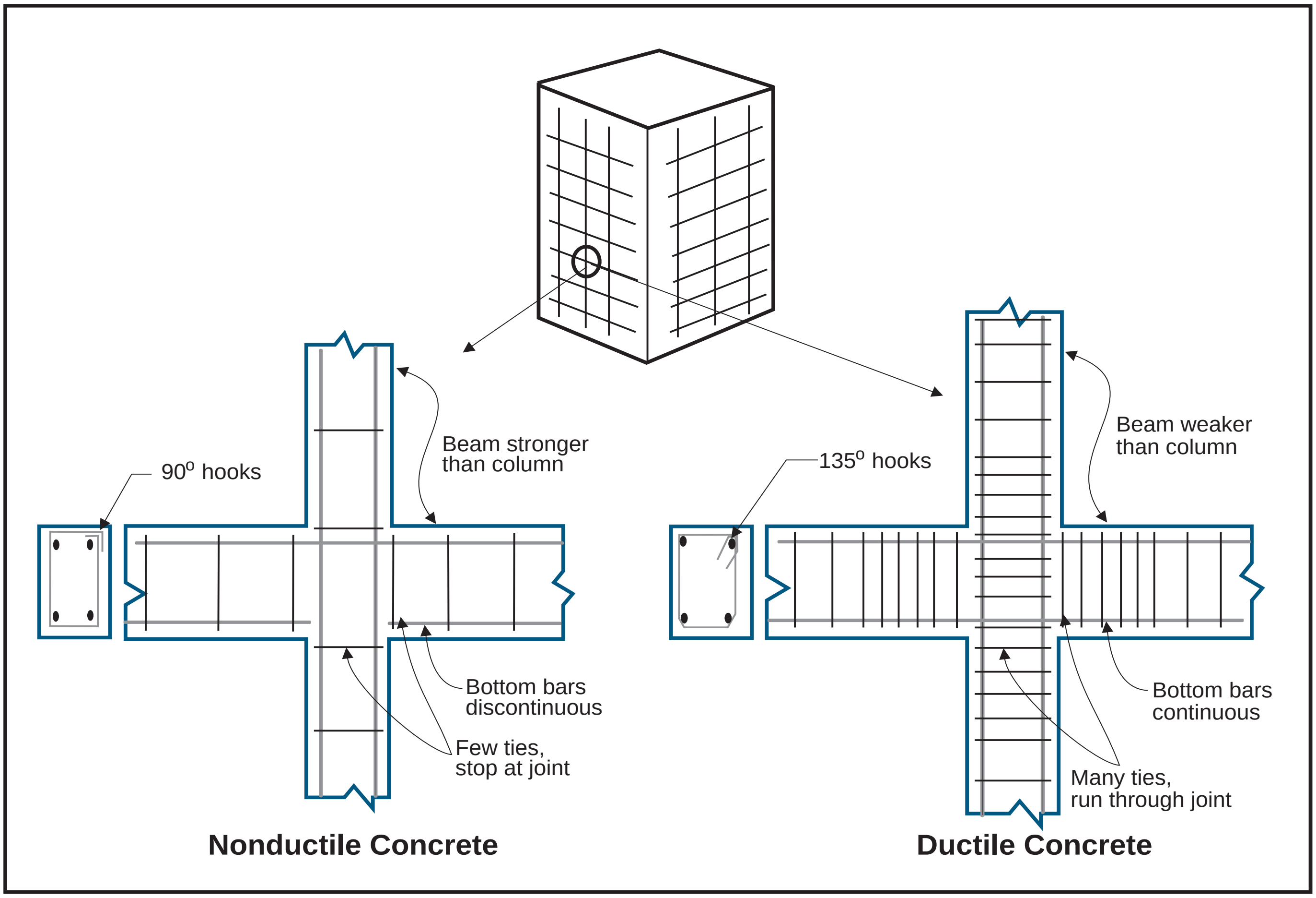


Diagram of typical detailing of ductile versus nonductile reinforced concrete columns.

damaged buildings in Kobe were also constructed with undeformed reinforcing bars.

Similar nonductile concrete construction has been the source of building and elevated highway or overpass collapses in past earthquakes, such as Southern California's 1971 San Fernando and 1994 Northridge earthquakes. Current code requirements include closer and larger ties of deformed steel, 135° hooks that extend into the confined concrete, and cross-ties to supplement the rectangular ties around the perimeter bars. In addition, ties must be closely spaced and extend through the joint created by the beams and columns. Buildings possessing these enhanced detailing features are referred to as *ductile moment frames*. "Ductile" refers to a building's ability to dissipate energy and deform without having brittle or sudden failure. In general, designs produced using the Japanese code tend to result in stronger columns and beams that are detailed in such a way that they have less ductility than do typical U.S. buildings in high seismic zones.

Hundreds of thousands of existing buildings of similar nonductile construction are present in seismically active areas throughout the world. Unless these buildings are retrofitted, many lives will be needlessly lost in future major earthquakes.

Reinforced Concrete Shear Wall Buildings

Many concrete shear wall buildings were severely damaged, and some had partial collapses. Many of these were multifamily residential structures where the shear walls had severe cracking, and horizontal displacements occurred at construction joints. One mid-rise concrete shear wall structure overturned and fell into the street. Some of the damaged structures had concrete walls in one direction only, and it appeared that the

Top: Mid-story collapse of one wing of a Kobe hospital.

Bottom: Interior of a badly damaged reinforced concrete building.

concrete frames had initially failed and allowed deformations, which caused damage to the shear walls in their weak or out-of-plane directions.

Failures of shear walls often led to permanent offsets of one floor relative to the next. This, in turn, led to damage of the frame columns. It is not clear whether the walls in these buildings were intended to function as the primary lateral-load-resisting elements, or whether they were intended to share this function with the reinforced concrete frames.

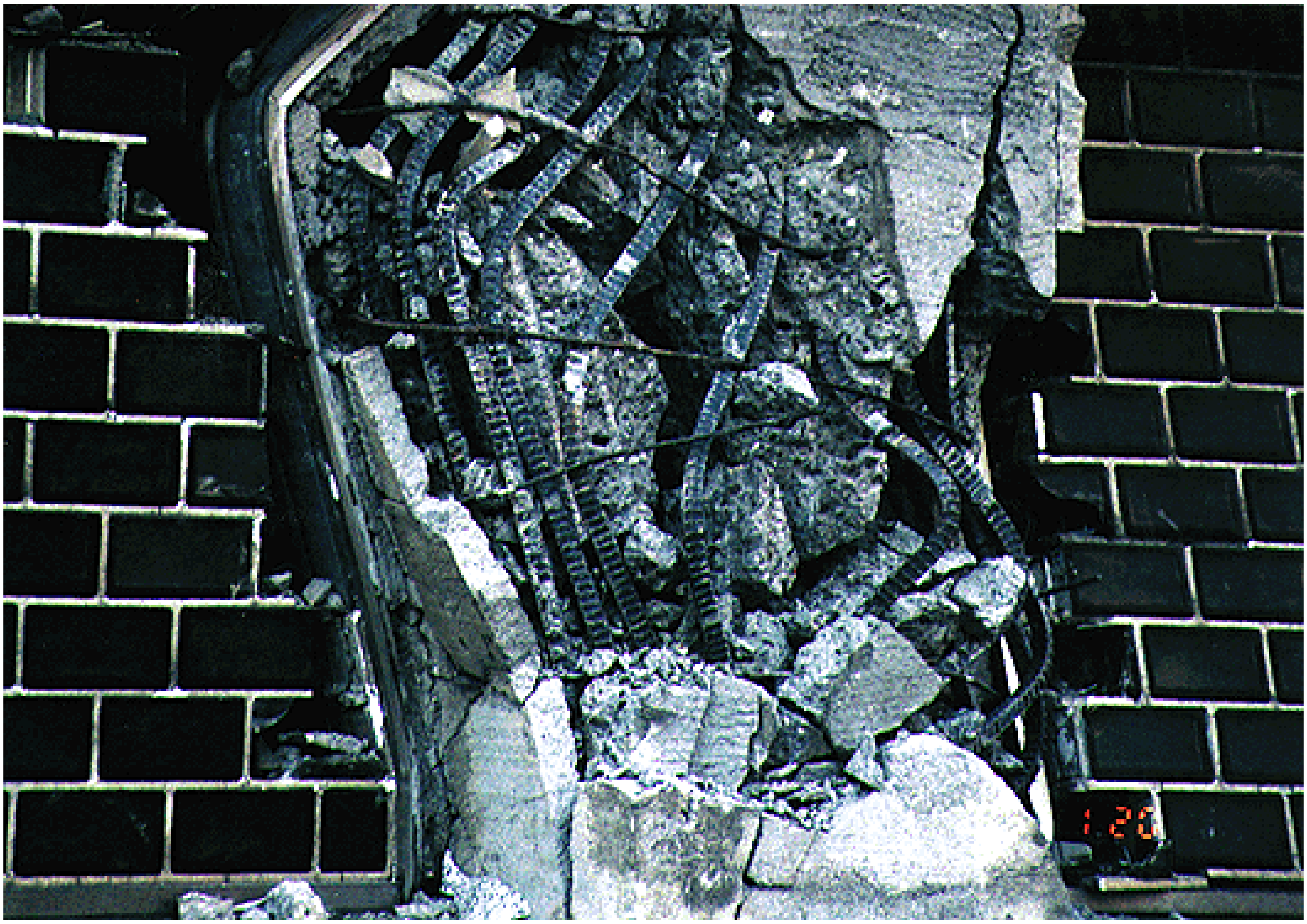
Again, the most severely damaged buildings generally appeared to be of older construction, dating from about 1950 to 1980. Newer structures with configurations that were not too irregular and did not have soft stories appeared to perform relatively well, generally ensuring the life safety of occupants.

Many severely damaged shear wall buildings, including newer buildings, had unusual configurations by U.S. standards. These included dramatically varied architectural details, such as many irregular wall openings for windows, in the lower floors. Such architecture makes it much more difficult (and expensive) to properly design the structural system for earthquakes. Many severely damaged large commercial buildings had mixed-use occupancies—for example, stores in the lowest three floors and offices above. Typically, the failures occurred in the lower stories where the structural framing was more irregular in order to accommodate large, clear spaces.

Badly damaged older reinforced concrete building in Sannomiya. Much of the damage is concentrated at structural discontinuities.

Reinforced Concrete-encased Steel-frame Buildings

As previously mentioned, a popular construction type in Japan for the last 25 years is a structural steel-frame building encased in reinforced concrete, termed *steel reinforced concrete* (SRC). Older SRC buildings commonly had solid structural steel elements in the frame connections, but used trusses constructed of smaller rolled steel shapes and plates in the center portions of the members. It appears that SRC construction generally performed better than did the older reinforced concrete-frame buildings; however, story collapses were noted in several SRC buildings. Some of the collapsed buildings thought to be concrete frame may actually be partially SRC. This is due to the requirement in the old code that a building exceeding six stories in height must use SRC in the lower six stories, but can use reinforced concrete framing in the upper stories. That results in a large stiffness and strength irregularity at the seventh floor. In newer construction of this type, the horizontal ties in the concrete encasement around the steel shapes are generally spaced closer together, and the newer structures tended to perform better.



Top: Badly damaged reinforced concrete column. Note the heavy longitudinal reinforcement, with scant shear reinforcement.

Bottom left: The two buildings in the foreground look similar, but their diverse performance indicates that they are probably structurally dissimilar. They may have been built at different times.

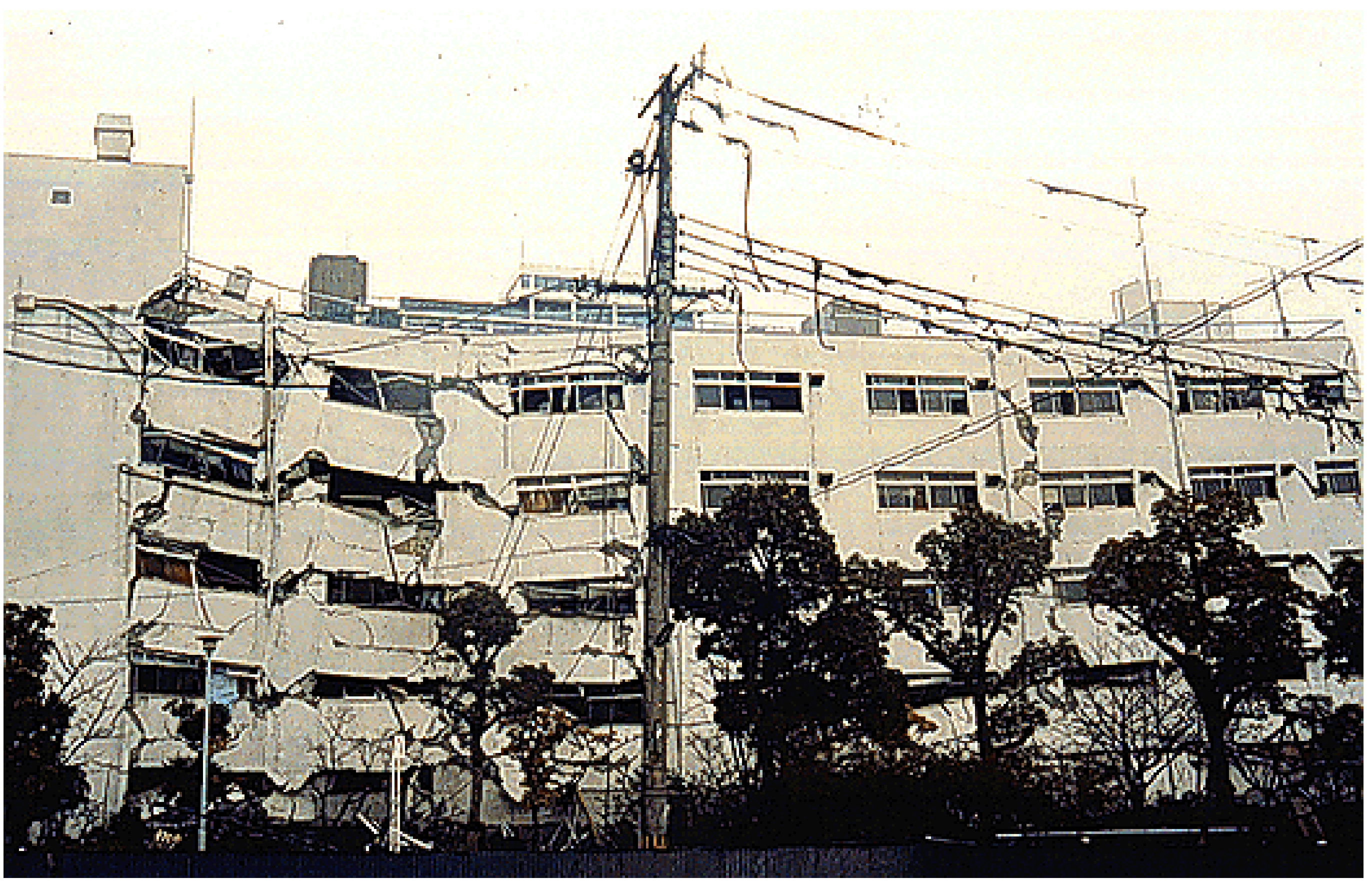
Bottom right: The collapse of this building was so complete that it was impossible to deduce an obvious failure mode.

Steel-frame Buildings

Generally, two types of steel-frame structures were observed, moment frames and concentric braced frames. Many smaller steel-frame structures in the central business district had severe damage or collapsed. In general, such structures appeared to have been minimally engineered. In many cases, these damaged buildings contained relatively light, flat-bar diagonal bracing members within the side walls, which buckled or were fractured at connections. In some cases, light steel moment frames in the front of the building were permanently distorted up to a few meters, causing the buildings to lean dangerously. Fracture of welded connections was observed in several steel-frame buildings in downtown Kobe.

At the Ashiyama Seaside Town, 21 of 52 mid- and high-rise condominium structures built between 1975 and 1979 had severe damage to the structural steel framing. This innovative and unconventional structural system consisted of macro-steel moment frames in which the column and girder members were large steel trusses. Girders were typically located at every fifth floor. Housing units consisted of precast concrete assemblies that had been brought to the site by barge. Damage observed included the brittle fracture of square, tubular columns up to 50 centimeters wide with 5-centimeter-thick walls, and fracturing of steel wide-flange diagonal bracing elements. Residual horizontal offsets in column elements were observed to be as large as 2 centimeters in some cases. In general, it appeared that the brittle fractures had occurred in framing elements subjected to high combined tensile and shear stresses. In one of the units, six of the eight main steel columns forming the lateral-load-resisting system had fractured.

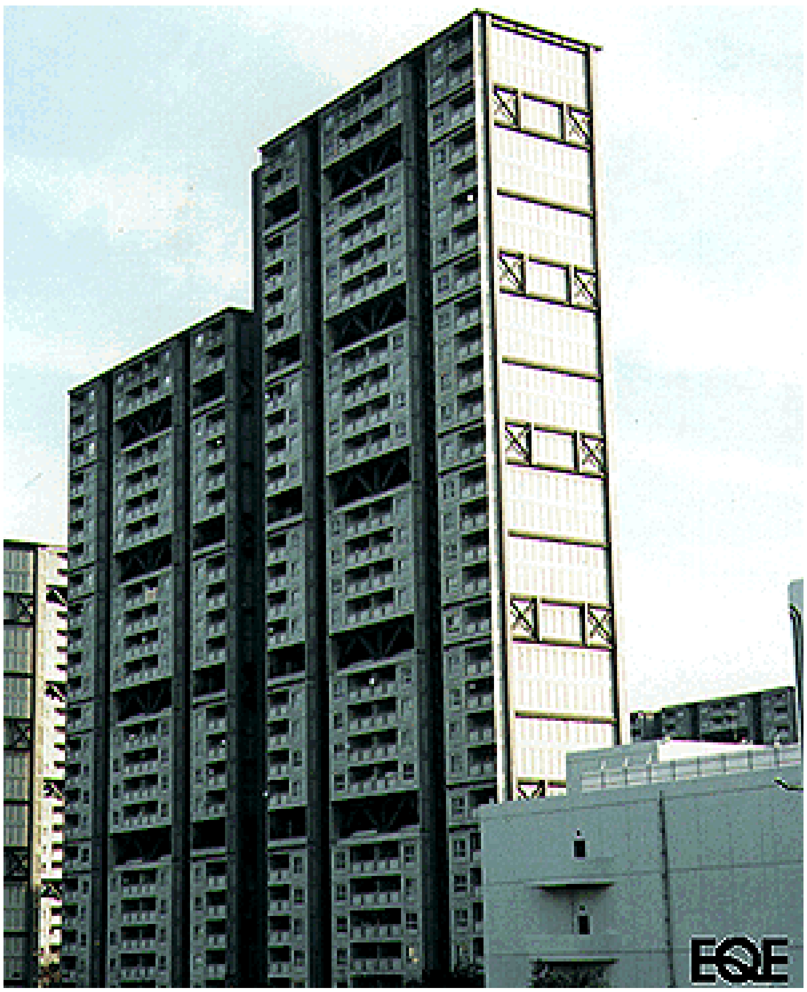
Despite the serious damage to the steel frames, the other elements (including windows) of the buildings did not appear to have significant damage. The steel framing in these



A reinforced concrete building (shear walls in the transverse direction) in Nagata Ward, Kobe. The bottom floor of this building collapsed.

Top: *Overview of the Ashiyama Seaside Town, consisting of steel-frame buildings along the shoreline of Ashiya, across from Rokko Island. The complex was built between 1975 and 1979.*

Bottom: *Typical units at the Ashiyama Seaside Town. Note the steel-truss elements forming a moment frame for the lateral-load-resisting structural system.*



modularly constructed buildings was located on the exterior of the building and was highly visible. In most high-rise steel structures in Japan, however, the framing is hidden by architectural elements and fireproofing. Consequently, there may be many other steel-frame structures where similar damage is present but hidden from view. That is what was observed with more than 140 modern steel-frame buildings in the Los Angeles area after the 1994 Northridge Earthquake. This may have been the reason that several steel-frame buildings with no obvious major structural steel damage were being demolished two months after the Kobe Earthquake.

A common Japanese method of constructing steel moment-frame buildings incorporates shop welding of beam stubs to the columns and field bolting of beam splices, away from zones of large strength demands. This practice has the advantage of allowing improved quality control at critical locations. However, this does not eliminate all the vulnerabilities inherent in beam-column connections, and some fractures like those observed following the Northridge Earthquake were reported. Although this method undoubtedly results in better-quality welds, it does not preclude the type of moment connection damage observed after the Northridge Earthquake.

In general, it appears that design philosophies and techniques used in steel construction in Japan result in structures with higher degrees of redundancy than in the United States. In typical Japanese new steel construction, all of the steel frames in buildings are included in the lateral-load-resisting system, whereas only a selected small number of frames in many structures in the United States have been detailed to resist seismic loads. Similarly, many braced-frame structures in Japan appear to have a large number of smaller braces, whereas in the United States it is common to see a smaller number of large braces. The redundancy provided by the frames and braces results in more locations where energy can be dissipated in a major earthquake. It is expected that such redundancy provides added resiliency for the buildings so constructed, and may have been a contributing factor to the relatively good performance of modern steel structures in the Kobe area.

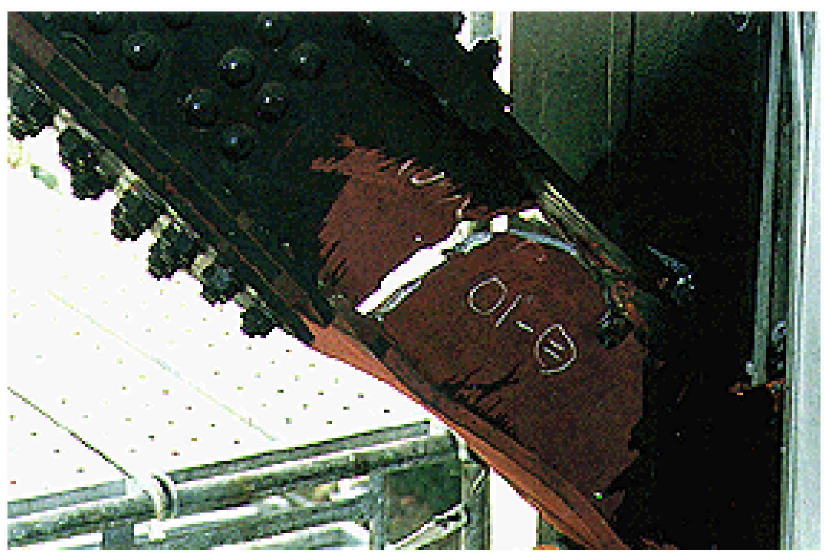
Modern steel high-rise structures appeared to withstand the earthquake with little damage. With the lessons of the 1994 Northridge, California, Earthquake and of the Ashiyama Seaside Town condominium structures, it will not be known how much damage steel buildings actually sustained until more detailed investigations are performed on the structural connections.

Wood-frame Buildings

Most of the heavily damaged wood-frame buildings were traditional one- or two-story residential or small commercial buildings of *Shinkabe* or *Okabe* construction. These buildings normally have very heavy mud and tile roofs (which are effective at preventing typhoon damage), supported by post-and-beam construction. Foundations are often stone or concrete blocks, and the wood framing is not well attached to the foundations. The Shinkabe construction has mud walls reinforced with a bamboo lattice. Okabe construction has thin-spaced wood sheathing that spans between the wood posts and is attached with limited nailing. The exterior plaster is not reinforced with wire mesh or well attached to the wood framing, so it falls off in sheets when cracked. In new (post-1981) construction, nominal diagonal bracing is required to resist lateral loads.

Traditional wood-frame construction had the most widespread damage throughout the region, resulting in the largest number of casualties. Collapses led to the rupture of many gas lines.

Failures in these buildings were typically caused by large inertial loads from the heavy roofs that exceeded the lateral earthquake load-resisting capacity of the supporting walls. The relatively weak bottom stories created by the open fronts typically collapsed.



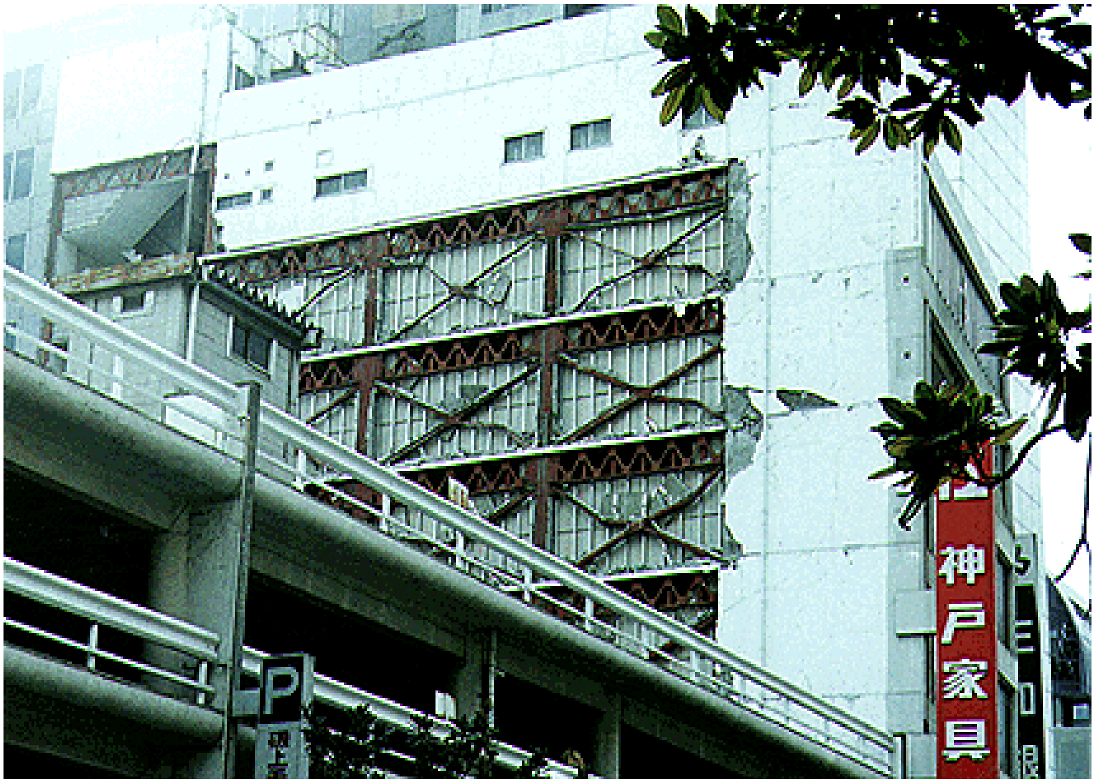
Top: Detail of the truss elements at the Ashiyama Seaside Town. Note the minimal damage to the concrete units. This photo shows the intersection of the vertical and horizontal frames.

Bottom: Fractured web in a diagonal truss element, Ashiyama Seaside Town.

Top right: Severe racking of a steel building in Sannomiya.

Top left: Fractured building column at Ashiyama Seaside Town.

Bottom: Buckled diagonal brace in a parking garage.



Top: Severely damaged steel-frame building in Sannomiya. This building illustrates the practice of bracing multiple bays.

Bottom: Steel buildings in the Nagata Ward. While the frames appear to be in good shape, the cladding was shaken off the building, posing a severe life-safety hazard.

Unlike most U.S. homes, Japanese homes typically have few if any substantive interior partitions to help resist the earthquake loads. In this respect, the bottom stories are similar to the U.S. homes that are supported on unbraced cripple walls.

In older homes, many framing members had been weakened by wood rot. Soil failures exacerbated the damage, because the foundations have virtually no strength to resist settlement, and connections between the residences and their foundations were weak.

The observed damage was reminiscent of that in the Marina District after the 1989 Loma Prieta (San Francisco Bay Area) Earthquake. In the Marina District, bottom stories of old, multistory, wood-frame dwellings were weakened by garage openings and a

Top: A steel building in the Nagata Ward. The building was probably very close to collapsing in the earthquake. High flexibility of the building probably contributed to the failure of the cladding.

Bottom: Collapsed housing was responsible for most of the deaths in the earthquake.

lack of partitions on the ground floor. Entire blocks of homes swayed in one direction, and the corner buildings or houses—which were the weakest because they were open on two sides—were often pushed out into the street.

Impact between buildings occurred often in Kobe's residential areas. This interaction usually involved the lateral collapse of a traditional housing unit impinging upon a neighboring structure. The impact of the heavy roof from one collapsing house often caused the destruction of neighboring buildings that probably would have otherwise survived the earthquake.

The poor performance of these structures did not come as a surprise. Failures of a large number of similar structures have been observed in past earthquakes, including the 1978 Miyagi-ken-oki Earthquake, during which 7,000 homes were destroyed. It was reported that some of the more modern and expensive house construction is similar to that in the United States and includes concrete foundations, wood stud walls, and plywood sheathing. The performance of these structures was much better, although, in general, they tended to be located in the less severely shaken areas (on the hillsides). Newer housing units, namely multistory concrete buildings and prefabricated single-family structures, tended to perform better than did their older wood-frame counterparts. It was common to find single newer structures left standing on otherwise destroyed blocks.

Top: These three-year-old houses collapsed from excessive loads imposed by heavy tile roofs. A similar house on the block with a lightweight roof had minimal damage (see bottom photo).

Typical post-war housing – these houses are probably less than 20 years old. Those units that did not collapse were heavily damaged. Note the very light framing with plaster or plasterboard over it. These buildings typically have very little shear resistance in their walls and very heavy roofs.

Unreinforced Masonry Buildings

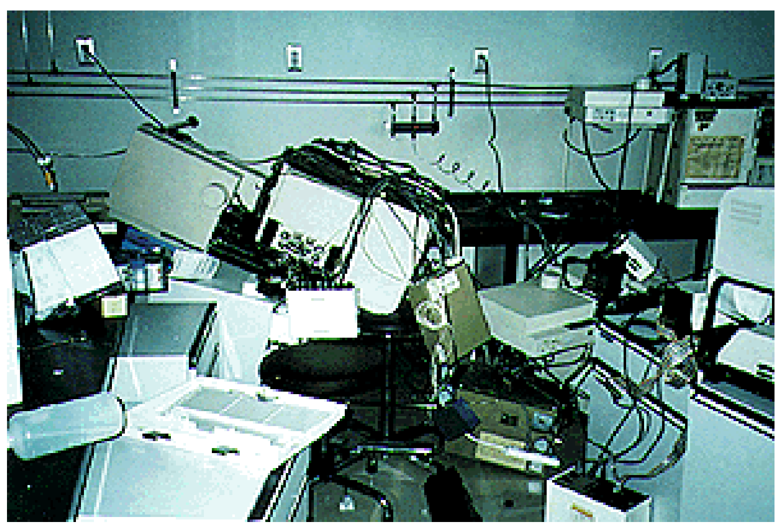
Few unreinforced masonry buildings were observed in the Kobe area. Those that were observed had extensive damage to the masonry walls and partial collapse of floor and roof systems. As could be expected from the performance of similar buildings in past earthquakes, nonbearing gable walls were especially susceptible to damage. Had these buildings been occupied at the time of the earthquake, they would have posed an extreme life-safety hazard to the occupants and to passersby.

Base Isolation

Base isolation is the name given to a technique that reduces the damage and vibration of a structure subjected to earthquake motions by isolating the building from the ground motion through the use of mechanical bearings. These bearings are designed to limit forces transferred from the foundation to the building. There was at least one such base-isolated structure in the Kobe area during the earthquake. This structure was located a significant distance (32 kilometers west of Kobe) away from the area of greatest destruction, and the intensity of shaking near the building's location was not nearly as severe as the level of shaking in downtown Kobe. Nonetheless, the reported data indicate that the base-isolation system worked well, significantly reducing the level of motion in the structure. The peak acceleration (0.10g) on the roof of the six-story isolated structure was reported to be only one-third the level of acceleration of the ground (0.30g). This indicates that the isolation system worked well in the earthquake.

INDUSTRIAL FACILITIES

Somewhere between 3% and 5% of Japan's industry is located in the area of strong ground shaking in and around Kobe. This includes most types of industry—from light manufacturing to high-technology and heavy industry. As in most of Japan, and particularly Tokyo, much of the industry is concentrated near the port on landfill or very recent, soft soils. Due to strong ground motion amplification on soft soils and the extensive ground failures (caused by settlement and liquefaction) in these areas, damage to industry in the Kobe area was severe. Observed failures included extensive damage to large building foundations; all types of industrial buildings, equipment, and equipment systems; fire protection systems; racks; and inventory. The reduced ability to transport raw materials and finished goods to, from, and within the region will also greatly impact industry in the Kobe area. Industries affected include shipbuilding, steel plants, breweries, pharmaceutical firms, computer component manufacturing plants, and consumer goods production facilities.



Structural Damage

Access to industrial facilities in the region was very limited. The EQE team did have access to the facilities of some U.S. and European multinational companies, of which there is a large percentage in Kobe. In those facilities, structural damage was generally minor. Other damage, however, was not.

Top: A heavily damaged steel plant in the Nishinomiya Port area. The most apparent damage was caused when the top third of the concrete stack sheared off. The top portion of the stack plummeted into a neighboring portion of the facility.

Bottom: Damage to unanchored laboratory equipment.

The most severe structural damage, as well as associated damage to exterior storage areas and tank farms, occurred to industrial structures immediately adjacent to wharves and other retaining structures at navigable watercourses and other coastal facilities. Severe damage to industrial structures along shorelines was observed from Nishinomiya to western Kobe. Numerous structures settled more than 2 or 3 meters and were partially or fully submerged in water. Other structures partially collapsed or tilted severely because of foundation failures. Most tilted structures were probably buildings on mat foundations (usually pre-1980s' vintage) without supporting piles.

Wherever there was lateral spreading of soils and retaining structures along the shoreline, extensive damage was observed to tank farms (tank tilting), silos (tilting and collapses), cranes, stacks, and other such structures. Several tall, industrial, reinforced concrete stacks were leaning, and at least one collapsed. The collapsed stack was observed at a steel facility along the waterfront in Nishinomiya. The upper one-third of the stack broke off and embedded into the adjacent building.

Away from the shoreline, structural collapse of industrial facilities was relatively rare compared to the collapses in the housing, transportation, and commercial sectors.

Opposite, top: These sake tanks appear to have survived the complete collapse of the traditional wood-frame building that housed them.

Opposite, middle: These unanchored tanks fell off their supports.

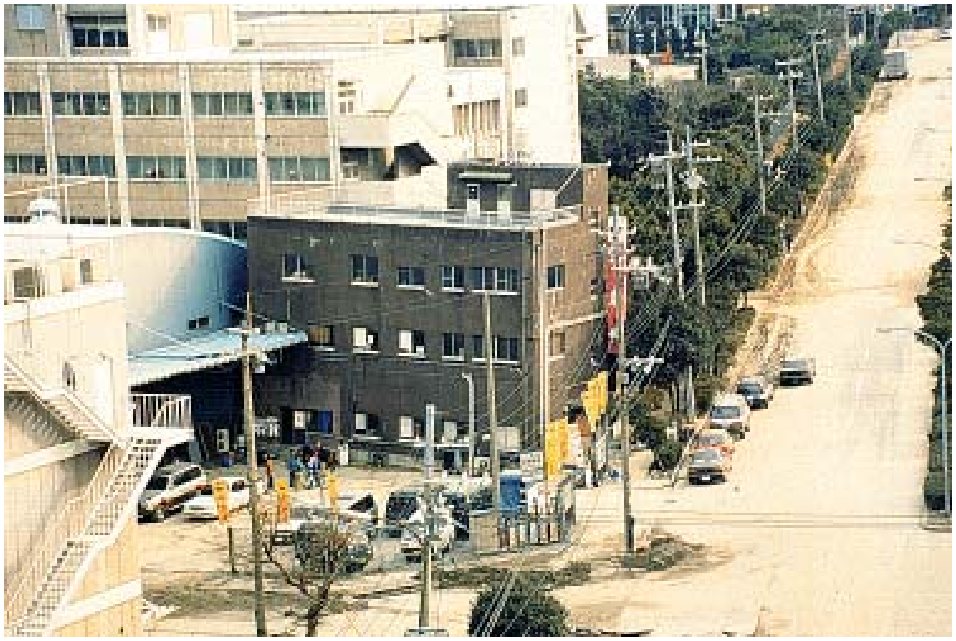
Opposite, bottom: Rocking and displacement of the quay wall was caused by lateral spreading of reclaimed land. This area, on the Nishinomiya Port, was flat before the earthquake.

Left: A damaged port crane on Rokko Island. The damage occurred when the quay wall moved to the left from the overall lateral spreading and settlement of the island. There was differential lateral movement of the two crane rails, pulling the crane legs apart. This phenomenon continued to occur for days after the earthquake.

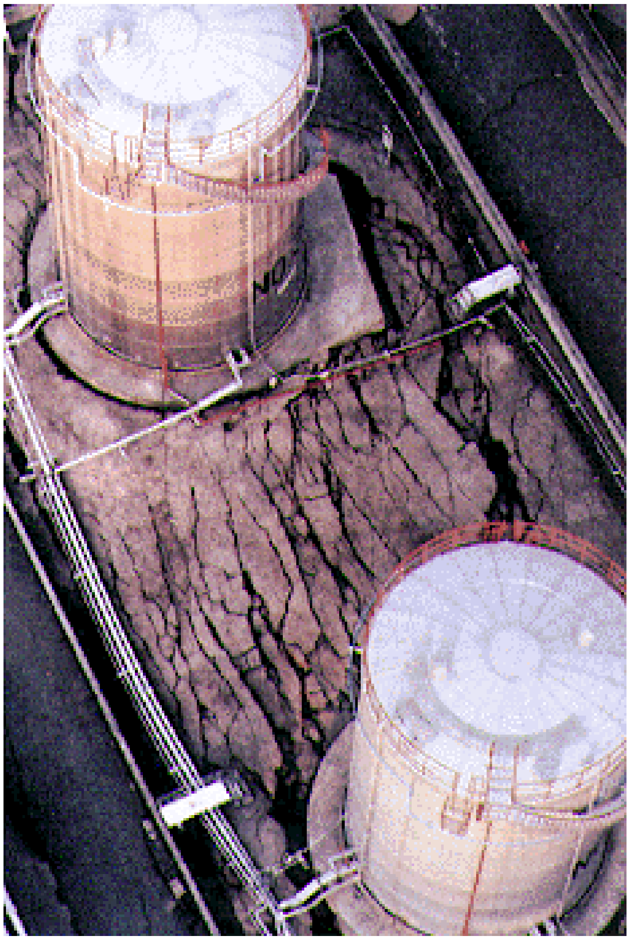
Top: An example of a heavy concrete structure supported on a slab-on-grade. When the underlying soils liquefied and settled, the building settled and rotated. Buildings on piles typically performed much better.

Bottom: Typical damage to Port of Kobe facilities. The large warehouse in the center was damaged when the interior slab settled. The center of the roof was supported by a column on the slab and was pulled in when the settlement occurred. Also note the severe displacement of the quay wall to the right.

Opposite: Severe damage to piers and warehousing along damaged quay walls. The quay walls have rotated toward the water, pulling the structures with them. The partially collapsed Hanshin Expressway can be seen in the background.




HWL

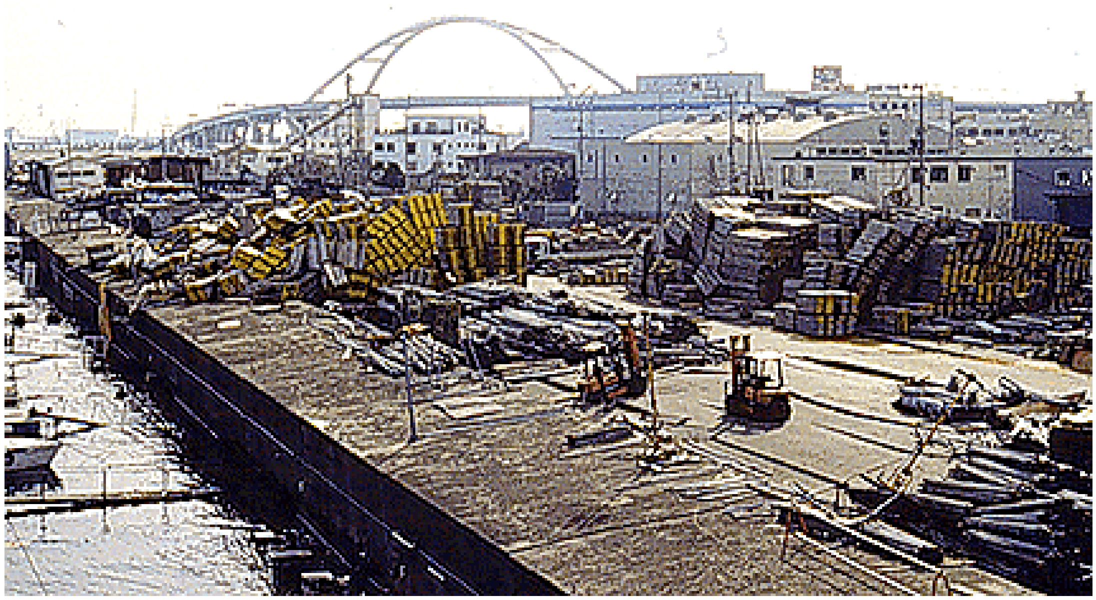


However, ground settlement caused extensive damage to the interiors of buildings, as well as to the infrastructure that is routed into the buildings. One case involved a pile-supported industrial building with a floating floor slab (or slab-on-grade). Although the peripheral piles successfully supported the structure, the floor slab failed when the underlying soil settled; this failure pulled down the columns that had supported the roof and caused it to collapse. Loading platforms, roads, storage and parking areas, various utilities, and other appurtenant structures were often observed to be severely damaged. Such damage was particularly severe on the numerous recently engineered islands in Osaka Bay. Many square kilometers of such land were observed to be affected.

Steel manufacturers in the Kobe area were severely affected by the earthquake. One steel company—Japan's fifth largest—estimated that it would take months to resume full operations in its Kobe plant, while another steel company was unable a week after the earthquake to provide an estimate of restoration time. Both firms' Kobe headquarters buildings were declared unsafe structures and could not be occupied. It was

Top: Tanks in the port area. The ground shows signs of massive liquefaction and settlement. The tanks appear to be on pile-supported foundations.

Bottom: Damage to facilities on reclaimed land, Nishinomiya Port. The quay walls have rotated and displaced, with the full surface dropping as much as 3 meters in some areas. In the background is a badly damaged bridge.



reported that four buildings at the first steel company collapsed, and the company was considering closing its Kobe industrial facilities and shifting operations north to its Kakogawa plant.

Very large, multistory, reinforced concrete shear wall warehouses on Rokko Island and in central Kobe had very little damage. These buildings appeared to have superior lateral strength and were evidently designed considering the contribution of heavy storage to the design earthquake loads. The observed damage to contents resulted primarily from toppling of stacked goods or unanchored storage racks.

Small- and medium-sized manufacturing firms were heavily damaged. Structural, fire, or contents damage affected more than 40% of the local knitted goods manufacturers and more than 90% of the synthetic leather shoe manufacturing facilities. City officials worry that production will now be moved to low-wage countries like China.

Heavy damage to the numerous liquor (sake) production facilities also occurred in the area stretching over Kobe's Higashi Nada and Nada wards and Nishinomiya. About one-third of the country's entire liquor production takes place in Kobe. Traditional wooden plants and storehouses collapsed, and some reinforced concrete structures had severe damage. At many of the major facilities, modern reinforced concrete buildings appeared to be undamaged. High-technology equipment housed in these structures, however, may have been severely damaged or destroyed, compounding business interruption losses.

A damaged concrete plant on reclaimed land east of Rokko Island. The conveyors are severely damaged, and several tanks have toppled.

Industrial Success

Following a disaster of the Kobe magnitude, it is easy to focus on the negative—buildings and roadways collapsed, fire caused destruction, industries were disabled, lifelines ruptured, and people were killed. It is important to understand, however, that as many lessons can be learned from the *successes* of buildings and infrastructure during the earthquake. These successes indicate not only that earthquake-resistant structures and facilities can be built, but also that the problems posed by intense earthquake motions on poor soil can be mitigated, even in an area close to the epicenter. The success stories of buildings and equipment that withstood an earthquake also provide valuable data on ruggedness and survivability that are unobtainable through other means. Design philosophies and calculation methods are validated when the fruits of these efforts withstand the effects of an earthquake.

In the Kobe area, there are many examples of such successes. The relative lack of damage to modern pile-founded structures in areas with tremendous soil liquefaction and settlement demonstrates the degree to which the engineering of such foundations has succeeded. Post-1981 buildings, in general, had a very good success rate. While there are many examples of industrial facilities with considerable operational problems and damage caused by inadequate anchorage of equipment and fire protection systems, there are also examples of industrial facilities that had minimal damage because proper seismic equipment detailing had been implemented before the earthquake. Two such facilities were found on two of the reclaimed islands, which were severely hit areas of Kobe.

Incinerator Facilities

One success story is an incinerator facility on Rokko Island, which is used to burn sludge from a neighboring sewage treatment facility. The facility is a reinforced concrete shear wall structure supported on piles and was completed in March of 1986.

The earthquake caused significant ground settlement (up to 50 centimeters) at the site. The facility's equipment was well supported, anchored, and heavily braced, however, and there appeared to be no major damage to either the equipment or the structure. The incinerator was operable during the earthquake and for 30 minutes after the event—at which time fuel for the backup power source, a 1,000-kW gas turbine generator, was exhausted.

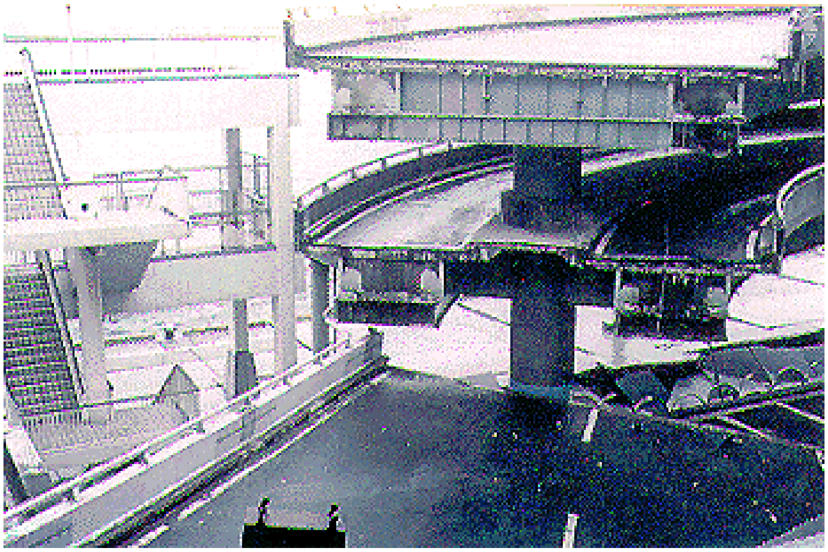
The facility has had some trouble operating because settlement of the roadway has made it difficult to weigh and unload trucks bringing waste to the facility. Loss of cooling water has also caused some difficulty. Normal operating procedures call for the use of cooling water supplied from the Higashi Nada sewage treatment facility, which was rendered inoperable by severe damage during the earthquake. As an alternative to this water supply, the sludge center used seawater for its cooling needs.

Although there was no instrumentation for recording ground motion at the site, it is estimated that peak ground acceleration was in the 0.6g range. This estimate is based on accelerations recorded in the vicinity and the level of damage to neighboring facilities.

There is a similar incinerator facility on Port Island. This facility is a six-story, reinforced concrete, shear wall structure founded on piles. Ground settlement around the main structure was on the order of 50 centimeters. The only structural damage observed was partial failure of a walkway connecting the main structure and the stack. Like the Rokko Island facility, this plant was built to the post-1981 building code. The only known damage to the mechanical systems was a leak in a small-diameter air line containing threaded connections. Similar equipment and details were found at the plant on Rokko Island.

Top: Silos and port facilities on reclaimed land next to Rokko Island. Tanks in the foreground are leaning. The silos in the background are severely damaged.

Bottom: Damage along the Port of Kobe shore. The severe rotation, lateral spreading, and settlement of the quay walls and fill material are typical of almost the entire developed border of the port. The building in the foreground has split into two parts.



Damage to major transportation routes was a factor in business interruption.

Nonstructural Damage

Differential settlement and tilting of ground-supported slabs within buildings damaged equipment. In one case, the slab-on-grade in a pile-supported structure settled differentially between the pile caps. While not structurally significant, this resulted in extensive misalignment of manufacturing equipment. Re-leveling of the machinery was expected to take several weeks.

The shaking itself also caused damage to more sensitive equipment and equipment that was not properly anchored. For some plants, short-term fixes to equipment that had been affected by settlement involved jacking up machinery as much as 30 centimeters in order to achieve proper alignment. This procedure often caused significant delays in resuming production.

Breakage and leakage of fire sprinkler lines in manufacturing facilities were observed from Akashi to Osaka, resulting in extensive damage to manufactured goods, stock, and machinery. Virtually all of the leakage can be attributed to the failure of unbraced or inadequately braced piping. Fortunately, there were no fires reported at these facilities. Had proper bracing been in place, considerable damage and business interruption could have been avoided. It should be noted that it was not sufficient to simply clean up the water damage to resume operations. Repairs to the fire suppression systems also had to be completed.

One research facility located about 20 kilometers northeast of central Kobe had only minor structural damage to most of its buildings, and breakage of water and wastewater lines caused by minor ground settlement. Extensive damage to the contents, however, was noted. Unanchored lab hoods shifted, bookshelves and cabinets toppled onto desks, and computer equipment fell to the floor. There was extensive breakage of glass jars containing a variety of chemicals. Most of this damage could have been easily prevented with simple anchorage.

Other Causes of Business Interruption

Many of the industries affected by the earthquake are suppliers of parts for industries outside the affected area. Since much of Japanese industry relies on "just-in-time" delivery, damage to industry located in Kobe and the breakdown of the transportation system in the area are causing business interruptions to a variety of industries not directly affected by the earthquake. Business interruption insurance is typically not available in Japan, which will add significantly to the overall industrial losses.

One report stated that by January 21, at least four major electronics plants, six steel or heavy industrial plants, and three beverage plants had been shut down because of the earthquake. In some cases, facilities were closed because employees were unable to get to work, rather than because of severe physical damage to the facility itself. By Monday, January 23, nearly one week after the earthquake, many of these plants had reportedly resumed at least partial production. In some cases, the availability of water, gas, and power determined whether or not a business reopened.

A reduction in work force availability is an important factor in industrial operations. Personal tragedy, loss of housing, and the debilitation of mass transit meant that many employees were unable to work right after the earthquake. This, in turn, means that many businesses will be unable to recover from the disaster in a timely manner, which may bankrupt some industrial concerns.

TRANSPORTATION

A failed portion of the Hanshin Expressway. The most heavily damaged portions of the expressway had concrete road deck (background); the less damaged portions typically had a steel superstructure (foreground). Where the two types joined, the heavier concrete deck portion pulled down the adjoining parts.

One of the most far-reaching and disturbing aspects of the earthquake was the severe and extensive damage to the transportation system. Kobe sits astride the principal transportation corridor between the central and southwestern parts of Japan's main island, Honshu. The corridor is less than 5 kilometers wide between Osaka Bay and the mountainous terrain on the north side of Kobe. Earthquake damage to highways, bridges, and rail systems left Kobe's city streets as the only land access along this corridor, resulting in major congestion and greatly impeded relief efforts. Many of these surface streets were also unusable, blocked by debris from collapsed structures and damaged by ground settlement. Use of alternative road or rail lines added hours to normally short trips.

Damage to the transportation system had the potential to contribute greatly to the number of fatalities. Had the earthquake occurred during rush hour, there would have been many hundreds of fatalities on collapsed freeways, and numerous crowded trains would have derailed, in some cases plunging onto city streets.

Major Highways and Bridges

Two limited-access highways service the Kobe-Osaka transportation corridor, the Hanshin and Wangan expressways. Built in the mid- to late 1960s, the Hanshin Expressway is the main through road and is almost entirely elevated for more than 40 kilometers. Much of the roadway is supported by single, large reinforced concrete piers spaced

Collapsed sections of expressways.

every 32 meters, many of which failed in shear or bending over a 20-kilometer length. Similar failures of the roadway occurred at many locations, including complete toppling of large reinforced concrete pillars supporting a 500-meter section. It was observed that the road deck changed from steel to a heavier concrete section at the location where this collapse occurred. These failures have not only closed the Hanshin Expressway for an indefinite period, but have severely impeded traffic on Route 43, a street-level highway beneath the expressway.

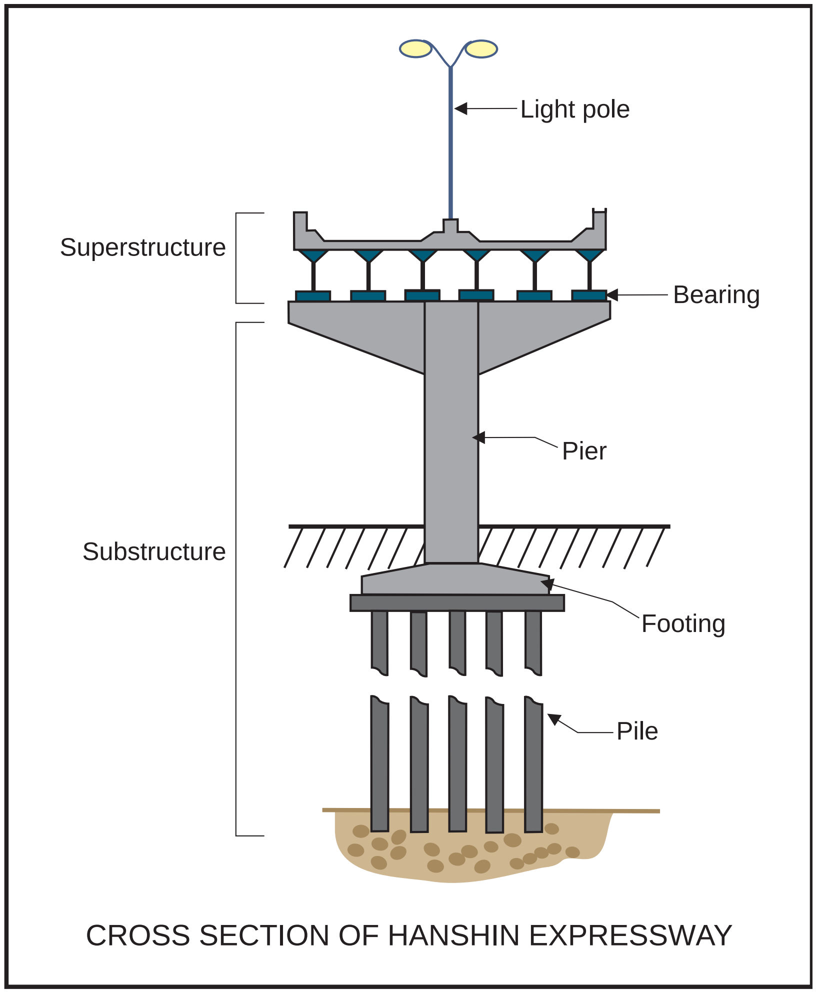
Elevated highways in Japan typically consist of single spans that have roller bearings at one end and are fixed at the other. To conserve valuable space, single-column, cantilever structures are common. Bearing widths on Kobe area expressways appeared to be inadequate in some instances. Column shearing revealed small reinforcing steel ties at relatively large spacing. Failed welds at splices of longitudinal bars were also observed.

The details that caused the failure and collapse of the columns are similar to those that caused the failures of the older freeways in the Los Angeles area in the 1994 Northridge Earthquake. These details received considerable attention shortly after the 1989 Loma Prieta Earthquake, when the California Department of Transportation (Caltrans) initiated a massive program, amounting to several billion dollars, to strengthen all similar elevated structures and bridges in California. The collapses in the Northridge Earthquake were entirely of structures that had not yet had the post-Loma Prieta retrofits. Other

U.S. states, such as Illinois, Missouri, and Washington, have initiated similar programs in their earthquake-prone regions.

The Japanese design philosophy includes much larger columns, which result in stiffer structures that can be twice as strong as those in the United States. Japanese-designed expressways require 50% more steel and sit on squat columns. However, it was assumed that the column would have more strength than required, so until recently, reinforcing steel detailing has provided little ductility, resulting in more fragile structures. The consequence of unexpectedly large ground motion can be catastrophic failures.

Japan has started five seismic retrofit programs since 1971, but the major highways in the Kobe-Osaka area had not been upgraded because the threat of earthquakes was perceived to be low. So far, Japan has retrofitted 25,000 out of 110,000 bridges. Certain columns of the Hanshin Expressway were retrofitted with steel jackets that were similar to the jackets used by Caltrans. These details were found in areas that had been strengthened to accommodate the weight of new on- and off-ramps and did not appear to be intended for additional seismic resistance.



Top: Diagram depicting a typical cross section of the Hanshin Expressway.

Bottom: A failed hammerhead support for the Hanshin Expressway.

Top right: Typical damage to a massive reinforced concrete column supporting the Hanshin Expressway. This column had inadequate horizontal shear reinforcement.

Top left: Damaged vehicle on the remains of the Hanshin Expressway.

Bottom: Damage to columns supporting the Hanshin Expressway. The damage seen here was probably caused by both horizontal shear and high axial loading. This is a result of both the earthquake motion and the collapse of nearby portions of the freeway.

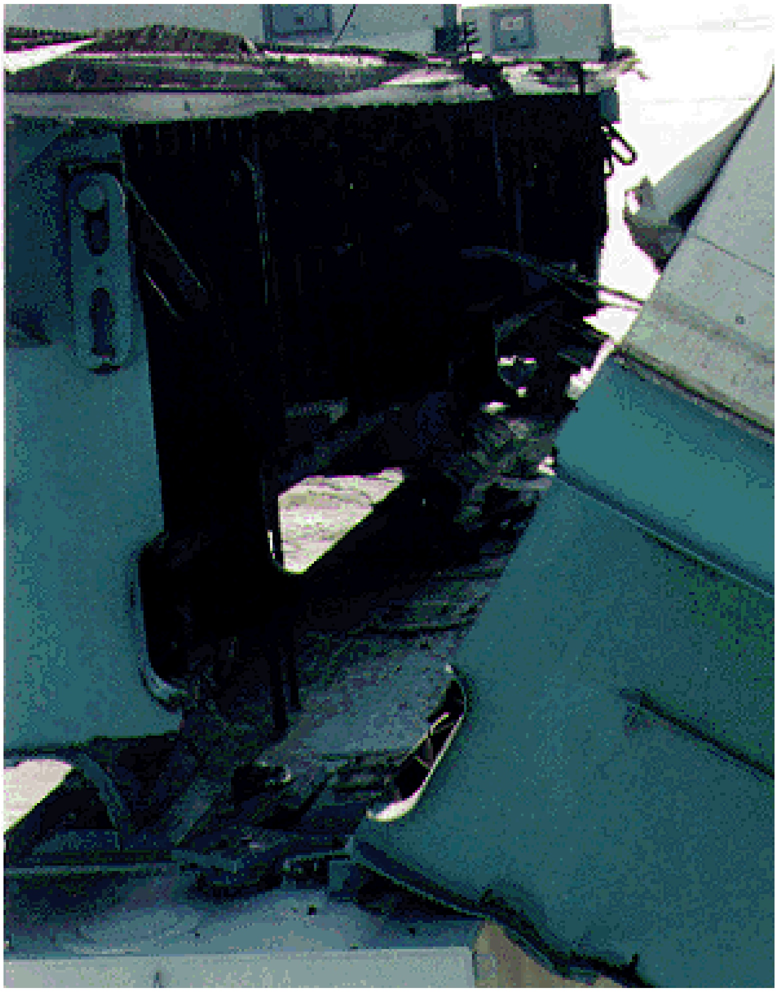
Top: Buckling failure (bending) of steel-encased columns supporting the Hanshin Expressway.

Bottom: A steel-jacketed column (foreground) next to a non-jacketed column (far right). Although the steel-encased column shows signs of critical damage, it appears to have much more reserve capacity than the non-jacketed column does. It is thought that the jacketing was a retrofit for increased gravity loads – not for seismic resistance.

Typically, these details performed well, indicating that the Caltrans retrofit approach may be correct.

The Hanshin Expressway is paralleled to the south by the new Wangan (Harbor) Expressway from Osaka to Rokko Island. The Wangan Expressway is a modern elevated freeway and includes several large bridges, some of which were under construction at the time of the earthquake. The roadway is supported on a steel-frame deck. The deck is supported on bearing pads, which sit on either steel or concrete piers. Long sections of the expressway have double decks. The bridges along the expressway include long arch structures and a long cable-stayed suspension span. These, and many smaller spans, cross various navigable channels between the mainland and numerous recently constructed islands, which form parts of the Port of Kobe. All of the expressway is located on soft native soils and engineered landfill.

The Wangan Expressway was severely damaged along its entire length, from Nishinomiya Port to Rokko Island, a distance



of more than 8 kilometers. At many expansion joint locations, the bearings (hinges and rollers) supporting the roadway structure were damaged. In a number of cases, the bearings collapsed, allowing the road deck to drop from a few centimeters to more than a meter. This damage was caused by forces that exceeded those assumed in the design and very large longitudinal (along the roadway) and transverse (perpendicular to the roadway) displacements.

Typically, the columns (piers) supporting the expressway appeared to be undamaged, indicating that the current reinforcing details, in the case of concrete columns, are adequate, as opposed to the old details of the Hanshin Expressway. The soil around the pile-supported columns typically settled from a few centimeters to more than 1.5 meters along the length of the expressway. A few columns rotated, almost dropping the highway spans, because of ground failures—typically lateral spreading.

The approach to a large, 252-meter-long, cable-tied, arch bridge in Nishinomiya collapsed, apparently the result of excessive

Top: Detail of the east end of the failed approach span to a cable-tied arch bridge on the Wangan Expressway. This photograph shows the failed mechanical bearings, linkages, and other details of the roadway construction.

Bottom: Failed welds at splices of longitudinal reinforcement in a column supporting the Hanshin Expressway (at the 500-meter-long failed section). These gas fusion welds are 1960s' technology and are not common today in the United States. All splices were at the same section—another practice not common in the United States. However, these welds failed only after the initial shear failure of the columns.

longitudinal displacements of the roadway. Due to the early hour, only two casualties resulted from the collapse. This bridge was three years old. The six-lane freeway will be unusable for an extended period while this damage is repaired. The bridge also had some distress: At least one of the cables supporting the deck showed a large permanent lengthening.

At the other end of the Wangan Expressway, where it crosses to Rokko Island, a smaller (about 200 meters long) braced-arch bridge failed, almost catastrophically. This bridge displaced laterally more than 30 centimeters and was in imminent danger of falling completely off its southern pier. The damage mode appears to be a bearing failure. Marks on the pavement made by sliding, unanchored concrete crash barriers on the upper bridge deck indicate that the bridge deck displaced laterally more than 1.2 meters. Part of this displacement could have occurred because the bridge tilted when the southern bearing failed. Numerous approaches to the Wangan Expressway, including the elevated toll plaza for the cable-stayed bridge, failed because of ground settlement bearing failures, column rotations, and other inadequate support details.

The damage to this new expressway is quite disturbing. It indicates that the latest design criteria and practices for bridge structures, at least in areas of soft soils, may be inadequate. In light of this damage, it is appropriate to reevaluate design criteria for both new and retrofit designs of bridges worldwide. This is the first real earthquake test that large modern bridges have had, and the results are rather disappointing.

The Akashi Ohashi Bridge, with a main span of 1,990 meters, will be the world's

Pier failures beneath the Great Nishinomiya Bridge. At least two of the bridge's six supporting piers were severely damaged. Damage appears to be caused by large settlements at the bridge's abutments, probably overloading the first set of piers.

Top: The collapsed approach to the 252-meter-long main span of the Nishinomiyako Bridge east of Nishinomiya Port on the new Wangan Expressway. The failure was caused by inadequate strength and capacity of the mechanical bearings to take very large displacements in both the transverse and longitudinal directions.

Bottom right: Ground failure at the base of an abutment of a bridge that crosses a shipping channel along the Wangan Expressway.

Bottom left: In the same abutment, the bent can be seen to have rotated, and there is evidence of longitudinal movement of the roadway and lateral spreading of the soil.

Top: The cable-stayed bridge linking Rokko Island to the mainland. Note the failed 46-centimeter water line dangling beneath the deck. All monorail lines to the island failed in the earthquake; the other bridge to the island is the steel-arch bridge shown on page 54.

Bottom: Failed bearings were typical along the Wangan Expressway. This photograph shows a 50-centimeter vertical drop at the expansion joint from the bridge approach to the first span of a large cable-stayed bridge. The failures were typically more dramatic at both sides of major crossings along the Wangan Expressway.

Top: The main span of a steel-arch bridge for the Wangan Expressway. Note the discontinuity in the road deck and the tilt of the bridge to the right.

Bottom: An overall view of the same bridge. The span is on the verge of falling off the pier at the south (closest) end of the bridge. The bearings supporting this end of the bridge failed.

largest suspension bridge when it is completed in 1998. It is currently under construction and will span the strait between Honshu and Awaji islands. The fault that ruptured reportedly passes between the two towers of the bridge, and the two abutments have moved apart more than 1 meter. At this time, it is not known if significant damage occurred to the structure.

Numerous other bridges, both new and old, were damaged. Other highways and roads were also damaged. Most of the damage to roads was from ground settlement, typically caused by liquefaction.

Railways

Elevated railroad structures and railway stations were particularly hard hit. Three main lines (JR West, Hankyu, and Hanshin) run through the Kobe-Osaka transportation corridor, generally on elevated structures and embankments. All the lines had elevated structure and embankment failures, overpass collapses, distorted rails, and other severe damage. A large number of cars were damaged, and some fell onto city streets. Several stations and several kilometers of reinforced concrete elevated structures were destroyed, and numerous spans collapsed.

The Rokkomichi Station (built in 1972) of the JR West line was virtually destroyed.

The Shinkansen (Bullet Train) was constructed circa 1964. Most of its path in the Kobe area is through two long tunnels under Rokko Mountain. No information on the tunnels' performance was immediately available. At the east portal of the tunnel, the line is carried on an elevated viaduct built in 1968. For a length of 3 kilometers, this viaduct was severely damaged, with a number of the longer spans collapsing. In general, these collapses were caused by shear failure of the supporting concrete columns.

Included in this area is a multispan crossing of a river, consisting of approximately 40-meter spans carried on large, single, reinforced concrete piers, all of which had severe cracking and transverse reinforcement failure.

It was estimated that service on the Hankyu line and the Shinkansen would be disrupted for six months. The JR and Hanshin lines were expected to be interrupted for lesser periods. Within about a week after the earthquake, rail service was restored to Kobe from Osaka via a major detour, which resulted in a 2-hour trip versus the normal half hour.

Top: Failure of the elevated train railway near Rokkomichi Station.

Bottom: Heavily damaged viaduct of the Shinkansen (Bullet Train).

The damage to the elevated rail structures and to the stations was predictable. Similar damage has occurred in numerous past earthquakes, most significantly during the 1971 San Fernando Earthquake near Los Angeles. Japanese engineers believed that the columns were adequate, because the columns were typically larger in cross section and therefore stronger than similar structures in California. The structural details that resulted in damage to the Shinkansen and to the other elevated structures, however, were virtually identical to those that resulted in the collapse of the nearby Hanshin Expressway, and were similar to those that resulted in earlier California highway damage in 1989

Top: Destroyed railway car storage structure.

Bottom: Collapsed two-story Rokkomichi Train Station. The structure collapsed due to inadequate shear reinforcement in the supporting columns.

Opposite, top: Failed column supporting Rokkomichi Station, built in 1972. Note the minimal amount of shear reinforcement and nonductile detailing of the steel reinforcement.

Opposite, bottom: The severely damaged Sannomiya Station in the center of Kobe.

and 1994. The damage to the Shinkansen is particularly troublesome, because the line is so critical to Japan. Further, it was fortunate that the earthquake struck about 14 minutes before trains in Kobe began to move. Thousands of commuters would have been in moving trains had the earthquake occurred later, and the number of deaths could have been even higher.

In the port area, Rokko Island is served by a dual monorail (people mover), which


Coca-Cola

Top: A section of the severely damaged Shinkansen (Bullet Train) elevated roadway. The structure is very stiff and very strong, but had inadequate shear reinforcement.

Bottom: Daikai Subway Station, Kobe. Columns supporting the roof at midspan have failed in shear, resulting in the roof's collapsing.

collapsed at several locations (downtown Kobe, on Rokko Island, and on a major cable-stayed crossing to Rokko Island).

Kobe Subway System

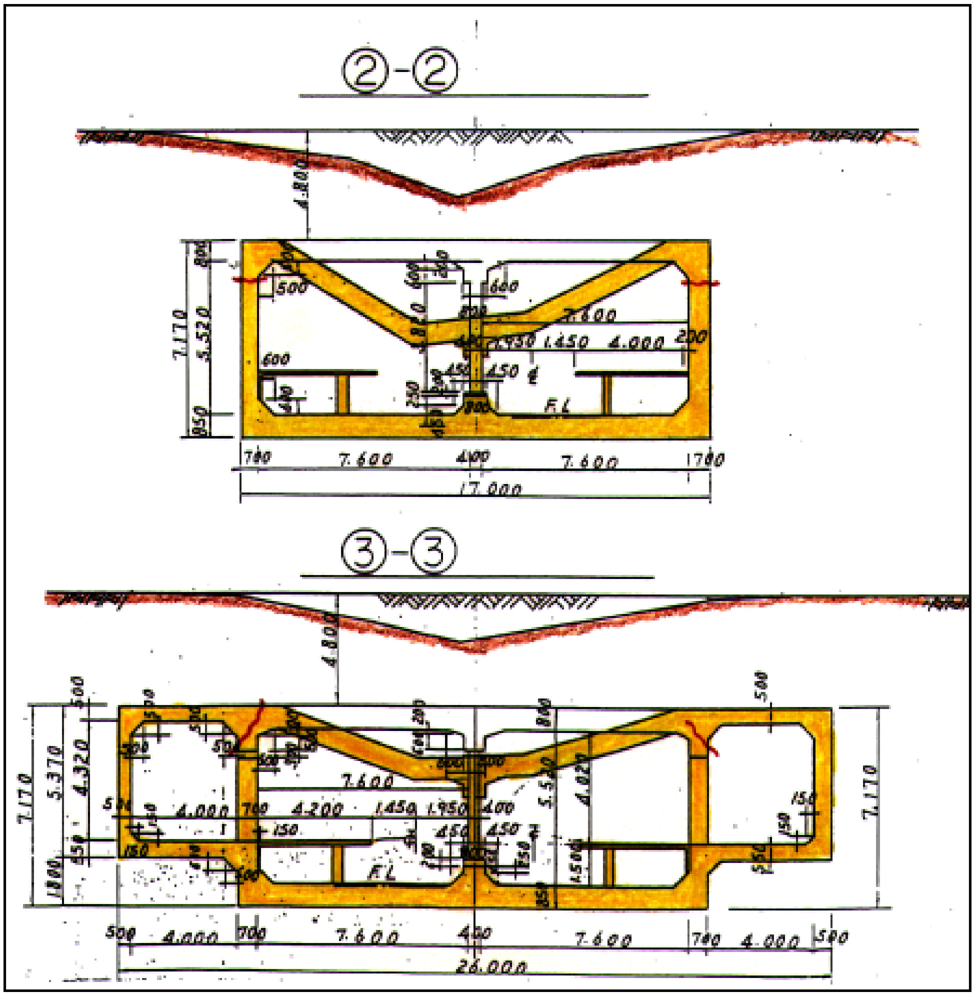
Damage to underground facilities, such as mines, tunnels, or subways, is rare in earthquakes. An unusual example of severe damage to this type of facility occurred in the Kobe subway system, a two-track line running under central Kobe, which was generally built by cut-and-cover methods in the mid-1960s. The double track is typically carried through a concrete tube 9 meters wide by 6.4 meters high, which widens to 17 meters at the stations. The tube typically has about 5 meters of overburden, which is supported by 0.4-meter-thick walls and roof slabs. The walls and roof slab are supported midspan (between the tracks) by a series of 5-meter-tall, 1.0-meter-long by 0.4-meter-wide reinforced concrete columns.

At the Nagata and Daikai stations, and in the tube section between, the between-track columns failed catastrophically in shear, dropping the roof slab almost onto the tracks over about a 90-meter length. More than 30 of the 35 piers supporting the platform and the ceiling at the Daikai Station were badly damaged, causing a 3-meter-deep cave-in on the street above, National Route 28. At the Sannomiya Station, 20 piers were damaged. Because the failed section is central to the entire Kobe system, most of the subway is out of service, with repairs scheduled to be completed in the fourth quarter of 1995.

Failure of the columns was caused by excessive deflection of the roof slab diaphragm combined with very light transverse (shear) reinforcement, relative to the main (bending) reinforcement. Excessive deflection of the roof slab would normally be resisted by (1) diaphragm action of the slab,

Massive depression in the roadway caused by partial collapse of the Daikai Subway Station below.

Cross sections of Daikai Subway Station after the earthquake, showing the roof collapse.



Courtesy Japan Rail Corporation

supported by the end walls of the station, and (2) passive earth pressure of the surrounding soils, mobilized as the tube racks. Diaphragm action was less than anticipated, however, due to the length of the station.

The lack of passive earth pressure is extremely interesting, because it highlights a common cause of failure—the difference between design assumptions and constructibility. That is, designers in this situation often assume that passive earth pressure of the surrounding soil will provide partial support for the tube under lateral loading. Because of the method of construction (cut-and-cover, involving sheathed excavation with narrow clearance between the sheathing and the tube wall), compaction of backfill would have been difficult to impossible, resulting in the tube's inability to mobilize passive earth pressures. In effect, the tube behaved almost as a freestanding structure with little or no extra support from passive earth pressure.

Airports

Kansai International Airport was only recently completed (1994) on a human-made island some 30 kilometers to the southeast of the epicenter. Itami is the former international airport for Osaka and now handles much of the domestic traffic. It lies about 10 kilometers east of the heavily damaged area. Neither airport appears to have been significantly damaged, but neither was located in an area that had severe ground motion.

The Port of Kobe, one of the largest container facilities in the world, sustained major damage during the earthquake. In effect, the port was practically destroyed. The total direct damage to the port will easily exceed U.S.$11 billion. Reconstruction costs, if in fact the port is restored to its pre-earthquake condition and capacity, will probably exceed the cost of the damage. The port complex, constructed on three human-made islands—Maya Container Terminal, Port Island (with an area of 10 square kilometers), and Rokko Island (with an area of 6 square kilometers)—accounts for approximately 30% (2.7 million containers per year) of Japan's container shipping. At the time of the earthquake, the three facilities included 27 active container berths and various other wharves, ferry terminals, roll-on facilities, and warehousing. In addition, the older parts of the port contain numerous other facilities, such as an extensive shipyard. Also, at the time of the earthquake, several new islands were under development, and new berths were under construction to the east of Rokko Island.

The port is owned and managed by the Port and Harbor Bureau of the Kobe City Government, and the various berths are leased to more than 50 major international shipping lines. The container port was constructed in phases commencing with the Maya Container Terminal, followed by Port Island and then Rokko Island, where construction started in 1972. A second development phase on Port Island, including five container terminals and other berths, was under construction and nearly complete when the earthquake struck.

Top: Water behind a failed quay wall. Caissons have tipped and slid toward the water, allowing the supported deck to collapse behind them.

Bottom: Failed structures at the edge of the port across from Rokko Island.

Top: Damage to crane legs at a port facility. Damage was the result of the relative movement between the crane rails on top of the quay wall and those supported on fill.

Middle: Lateral spreading, settlement, and liquefaction along the shore of the Port of Kobe.

Bottom: Detail of a failed gantry crane, Rokko Island.

Opposite: Typical failure of a caisson wall; the wall has moved to the right (lateral spreading), allowing the fill behind to settle. This island is newly constructed. An unused caisson can be seen to the left.

Sixty-seven gantry cranes operated in the various berths. Fifty-five were wide-gage (30.5 meters between the rails) and 12 were narrow-gage (16 meters between the rails). The cranes were fabricated by different manufacturers including Pacheco, Sumitomo, Kawasaki, Mitsubishi, Mitsui, and IHI. These cranes have lift capacities ranging from 30 to 40 tons, and their loading outreach ranges from 36 to 40 meters. At the time of the earthquake, most cranes were in their stowed position with the pins engaged.

Land reclamation at all three main human-made islands and at numerous other parts of the port was done by means

Cranes damaged by lateral spreading, Rokko Island.

of gravity-founded, concrete caisson quay walls enclosing the perimeters of the islands. Prior to installing the caissons, some of the native soils beneath were dredged and replaced by a screeded sand and gravel base. The caissons are rectangular in plan and have internal bulkhead walls, creating a cellular structure, which is designed to withstand the imposed hydrostatic pressure while afloat. The caissons were lowered on the prepared seabed by filling the caisson cells with sand ballast. Caisson dimensions vary, but in general, they were designed to accommodate water depths in the range of 13 to 14 meters.

Once the quay walls along the islands' perimeters were nearly complete, granular fill, quarried from the nearby Rokko Mountain, was transported and placed using bottom dump barges. In general, only the upper few meters of fill above the mean sea level were compacted in an engineered manner. A concrete cap beam was placed over the caissons to support the waterside crane rails and to provide some continuity among the quay wall caissons. Narrow-gage landside crane rails were mounted on top of pile-supported grade beams. Wide-gage landside crane rails were mounted on grade beams supported by the fill. Storage yards were generally topped with asphalt or concrete pavement.

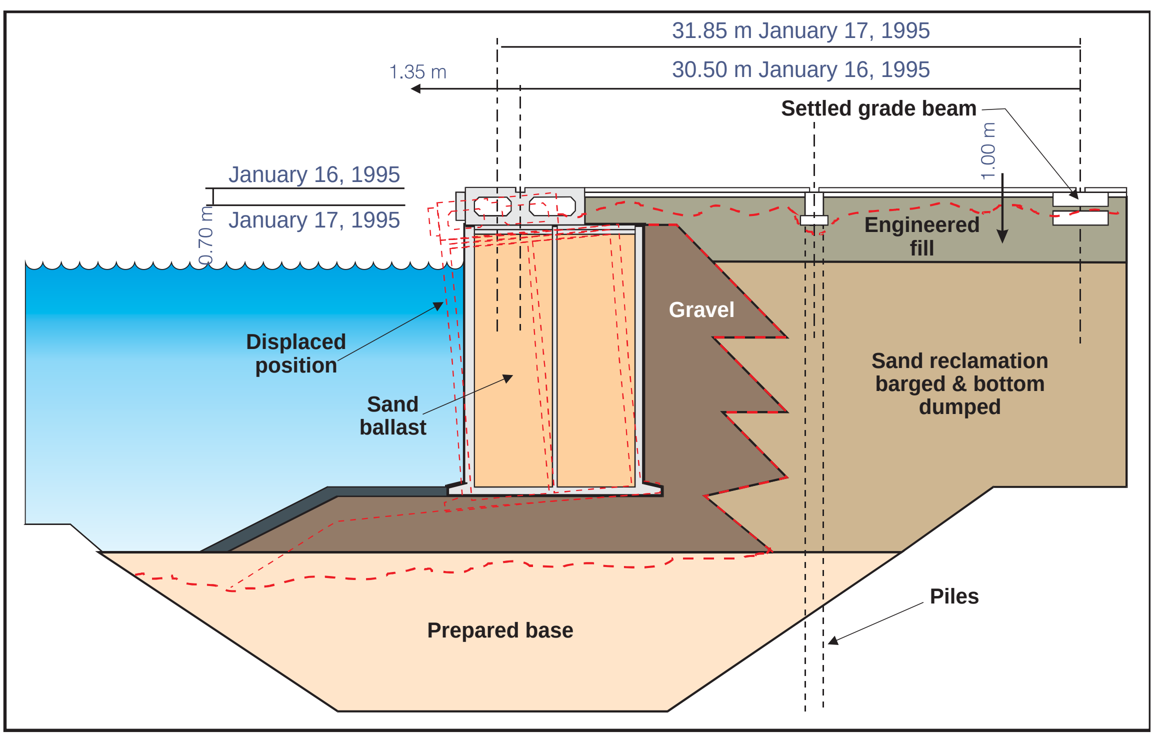
The predominant damage to the port facilities resulted from soil liquefaction and lateral spreading. A large number of the gravity-founded quay wall caissons rotated and slid outward. Soil settlements immediately behind the caissons were as much as 3 meters and generally decreased toward the center of the islands. Pile-supported structures remained at their original elevations, while the surrounding ground settled substantially. Significant quantities of sand were ejected because of liquefaction and covered large portions of the pavements. Most gantry cranes were damaged, and one collapsed because the quay wall caissons were displaced.

Damage to the gantry cranes was in the form of leg and cross-beam buckling, as well as rupture at the wheels. The extent of buckling varied, depending primarily upon the relative horizontal displacement resulting from the movement of the caissons. Relatively few cranes jumped off the tracks, which can be attributed to most of the cranes being in the stowed position with their pins engaged at the time of the earthquake. Numerous other cranes throughout the port were damaged because of foundation damage. Several cranes collapsed; some collapsed because of structural damage caused by inertial forces generated by the earthquake.

Quay wall caisson displacements, which undoubtedly propagated the major damage in the port, may be attributed to several phenomena. Earthquake accelerations applied to the massive sand-filled caissons resulted in large horizontal forces, which may have exceeded the sliding resistance offered by the base. This can be further aggravated by the rocking motion of the caissons, which may result in excessive bearing pressures at the toe of the base. The latter coupled with the possibility of liquefaction may explain the observed tilting of many caissons. Since the islands' fill placed below water was dumped

Top: Partially submerged pier and buildings at the older section of the Port of Kobe.

Bottom: Typical quay construction, Rokko Island.



Container pier on Rokko Island. Severe damage to the pier and cranes was caused by lateral spreading. Note the damage to the legs of the cranes.

from barges, it was relatively uncompacted. Hence, soil settlements resulted from lateral spreading as well as compaction. Such settlements continued during the first few days after the earthquake and are likely to continue for some time, especially in the event of further aftershocks.

Severe damage to other types of piers and their quay walls was observed throughout the port. In the older parts of the port, particularly to the south of central Kobe, such as Hyogo Pier, large parts of piers were submerged because of massive soil settlement. Settlements in excess of 2 to 3 meters were observed. Numerous warehouses and other facilities were also submerged and/or severely distorted and damaged because of ground settlement. Severely damaged, partially submerged, and collapsed cranes were observed throughout the older parts of the port, the shipyards, and other facilities.

Container and other operations at the Port of Kobe were essentially halted by the earthquake. Other ports at nearby Osaka, Nagoya, and Yokohama are being used to process container and other traffic. These ports had little damage.

Ferry service was gradually restored in the days following the earthquake. While the direct damage to the port is severe, the loss of port service to the local economy is devastating.

Much of the damage to the container operations was caused by the failure of the caisson quay walls. All of the walls examined by the EQE team were severely damaged. Many of these walls were new or were under construction and presumably designed to the latest standards. This generic failure indicates that the current design standard for such caisson walls is inadequate. In addition, the generic failure indicates that other commonly used systems for quay walls—such as those used on the West Coast of North America, and which have not yet been tested by very strong earthquakes—may also have generic weaknesses. Fortunately, these designs rely on pile-supported systems and are quite different from the caisson walls that failed in Kobe. Considering the devastation in the Port of Kobe, it would be prudent for U.S. and other ports in earthquake regions to evaluate carefully the designs that are commonly used. Detailed and independent risk analyses are one method that may be used to assess their strengths and weaknesses.

OTHER LIFELINES

Lifeline performance varied in this event, with electric power and telecommunications quickly restoring most system functionality, and water, wastewater, and gas basically losing service to most of Kobe. All of these lifelines, however, were extensively damaged.

Electric Power

EQE, with support from the Electric Power Research Institute (EPRI), dispatched a team of engineers to investigate the performance of the electric power system during and after the earthquake. The following are preliminary observations based on field investigations and technical information provided by Kansai Electric Power Company Inc. (Kansai Electric).

Kansai Electric's service area covers 28,663 square kilometers, which includes the cities of Osaka, Kyoto, and Kobe, three of Japan's major economic and cultural centers. The service area covers 8% of Japan's total land area and 16% of the nation's electricity consumption. Kansai Electric operates an installed generating capacity of 35,035 MW to service the highly urbanized and industrialized region: 18,581 MW nuclear; 9,768 MW fossil fuel; and 6,686 MW hydroelectric. The Power System Engineering Department manages 62 control centers; 868 substations; 15 switching stations; 10,819 kilometers of overhead transmission lines; and 1,740 kilometers of underground transmission lines.

The Kansai Electric transmission system includes a 500-kV system that loops around the region, connecting to nuclear generation plants in the north and neighboring utilities to the east and west, and looping around Osaka to the south. The earthquake's epicenter was located in one of the few areas of the Kansai Electric service area that would not significantly affect the 500-kV transmission system. The earthquake's location also spared a cluster of fossil fuel plants to the southeast from the high ground motion and did not affect the nuclear power plants located more than 100 kilometers to the north. The greatest damage occurred at 187- and 275-kV substations, a few of the fossil plants, and a gas turbine plant. Details on distribution system damage are not currently available.

Widespread blackouts such as those during the Northridge Earthquake did not occur, in part because of the earthquake's location relative to the 500-kV loop. All of the 500-kV substations continued normal operation. Nevertheless, 1 million customers were without power for a few hours following the event. More than 4,700 restoration crews from Kansai Electric, contractors, and six other electric utilities successfully restored the system within a few days. System restoration in terms of the number of customers

Undamaged, well-anchored ash filter at a waste disposal plant, Port Island.

KANSAI ELECTRIC POWER RESTORATION

DATE	TIME	CUSTOMERS WITHOUT POWER
January 17	5:46 A.M.	(Data not available)
January 17	7:30 A.M.	1,000,000
January 17	8:00 P.M.	500,000
January 18	5:00 P.M.	200,000
January 19	7:00 P.M.	110,000
January 20	1:00 P.M.	70,000
January 22	9:00 A.M.	17,000
January 23	9:00 A.M.	2,000
January 23	3:00 P.M.	0[1]

1. Does not include more than 70,000 customers whose buildings or houses were destroyed by the earthquake or the fire thereafter.

Failure of seismic ties for the boiler at the Amagasaki No. 3 plant.

without power following the earthquake is summarized in the table above.

Power-generating station damage during the earthquake was limited to 10 of Kansai Electric's 63 fossil-powered units, with 12 out of 36 units that were on-line before the earthquake tripping off-line. None of the 141 hydroelectric power stations or three nuclear plants (11 units) were damaged.

Ten units with a total capacity of 1,631 MW were damaged. Five units had a few broken boiler tubes each. Amagasaki-Higashi Units 1 and 2; Amagasaki No. 3, Units 1, 2, and 3; and Higashi Nada Gas Turbine Units 1 and 2 had substantial ground settlement and liquefaction. Himeji No. 2, Unit 2, had a safety valve seat leak that was most likely not earthquake related.

The EPRI/EQE reconnaissance team visited Amagasaki No. 3, Higashi Nada, and the Itami Substation. The two generating stations had the highest ground motion and the most serious damage.

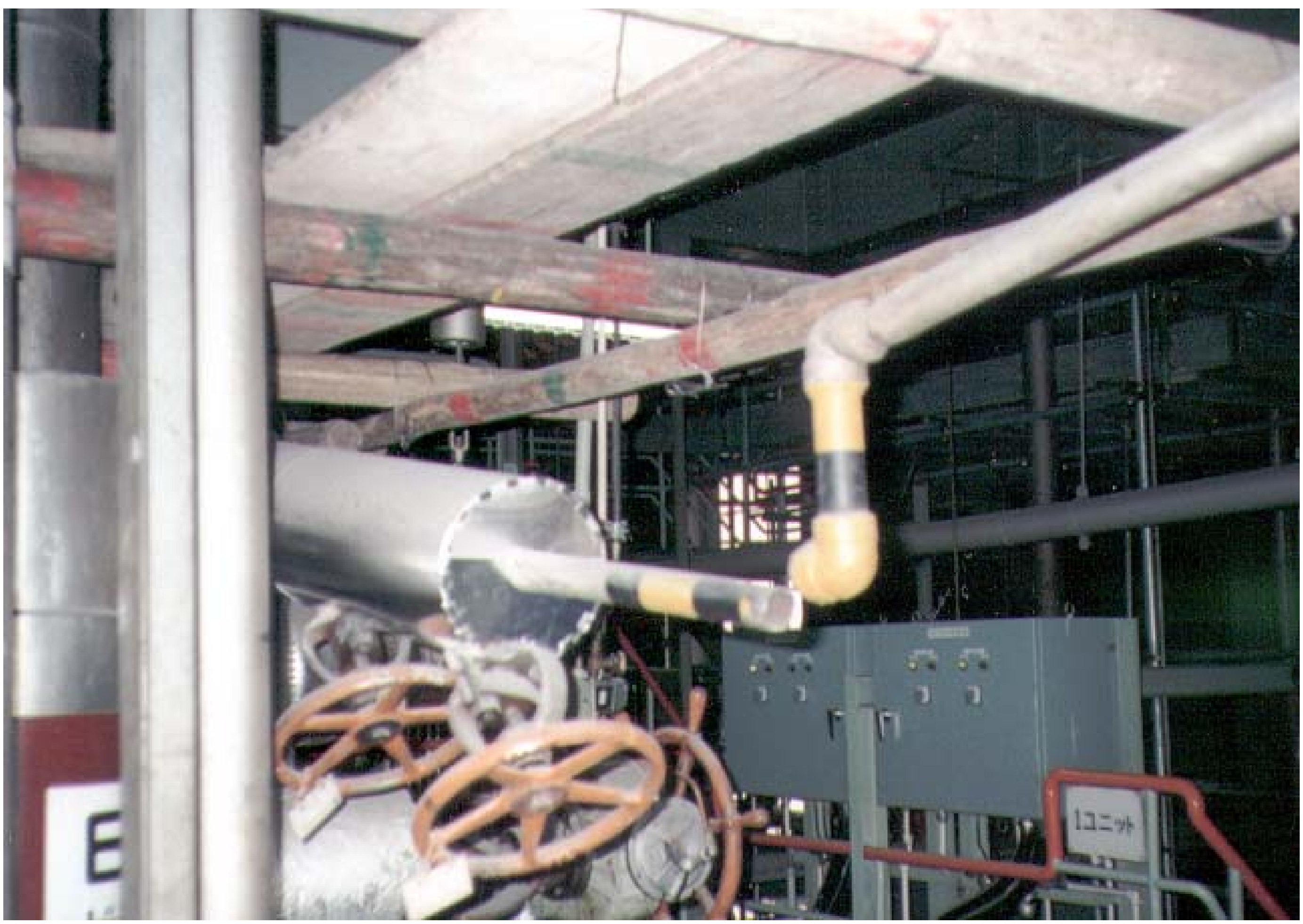
Amagasaki No. 3 is an oil-fired steam plant that includes three units with a capacity of 156 MW each. Horizontal peak ground accelerations at the site were about 0.3g, with significant ground settlement observed. The most significant damage was the failure of seismic ties between the boiler and its support structure. Preliminary observations indicate that the ties were not loaded linearly, resulting in dramatic failure of the ties near the top of the structure. U.S. fossil plants with suspended boilers have undergone similar ground motion but have seismic stops rather than ties. The stops absorb energy by deforming during an earthquake, while ties are stronger but less ductile. Both the seismic ties observed at Amagasaki No. 3 and the stops found at U.S. stations have had substantial damage from moderate ground motion, although stops do appear to prevent damage to the boiler.

Amagasaki No. 3 also had a small pipe failure caused by steam drum displacement relative to the structure and miscellaneous failures from ground settlement. Pipe and electrical raceway supports adjacent to the building foundation were damaged by ground settlement. The piping and raceways remained functional.

Higashi Nada includes two gas turbine units that were constructed in 1974 on reclaimed land. The soil conditions at the site consist of 7 to 8 meters of very soft clay overlying a layer of sediment more than 10 meters thick. The plant underwent a peak ground acceleration of about 0.6g during the earthquake, but it was not operating at the time because the plant is used only during peak demand periods, typically in the summer months.

Major buildings, equipment, and tanks at Higashi Nada are founded on piles. There are four major flat-bottom tanks, including

Pipe failure caused by steam drum displacement at the Amagasaki No. 3 plant.



two fuel tanks with a weight of about 4,000 kilograms, one raw water tank (about 1,000 kilograms), and one purified water tank (about 500 kilograms). All the tanks are supported on concrete foundations without anchorage, and the foundations are supported on 30-meter-long precast concrete piles. The ground settled near the tanks by as much as 70 centimeters. As a result of the settlement, the tops of the piles could easily be seen beneath the foundations. The foundations were observed to have tilted slightly, with no damaging effects to the tanks.

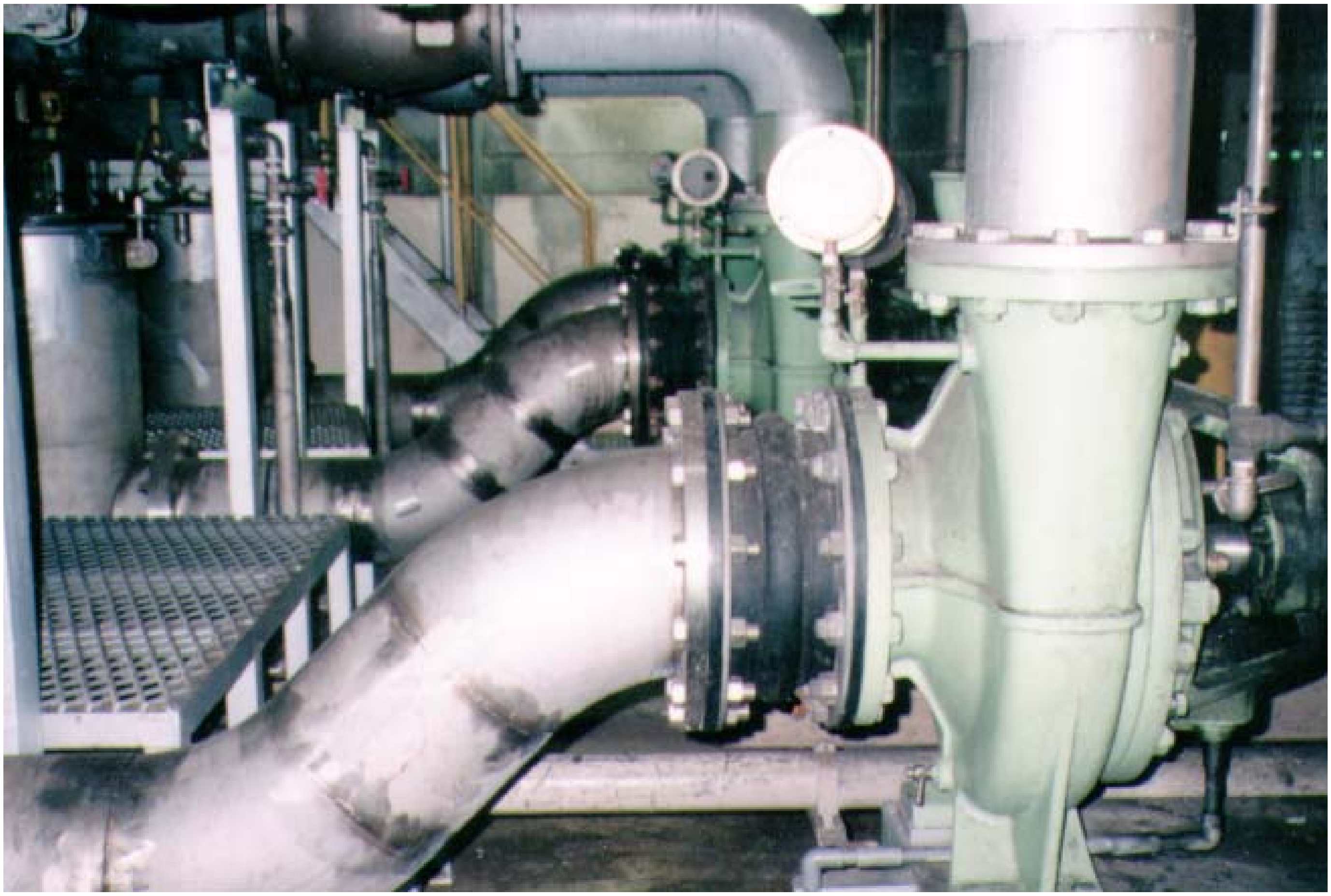
The buildings and equipment at the plant withstood the earthquake without direct damage. However, differential settlement of foundation slabs did result in misalignment of equipment on adjacent foundations. At several locations, ground settlement exceeded a meter relative to the pile-supported foundations. Piping systems had substantial deformation, but the only failure was associated with a clamped mechanical coupling. In several cases, the ground settled to such an extent that several pipe supports and their concrete foundation blocks were left dangling in the air, supported by the pipes to which they were attached. Virtually all damage was related to ground settlement and relative displacement between foundations.

Nine 275-kV substations were damaged, including bus disconnect switch failure, transformer oil leaks, transformer anchorage failure, transformer bushing failure, and other miscellaneous damage. Liquefaction and ground settlement were evident. The extensive use of dead-tank gas-insulated and oil-filled circuit breakers resulted in positive circuit breaker performance.

Telecommunications

Telecommunications systems did very well in the earthquake, with very few service interruptions. Telephone service was available on a limited basis in the most heavily

Broken arresters at the Itami Substation.



These expansion joints at pump discharges at a Port Island wastewater disposal plant had no damage.

damaged areas on January 18, although a week after the earthquake, more than 25,000 telephone lines were still disconnected in the 18 municipalities hardest hit. More than 2,000 telephones were installed for public use at shelters and public offices.

Water

The Kobe area had a water system designed to be operable after earthquakes. There are approximately 30 reservoirs supplying water to the Kobe area through a gravity-fed system. Of these, 22 reservoirs had automatic emergency shutdown valves and multiple storage tanks. In the event of an earthquake, these valves are designed to automatically shut off water flow out of half of the reservoir tanks. All 22 valves tripped and worked correctly. This enabled 30,000 cubic meters of water (8 million gallons) to be stored in reserve in the reservoirs equipped with automatic shutdown valves.

As a result of extensive ground settlement and other failures, underground water pipelines were severely damaged in the earthquake, with approximately 2,000 breaks resulting in general lack of service in Kobe, Ashiya, and Nishinomiya. The massive damage to the water transmission lines caused the tanks without automatic shutoff valves to drain in the first 1 to 8 hours after the earthquake. By the time the fires had started, much of the unreserved water had already drained from the system. With the transmission lines destroyed, the reserve water was also unavailable for fire fighting.

Nine days after the earthquake, 367,000 households in Kobe still had their water supply cut, and 98% of Ashiya households and 85% of Nishinomiya households were also lacking service. The population in the heavily impacted areas was notified to plan for no water service for about two months.

Workers repairing damage to a water treatment plant across from Rokko Island.

Emergency water distribution was very limited in the days after the earthquake, with citizens resorting to buckets, tubs, and other makeshift containers in order to haul limited quantities of water to their homes from a relatively few tank trucks. In areas near the harbor, private construction and shipping companies brought in tugboats and other smaller vessels and set up water distribution centers for nearby neighborhoods, supplied by condensers on the ships.

The condition of the sewer system was similar to that of the water supply system. This damage was of less consequence since water was not available for flushing toilets. Public rest rooms overflowed, and sanitation was a concern.

In summary, the city of Kobe had made a sincere effort to provide an earthquake-resistant water and fire protection system (see the following section, “Fire Following Earthquake”). However, the system failed and was not scheduled to be fully restored for many months.

Gas

The gas system had at least 1,400 breaks in its underground distribution system, primarily at service lines, with general curtailment of service by Osaka Gas Company to 834,000 households. Japanese buildings and homes have automatic gas shutoff systems, but many failed to work because of building collapses, other building damage, and broken pipes. The population in the heavily impacted areas was also notified to expect no gas service for about two months.

Information on other gas system facilities was not available at the time of this writing, although a large gas holder near the Port of Kobe did not have any obvious structural damage. There are a number of petroleum and other at-grade fuel tanks in the port area, the largest being perhaps 25 meters in diameter and 15 meters high. Only a few were observed to have any damage, and only one was observed to have collapsed. Many of these tanks were at-grade and freestanding, while some were bolted to their foundations. Most appeared to have fixed roofs.

Several liquefied petroleum gas (LPG) tanks exist in the port area, and one was reported to have cracked, resulting in the temporary evacuation of 70,000 people. Two groups of three large spherical tanks were seen along the waterfront in Kobe. They were well braced with heavy diagonal pipe bracing between column supports and appeared to have no damage. There were no reports of liquid fuel pipe breaks, with the exception of one line at Kansai International Airport.

FIRE FOLLOWING EARTHQUAKE

UPI/Kyodo

Fire in central Kobe.

Large fires following strong earthquakes have long been considered to be capable of producing losses comparable to those resulting from the shaking.

The risks are particularly high in Japan because of high population densities; very narrow streets and alleys, which cannot act as fire breaks; numerous old wood-frame smaller commercial and residential buildings mixed in the commercial zones of towns; unanchored or unprotected gas storage tanks or heaters; and a mix of collapse-prone old buildings in all built-up areas. These risks were most recently exhibited in the large fire that destroyed much of the town of Aonae on the Island of Okushiri during the M_w7.8, July 12, 1993, Hokkaido Nansei-oki Earthquake.

Many Japanese municipalities, and particularly Tokyo, have long considered earthquake-generated fires to be very high risks, and various risk management programs have been started in Japan. Kobe, for example, had specially constructed underground cisterns for fighting fires if parts or all of the distribution water lines failed. However, whatever measures had been taken in Kobe were overwhelmed following the January 17 earthquake.

The Kobe Fire Department (KFD) is a modern, well-trained fire response agency, organized into Prevention, Suppression, and General Affairs sections, and a Fire Academy. The city is divided into 11 wards for fire protection purposes. KFD maintains 11 fire stations and 15 branch stations, served by 1,298 uniformed personnel. Equipment includes two helicopters, two fireboats, and 196 vehicles. Other equipment includes 72 portable pumps. Fire engines carry predomi-

Top: The state of the fires at 4:30 P.M. on January 17.

Bottom: Burned area in the Nagata Ward.

nantly 50- and 65-millimeter hose; larger hose is not available except for drafting purposes.

KFD has a civil disaster prevention program as well as a cadre of volunteer fire corps with about 4,000 members. This corps provides the first on-scene engagement of the fire, performing functions such as giving directions to arriving emergency vehicles and helping to guide people to safety.

Fire water is primarily from the city water system, served by gravity from 30 reservoirs. Of these, 22 have dual tanks, with one tank having a seismic shutoff valve so that, in the event of an earthquake, one tank's contents is conserved for fire fighting. In this event, all 22 valves functioned properly, conserving 30,000 cubic meters of water, which, however, could not be delivered because of approximately 2,000 breaks in the underground piping. Kobe has approximately 23,500 fire hydrants, typically flush-mounted (i.e., under a steel plate in the sidewalk or street) with one 150-millimeter-diameter hose connection. The city has provided underground storage of water for disaster fire fighting in 968 cisterns, generally of 40,000-liter capacity, sufficient for about a 10-minute supply of a pumper. All engines carry hard suction, so that additional water can be drafted from Osaka Bay or the several streams running through Kobe.

KFD had minimal staffing on duty at the time of the earthquake, possibly because the previous day had been a holiday. Initial actions included recalling off-duty personnel and responding to fire calls. Approximately 100 fires broke out within minutes, primarily in densely built-up, low-rise areas of the central city, which comprise mixed residential-commercial occupancies, predominantly of wood construction. Within 1 to 2 hours, several large conflagrations had developed. There were a total of 142 fires reported in Kobe on January 17, the majority being in the wards of Higashi Nada (24), Nada (24), Hyogo (37), Nagata (19), and Suma (18). Modes of fire reporting were unclear as of this writing, and fire response was hampered by extreme traffic congestion, and collapsed houses, buildings, and rubble in the streets. Because of the numerous collapses, many areas were inaccessible to vehicles.

A typical street scene in a residential and light commercial area of Kobe. A house has collapsed, blocking the very narrow street and preventing access to the area by the fire department. Thousands of narrow streets were blocked like this. In other areas, many of the collapses were traditional buildings with ground-floor stores or shops and second-floor residential units.

Water for fire-fighting purposes was available for 2 to 3 hours, including the use of underground cisterns. Subsequently, water was available only from tanker trucks. KFD attempted to supply water with a fireboat and relay system, but this was unsuccessful due to the relatively small hose used by KFD. An EQE engineer overflew the area at about 5:00 P.M. on January 17 and was able to observe all of the larger fires (about eight in all)

This truck carrying kerosene caught fire when the overhead roadway collapsed onto it.

from an altitude of less than 300 meters. No fire streams were observed, and all fires were burning freely—several with flames 6 meters or more in height. No fire apparatus were observed in the vicinity of the large fires, although fire apparatus could be seen at other locations (their activities were unclear from the air). Some residents formed bucket brigades (with sewer water) to try to control the flames.

Fire spread was via radiant heat and flame impingement, building to building in the densely built-up areas. The wind was calm, and fire advance was relatively slow. In a number of cases, fires were observed to have stopped at relatively narrow fire breaks (e.g., 10 meters) or, in at least one case, at a high-rise apartment building, probably as a result of active fire fighting. The final burned area in Kobe was estimated at 1 million square meters, with 50% of this in the Nagata Ward.

The Ashiya Fire Department reported 11 fires on January 17; nine of them were before 7:30 A.M. Distribution of the fires was along an east-west line about 1 kilometer wide centered on National Route 2. The total burned area for the 11 fires was about 4,400 square meters.

ECONOMIC IMPACT

Residents walked the streets of Kobe after the earthquake examining the damage.

While it is still too early to estimate the total economic impact of the Kobe Earthquake, it is already clear that the extent of the regional economic disruption exceeds the experience of any modern urban area in a natural disaster. The direct and indirect business interruption losses will most likely outweigh repair costs, particularly with respect to the consequences of the transportation and other lifeline failures. The impact on the national economy will likely be minimal, although uncertainty and speculation caused the Nikkei Index to drop as much as 5.6% of its value in one day. The overall economic impact and long-term effects of this disaster will be influenced to a large extent by the speed with which physical infrastructure can be repaired and business activity resumed.

Repair Costs

Current estimates of the repair costs in this earthquake have been reported in the range of U.S.$95 billion to U.S.$147 billion, many times the damage inflicted by the 1994 Northridge Earthquake. These figures do not include the loss to building contents such as equipment and inventory, which will also be substantial. Repair cost estimates made by the Hyogo Prefectural Government, the National Land Agency, and the Ministry of Transportation three weeks to a month after the disaster are shown in the table on the next page.

Some of the cost of repair and reconstruction will be financed through a variety of government programs. The national

REPAIR COST ESTIMATES (U.S.$ BILLIONS)

AGENCY	BUILDINGS	HARBORS	ROADS	RAIL-ROADS	UTILITIES	OTHER
Hyogo Prefectural Government	65.7	11.8	6.8	4.6	– –	– –
National Land Agency	71.3	– –	24.9	– –	6.8	5.7
Ministry of Transportation	– –	8.4	– –	4.7	– –	– –

government is considering setting up an emergency budget of ¥900 billion (U.S.$10 billion) to deal with the impact of the earthquake, especially to repair roads, water and sewer systems, harbor facilities, and schools. It has announced preliminary plans to subsidize up to 90% of the cost of repairing public facilities. Earthquake victims are eligible for relief grants, low-cost loans, and tax breaks. To cover the cost of reconstruction, officials are planning to issue some ¥700 billion (U.S.$8 billion) in construction bonds and ¥600 billion (U.S.$7 billion) in deficit-covering bonds in anticipation of tax revenue drops. Taking into account earthquake-related reductions in corporate and personal income taxes, the Finance Ministry is anticipating a drop of ¥500 billion to ¥600 billion (U.S.$6 billion to U.S.$7 billion) in tax revenues for the fiscal year. Officials are also considering raising taxes, and the consumption tax increase scheduled for 1997 may be adopted sooner.

People carrying supplies and property into and out of Kobe on foot – the only available means of transportation for much of the population for weeks following the earthquake.

Lines of trucks bringing supplies to the populace, as well as equipment to start demolition and removal of damaged buildings.

Business Interruption and Recovery

In addition to the cost of repairing physical damage, the regional economy is also being severely affected by temporary business interruption and the loss of import/export capabilities. After the earthquake, all economic activity in Kobe virtually halted due to earthquake damage to buildings and contents, loss of water and other utilities, difficulties in obtaining supplies, and employee absenteeism. Hyogo Prefecture, which includes Kobe and the other most heavily impacted cities, produces about 4% of the national output but accounts for 19% of the country's production of leather goods, 10% of its rubber manufacturing, and 9% of the country's steel. One-third of the prefectural economy is engaged in manufacturing. The region shaken by the earthquake accounts for almost one-fifth of the Japanese economy.

Among Kobe's principal industries, steel production, shipbuilding, chemicals, and food processing were heavily damaged by the earthquake. Two of the three largest employers in Kobe closed their plants for several days. The third sustained severe structural damage to its facilities, and after one week was able to resume production at only one of its two area plants at 40% of normal production levels. These three companies together employ more than 14,000 people in Kobe.

The manufacturing sector had losses in both large and small businesses. Many major plant facilities were shut down for several days or more, including at least four large electronics plants, six steel or heavy industry plants, and three beverage production facilities. Small- and medium-sized manufacturing firms were reportedly heavily damaged in the earthquake, including structural, fire, or contents damage to more than 40% of local knitted goods manufacturers, more than 90% of synthetic leather shoe manufacturing facilities, and many Japanese wine (sake) manufacturers, which are heavily concentrated in this region of Japan.

The transportation and utilities sectors were also severely affected by this disaster. With systems restoration time frames typically on the order of several months, revenue losses during the interim will be significant. For example, Hanshin Electric Railway has estimated that in addition to ¥79 billion (U.S.$895 million) in damage to its rail facilities, it will also lose ¥4.5 billion (U.S.$51 million) in revenue. Osaka Gas, Japan's second-largest gas utility, estimates that in addition to ¥15 billion (U.S.$170 million) in pipe repairs, it may lose ¥6 billion (U.S.$68 million) in revenues because of the disruption.

During the first week after the earthquake, virtually no retail or service establishments were open for business. In addition to building and inventory damage, as well as employee absenteeism, these businesses were critically affected by the disruption of lifeline services. For the most part, those businesses that were able to open did not depend heavily upon water or natural gas, which were widely unavailable; for example, some gas stations, electronic repair stores, shoe stores, and convenience stores operating out of the storefront were in business.

Indirect business disruption was also felt by producers that had little damage to their own facilities but had difficulties in obtaining supplies and other input to production or in selling products. For example, one week after the earthquake, water for industrial consumption was still unavailable to 190 companies. The pearl industry in the region, which includes more than half of Japan's pearl processors, may not return to normal operations until June, because the earthquake has halted

Relief workers unloading boxes of supplies at a refuge center in the Nada Ward.

activity in the peak auction season, and growers are unable to sell their cultured pearls.

Just-in-time production methods employed by large manufacturing firms appear to be vulnerable to the widespread transportation disruption. Four auto manufacturers and a motorcycle manufacturer reported production cutbacks and partial or temporary shutdown of operations in plants outside the shaken region (as far away as Tokyo) because parts could not be obtained from or transported through the affected area. Japan's largest automobile manufacturer cut back production by 20,000 cars and closed plants throughout Japan for several shifts because of the difficulties in obtaining supplies.

Transportation disruption has also raised transportation costs for producers moving goods in the region. For example, the closure of the Port of Kobe has forced many businesses to divert cargo shipment to other facilities around Japan or East Asia. However, with the cost of shipping a container from Kobe to Tokyo/Yokohama approaching that of moving it across the Pacific to the United States, these alternatives will add substantially to producers' transportation costs. The impact of Kobe's port closing on regional industries will be greatest in manufacturing, because Japanese exports through Kobe to the United States, for example, consisted primarily of auto parts, tires and tubes, chemicals, engines, motors, and hardware. On the other hand, imports arriving in Kobe from the United States had included goods such as animal feed, chemicals, paper, cotton, vegetables, and meat.

The indirect effects of the earthquake will extend beyond the areas of greatest physical damage. The Port of Kobe served not only as a port for goods going in and out of Kobe, but also as a transshipment hub for transportation to and from the Far East. With its central location, modern shipping facilities, and infrastructure tailored to the modern shipping industry, the Port of Kobe was ideally suited to the transfer of smaller local ships' goods to and from large trans-ocean ships.

Completely destroyed pier at the Port of Kobe.

Immediately following the earthquake, other port facilities in the Far East, including ports in Kaohsiung, Singapore, and Hong Kong, temporarily took over this function from the Port of Kobe. It is feared that the development of these other transshipment hubs will result in the long-term decline in the use of Kobe as a transshipment hub. In addition to Osaka, which has been overburdened by the increased traffic, Maizuru Port in Kyoto Prefecture, and ports in Yokohama and Nagoya have been serving as alternate outlets for goods from the central region of Japan.

Indirect effects are also being felt in the regional real estate market: In Osaka, for

Japanese Versus California Residential Earthquake Insurance

While comparisons are very difficult, it is of interest to contrast the situation of two typical houses, one in Tokyo and the other in Los Angeles (this comparison is not based on particular structures, but rather on the general knowledge of several experts):

APPROXIMATE COMPARISON, TOKYO AND LOS ANGELES RESIDENTIAL INSURANCE COSTS[1]

	TOKYO	LOS ANGELES
Suburban neighborhood	Tachikawa	Northridge
Per capita income	$20,000	$22,000
Commute minutes to central business district	90	60
Typical house lot, square meters	80	500
Typical house floor area, square meters	140	180
Typical sales price (1995, estimated)	$750,000	$250,000
Typical replacement value (structure)	$250,000	$180,000
Ratio, structure replacement to total price	0.33	0.72
Total sum insured (i.e., Cov. A or structure only)	$100,000	$180,000
Earthquake premium (annual)	$500	$360[2]

Notes: 1. All sums in 1995 U.S.$
2. Northridge premium is prior to 1994 Northridge Earthquake

Several observations emerge from this comparison: U.S. homeowners receive more for their premium, not even considering the fact that the U.S. homeowner is already insured for fire following earthquake via the basic fire policy; and the bulk of Japanese residential values are in the land rather than in structures. Thus, even in the case of a total loss, the Japanese homeowner, while sustaining a monetary loss similar to the U.S. homeowner's, still maintains substantial equity (and borrowing power) via the land value. This is further reinforced by the fact that Japanese homeowners are typically not as heavily mortgaged (expressed in percentage terms) as are U.S. homeowners. In addition, another channel of relief for some homeowners in Kobe has emerged, reflecting the underlying nature of Japanese society. Recognizing the plight of their employees, some companies are offering low-interest mortgages, or are even rebuilding employees' houses in a few cases, while smaller businesses impacted by the earthquake are generally supported by their "parent" companies in the *keiretsu* (or Japanese conglomerate system).

example, the flood of households and businesses seeking temporary relocation has driven up the price of apartment and commercial office space by about 10% in many areas, despite the fact that there had been a depressed market for commercial space before the earthquake. Consumer spending, on the other hand, has reportedly dropped by 20% to 30% in Osaka after the disaster, largely due to the feeling among consumers that "self-restraint" in spending was appropriate when people in nearby Kobe were still suffering. Kyoto, which had very little damage, saw a sudden drop in tourism.

Recovery of local businesses will take months or even years, with some industries recovering more quickly than others. A government survey found that six days after the earthquake, two-thirds of the gas stations in the impacted region were back in operation. About a week after the earthquake, banks were widely in operation, with some chains reporting close to 90% of their branch offices open in the heavily impacted area. One week after the earthquake, many other businesses reported partial resumption of business operations. For example, in the case of Japan's largest supermarket chain, 25 of its 49 stores in Hyogo Prefecture were closed by the earthquake; after two weeks, 12 of these had reopened. At least one major department store, however, announced that it will permanently close its downtown Sannomiya store because of structural damage, while another expected to take at least a month to open its downtown store.

While the recovery will take some time, as reconstruction gets underway, the rebuilding efforts will provide a boost to the regional economy. Already, reports from one district in Osaka indicate that the number of construction day jobs has doubled from before the earthquake because of the need to clear rubble. The Hyogo Prefectural Government is currently considering designating Kobe as a duty-free zone to encourage rebuilding and investment in the region.

Insurance Aspects

While the estimates of the Kobe Earthquake's U.S.$95 billion to U.S.$147 billion in property damage are unprecedented, the impact of this event on the insurance industry will be significantly less than a number of other recent events, including Typhoon Mireille in Japan (which had total insurance claims of U.S.$5.7 billion), Hurricane Andrew (U.S.$16 billion), and the Northridge Earthquake (U.S.$12 billion). Total insurance payments arising from the Kobe Earthquake are presently estimated at about U.S.$6 billion, although this could rise because of two factors: (1) additional newly discovered damage, as buildings are inspected (similar to what occurred after the Northridge event), and (2) as-yet unreported claims against offshore insurers, either against multinational corporate policies, or for time element claims resulting from the need for shipping to be diverted around the Port of Kobe.

When compared with previous events in Japan or the United States, there appears to be a major disparity between property loss and the portion borne by the insurance industry in Japan. This difference exists because the government and the Japanese insurance industry, which consists of only about a dozen very large insurance companies, recognized the difficulties in insuring for earthquake in Japan. That is, they realized that earthquakes in Japan may be "uninsurable," in the sense that Japan has the potential for large earthquakes almost anywhere on the archipelago, and that for the most part Japan also comprises a relatively small number of major cities. In effect, Japan in its entirety represents a unique sort of adverse selection (particularly Tokyo), for which the government and the insurance industry have been unable to identify an adequate insurance solution.

The current scheme of residential earthquake insurance was introduced in 1966 following the 1964 Niigata Earthquake. This scheme established Japan Earthquake

The temporary office of a Kobe newspaper on January 18, after the regular office was closed by damage.

Reinsurance Company Ltd., which in turn is reinsured by the central government. Basically, the scheme offers a limited earthquake endorsement to the basic fire policy (note that, in contrast to the United States, fire following earthquake in Japan is not covered under the basic fire policy but rather requires the earthquake endorsement). The indemnity under this policy is typically limited to about 30% to 50% of the structure's replacement value, capped at about U.S.$100,000.

In the claims process, the structure is determined to fall into one of three categories: "total loss," "half loss," or "significantly less than half loss." If the structure is determined to be a total loss, then payment is for the total sum insured. If it is a "half loss," the indemnity is prorated at 50% of the total sum insured (i.e., 15% to 25%), with the contents further severely limited unless they are totally destroyed. Losses that fall under "significantly less than half loss" are not reimbursed. A minor allowance is made for incidental expenses. Earthquake premiums for this coverage are based on pure premium plus loading, with no profit (for the earthquake cover). The pure premium is based on an estimation of annualized loss determined from a 500-year record of earthquakes (i.e., since 1494). For example, typical premiums in the Tokyo area are about 0.5% of the Total Sum Insured (TSI), versus 0.2% in California.

Under this scheme, homeowners may purchase the earthquake endorsement. Nationally, about 7% of Japanese homeowners purchase this endorsement (versus about 25% in California), although this percentage varies significantly (about 3% in Kobe and 16% in Tokyo, versus perhaps 40% in the San Francisco and Los Angeles areas).

Total liability of the residential insurance scheme is limited to about U.S.$18 billion, with about U.S.$1 billion borne by the Japan Earthquake Reinsurance Company, about U.S.$2 billion by the direct writers, and the remainder (approximately U.S.$15 billion, or 85%) by the government.

Commercial lines insurance risk is not reinsured by the government, but capacity is limited by governmental intervention. A particularly large exposure that absorbs a significant portion of this capacity is the numerous oil refineries in and around Tokyo Bay. It is of interest to note that petrochemical facilities, in general, and tanks in particular, were not heavily damaged in the Kobe Earthquake, which is unusual. Because of the very limited commercial capacity in Japan, some risk is placed offshore, so that nonadmitted (overseas) insurers will bear more loss, due to both offshore primary insurance and offshore reinsurance.

In summary, while the Kobe Earthquake is perhaps the world's most damaging single event (in property terms), the insurance impact is relatively small. This small impact results from the specifics of the Japanese insurance industry, which reflect the unique exposure of Japan to earthquakes. This situation may change very rapidly, however, since the Japanese insurance industry will be largely deregulated within several years. Demand for earthquake insurance following the Kobe disaster, combined with increased competition among Japanese insurers and the entrance of foreign insurers interested in the commercial market, may result in a major shift offshore of the earthquake risk (as discussed above, presently borne largely by property owners). This could rapidly create a major increase in the global insurance industry's exposure to a catastrophic earthquake in Tokyo.

SOCIETAL IMPACT

Earthquake victims camped out at Kobe City Hall.

The most significant societal impact of the earthquake was the tremendous loss of human life. In addition, for more than 300,000 survivors in the heavily impacted cities of Kobe, Ashiya, and Nishinomiya who were displaced from their homes, there were the hardships of finding shelter; securing food and water; locating friends and family members; and acquiring warm clothing for the cold, damp winter weather.

Although some of the displaced people were taken in by relatives and friends, and others possessed the means to relocate to hotels, those requiring emergency shelter reached a peak of 235,443 on the evening of January 17. Many camped in public parks or assembled makeshift shelters from materials salvaged from the wreckage of their homes. The 1,100 shelters included community centers, schools, and other available and undamaged public buildings. Facilities were too few to avoid severe crowding in some shelters, however, causing sanitation problems and increased risk of communicable disease. Indeed, two weeks after the earthquake, reports of influenza and pneumonia were common.

Food, water for drinking and sanitation, blankets, and warm clothing were in short supply for at least the first few days after the earthquake, and many people from the hardest-hit wards made the long walk to the Nishinomiya Railway Station, journeyed to Osaka for necessities, then returned via rail with whatever they were able to transport by hand.

By Friday, January 20, both official and volunteer efforts to supply the basic needs of the impacted area were becoming increasingly evident. Corporations and other nongovernmental organizations donated goods, and transportation was provided by both business and government vehicles. In some cases, normal production schedules and processes were modified to assist in the relief effort. Kirin Breweries, for example, filled liter-sized beer bottles with drinking water and shipped thousands of cases into the Kobe area.

Amid the overwhelming need for safe shelter, some residents chose to remain in damaged residential buildings despite uncertainty regarding structural integrity. There was little evidence during the first week that access and egress of even the most severely damaged homes and apartment buildings were being monitored, and cordoned areas were few and unenforced.

Although temporary housing was being constructed within two weeks after the earthquake, and rent-free rooms were being offered by apartment owners, the demand for longer-term housing still exceeded availability by a factor of 10. Those displaced by the earthquake are likely to compete for available housing with construction workers, technicians, and engineers converging on the area to begin reconstruction.

Disproportionately, it was the poor and the elderly who lost their homes, jobs, and lives—high rises were scarcely affected, while two-story homes were at greatest risk.

Post-earthquake relief scenes.

CONCLUSIONS

The Kobe Earthquake dramatically illustrates the damage that can be expected to modern industrialized society from earthquakes. Most of what happened could have been predicted, and much of the damage was preventable. Hopefully, the disaster will spur building owners to continue—and to increase where needed—their efforts to improve the earthquake resistance of their properties.

Estimates of the potential effects of large earthquakes in the United States, Japan, and other countries have been developed by engineers and scientists over the past 20 years. The Kobe Earthquake now provides answers to many "what if" questions that those scenario studies raised. An event that lasted about 20 seconds caused 5,500 deaths and an economic loss that is greater than the gross national product of many countries. Much of the infrastructure and building stock of a modern city, which many considered to be prepared to withstand a strong earthquake, was destroyed.

While the true dimensions of what happened in Kobe and the surrounding region will not be fully understood for some time, the nature and magnitude of the known losses permit some conclusions to be drawn. While some of our conclusions are applicable primarily to Japan, California, and other parts of the United States, most are applicable to seismically active regions worldwide.

Are We Surprised by What Happened?

Little of the damage observed in Kobe represents new lessons. Most of the causes of the building damage have been observed repeatedly in past earthquakes—particularly since the 1964 Anchorage, Alaska, earthquake. For example, the design details that caused the collapse of elevated structures of the Hanshin Expressway and the Shinkansen (Bullet Train) were similar to those that caused freeway structures to collapse or sustain damage in Oakland and San Francisco in 1989, and in Santa Monica and Los Angeles in 1994. The types of damage observed at the Port of Kobe were also observed (to a lesser extent but because of the same engineering deficiencies) in numerous past earthquakes—several of which were in Japan, starting with the Niigata Earthquake of 1964 and the Tokachi-oki Earthquake of 1968.

A few important new lessons have been learned, however. Some types of new buildings and other structures performed very well, with minimal damage. These included both concrete and steel structures. Unfortunately, other innovative building designs failed dramatically, even though they were expected by some engineers to perform well. This inadequate performance demonstrates the need to incorporate adequate factors of safety when implementing innovative technology for which actual earthquake performance data have not been obtained. Although mathematical methods and small-scale tests are excellent tools for developing new technologies, additional conservatism is necessary until the new technology has been field proven.

Can It Happen Elsewhere?

Japan, in general, is earthquake country, and the Kansai region has a long history of major earthquakes, although the largest event in this century within the immediate vicinity of Kobe was magnitude 6.1 (in 1916). Perhaps because of the recent lack of seismicity in the immediate region, comments such as "we didn't think such a large earthquake could happen here" were frequently heard from the general public, as well as from city officials and emergency responders.

We constantly hear similar statements regarding the seismicity of areas in California, for example, which have not had strong earthquakes in this century. San Diego and Sacramento are two such areas. Like Japan, all of California and the entire West Coast of North America are earthquake regions. It is true, to the best of our knowledge, that the probability of a major earthquake near Portland, Oregon, or Vancouver, British Columbia, is lower than near Los Angeles. It was also true for Kobe, when compared to Tokyo, but

Similarities Between Kobe and the San Francisco Bay Area

The similarities between the geological, seismological, and land-use characteristics of the Kobe area and the East Bay of the San Francisco Bay Area are both striking and important in their implications for seismic safety along California's Hayward Fault. Although there are significant differences between the situation in Kobe and in the East Bay, the lessons learned from the disaster in Kobe should be carefully considered for earthquake disaster planning and damage-mitigation plans for the San Francisco Bay Area.

In both areas, cities lie nestled along a narrow strip of land between mountains and a bay. These strips of land consist mostly of soft to very soft alluvial deposits. The seismic similarities are striking—major faults run directly under the most densely populated section of both areas, along the toe of the mountain ranges. The earthquake in Kobe was a moment magnitude (M_w) 6.9 event. The Hayward Fault is thought capable of releasing enough energy to generate an M_w7.5 event.

The land use in Kobe and the East Bay is also quite similar. Both areas have high densities of residential, commercial, and industrial buildings that are a wide range of structural types and ages. For both areas, the faults run near important transportation and lifeline corridors, including elevated highways, buried subways, long-span bridges, and important railways. The port facilities of Oakland, the largest city in the East Bay, are built on soft soils that may be susceptible to damage similar to that which occurred in Kobe.

Although the residential stock in California may not be as vulnerable to earthquake damage as the residential buildings that were destroyed in Kobe, there is a much higher concentration of vulnerable unreinforced masonry structures in the San Francisco Bay Area than there was in Kobe. Also, just as in Kobe, most of the industrial buildings in the East Bay are built near the bay, where amplification of ground motion through soft soil deposits can be expected. As demonstrated in Kobe, and in San Francisco in the 1989 Loma Prieta Earthquake, these areas are susceptible to large-scale soil failures.

the earthquake happened in Kobe. That is the nature of estimates based on probabilities.

Lack of recent seismicity may only be a sign of accumulating seismic stresses. Areas of the United States and Canada, with clear signs of past large earthquakes—such as the Pacific Northwest; the Wasatch Front in Utah; the New Madrid region in the U.S. Midwest; Charleston, South Carolina; and similar regions—need to heed the lesson of Kobe. Stronger efforts are required in the areas of public education, and in strengthening public and private structures. Research to better identify hazards in the above regions should be increased.

Ground Motion

For Japan, near-record ground motions were recorded in and near Kobe. The strength of the shaking, however, was similar to that observed in several recent events in and outside of Japan. For example, the strength of the recorded shaking in the San Fernando Valley of Los Angeles in 1994 was about the same as in Kobe. The shaking is typical of what can be expected in a moderate- to large-magnitude event. What was different in Kobe, and the main reason for the relatively severe damage, was that the strong shaking occurred in the middle of a metropolitan area, underneath tens of thousands of structures.

Current building codes are based on the observed strength of shaking—which, until recently (mid-1980s), was believed by engineers to be on the order of 50% of that observed in numerous recent earthquakes. This belief was based on a limited data set obtained with relatively few strong-motion instruments. We now have many more instruments deployed, and the resulting many more near-field records being obtained are now telling us that near-field shaking is much stronger (2 times or more) than previously believed. We need to review building code design force levels, given these new data.

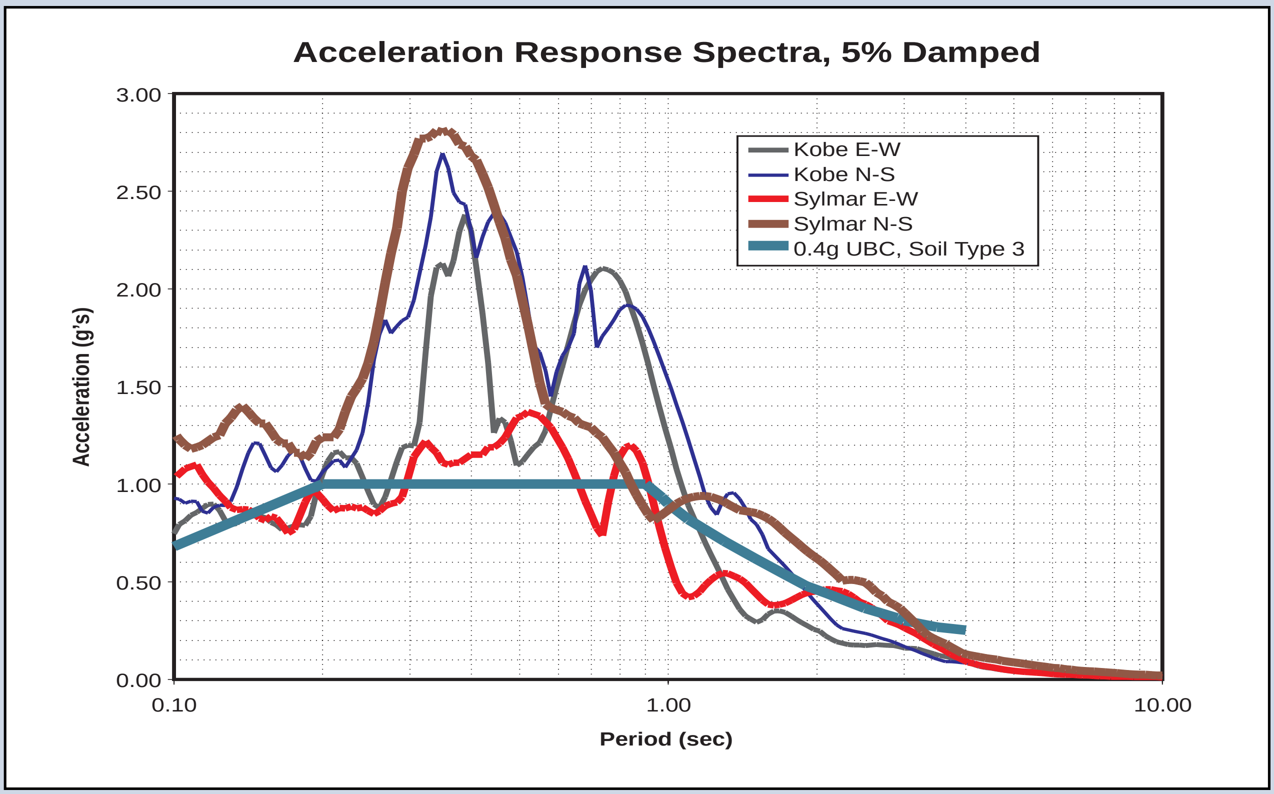
Building Performance

The large commercial and industrial buildings in the Kobe area, particularly those built with steel or concrete framing, are similar to buildings of the same vintage in California. Typically, those buildings were much stronger than buildings of similar vintage in other areas, such as the Pacific Northwest and almost all other countries. The Japanese building code had a major revision for concrete-frame buildings and a more limited revision for steel-frame buildings in 1981. The *Uniform Building Code*, as used in Califor-

Near-field Effects of Earthquakes

Buildings are much like the strings on a violin or guitar. Each building has a unique set of natural frequencies at which it will vibrate when disturbed by a transient load such as an earthquake or windstorm. This is particularly important in earthquake engineering, since the energy delivered by an earthquake to a building is strongly related to the natural frequency of the building. To characterize these effects, engineers use tools called *acceleration response spectra*. These are plots of the response of structures with different natural periods to specific earthquake ground motions.

Since the mid-1970s, building codes have incorporated standard response spectra as a basis for design. In effect, these response spectra set the minimum strength for which a building must be designed. In several recent earthquakes, including the 1992 Landers and Big Bear, 1994 Northridge, and 1995 Kobe events, seismographic instruments located within about 5 kilometers of the fault rupture have recorded ground motions with unusually large response spectra. Originally believed to be "freak" recordings, seismologists have now demonstrated that such large motions are to be expected within a few kilometers of a major event. The figure below compares the spectra recorded by instruments in the near field of the Kobe and Northridge earthquakes with one of several standard spectra contained in the *Uniform Building Code* and used as the basis for building design. These spectra clearly show that when a building is very close to the source of a large-magnitude earthquake, the forces produced in the building can be much larger than anticipated by the building code. The message is clear—buildings designed to the minimum provisions of the building code may not have adequate strength if they are very close to the source of a major earthquake. Seismologists and engineers are currently studying this problem to determine whether building codes should be modified to account for these "near-field" effects.



nia, had major changes in 1973, 1975, and several times since then, for various types of buildings. The changes in both California and Japan were first triggered by the lessons of the 1971 San Fernando Earthquake. In effect, the current Japanese code requires that buildings in Japan be designed for somewhat higher force levels than does the *Uniform Building Code*. These forces are much higher than those required in most other earthquake regions of the world.

Reinforced Concrete Buildings

Typically, pre-1981 concrete-frame buildings performed very poorly in Kobe, with many collapses. Post-1981 buildings performed much better—some were extensively damaged, but most had light damage. The buildings that fared best, and those without significant damage, had extensive concrete shear walls.

Many concrete buildings, similar to those that collapsed, have not been strengthened in California and other earthquake-prone regions and are expected to collapse in future seismic events. There is essentially nothing new in the lessons from Kobe for such buildings—similar damage and collapses have been studied in many recent earthquakes. The most dangerous buildings are the older nonductile concrete buildings and more modern tilt-up and precast concrete buildings in California and elsewhere, and even new concrete-frame buildings without massive shear walls elsewhere in the United States and in Canada. This includes many buildings that are more than 10 stories high. It is obvious, from the performance of these buildings, that a major strengthening program also needs to be initiated in Japan.

Steel Buildings

As in other earthquakes, large commercial and industrial steel-frame buildings performed better than any other type. However, major damage and a few collapses were observed by the investigators.

Pre-1981 steel buildings had most of the serious known damage. Certain innovative types of steel buildings, including high rises, had very serious damage, and collapses could have occurred if the duration of the earthquake had been a few seconds longer. Several types of different innovative building systems are popular in Japan, Seattle (Washington), and other parts of the United States, for example. The lesson here is that while innovation is necessary, the engineering analysis and designs are often inadequate; therefore, detailed third-party reviews should be conducted and detailed full-scale testing is absolutely necessary. Often, only earthquakes can provide such tests, so certain innovations, especially when developed to reduce costs, are potentially dangerous. Further, the typical codes in Japan, the United States, and elsewhere are prescriptive and do not deal well with innovation or with ideas and practices that fall outside of ordinary design practices.

One of the primary lessons from the 1994 Northridge Earthquake was that most of the damage to steel buildings cannot be uncovered immediately because it is often hidden under building finishes that are undamaged. This is proving to be the case in Kobe, and more time is needed to evaluate the overall performance of modern steel buildings in Japan. However, it is obvious from these two earthquakes that certain types of steel buildings, including high rises, may be collapse hazards in strong earthquakes with longer duration of shaking.

Building Performance Criteria

Building owners usually do not understand that the earthquake provisions of the *Uniform Building Code* do not have reasonable performance criteria for larger and stronger earthquakes. The current regulations, including those for all of California, are intended to protect a new building from collapse in an earthquake like the one that struck Kobe. A building is expected to be severely damaged—in fact, it may need to be torn down—but it should not collapse. This is understood by engineers, but they are usually not in a position during the design process to communicate this information to the owner. Further, some do not attempt to warn an owner that if “reasonable” or light damage is the owner's expectation, higher design standards should and can easily be applied, at some increase in cost. In California, higher performance criteria are actually mandated for certain types of structures—schools, hospitals, police and emergency response buildings, and certain power facilities. An owner may specify that these standards be used for other types of structures. Otherwise, a high-value, heavily occupied commercial building is, in effect, designed to the same performance level as a low-value farm building, if the basic code is merely followed.

In Kobe, many commercial buildings had spectacular and extensive damage to their finishes and certain structural elements, losing more than 50% of their value, yet they were considered by structural engineers to have performed well because they did not have fatal structural damage. Such buildings met the requirements of the code, but did not meet the expectations of their owners. The structural engineering profession needs to communicate better the limitations of their designs to the owners. In this respect, the Japanese engineers in Kobe appear to have been somewhat successful. It was apparent that many new buildings were designed to higher standards than required by code, and they performed much better.

Buildings on Soft Soil and Fill

Much of the newer construction in Kobe, particularly larger buildings, is built on very soft, recent alluvial soil and on recently constructed near-shore islands. Most of the serious damage to larger commercial and industrial buildings and infrastructure occurred in areas of soft soils and reclaimed land. The worst industrial damage occurred at or near the waterfront because of severe ground failures—liquefaction, lateral spreading, and settlement.

Such lessons have been observed in numerous other earthquakes, and no great surprises occurred in this event. Because of a severe shortage of constructible land, much of modern Japan, including Tokyo and most other large cities, is built on the worst ground possible for earthquakes. For Japan the lessons are critical. The engineering profession has tried hard to develop methods for strengthening existing and filled soft or weak soils to resist failures during earthquakes. Much has been built based on innovative techniques and theoretical analyses that had never been fully and adequately tested in real, very strong earthquakes. The results are decidedly mixed, but the failures are very costly. Most new buildings on piles appeared to perform well, often with no significant structural or even architectural damage. Older buildings not on piles often performed very poorly; many were tilted severely because of settlement. The infrastructure, particularly underground piping, also had severe damage because of settlement and lateral spreading. This caused extensive business interruption because of a lack of water and gas.

Industry in the port areas was severely affected because of lateral ground spreading and the failures of retaining walls and fills. Most retaining walls along the port failed, and the related ground settlement pulled buildings and other structures apart. This type of damage should be expected elsewhere in Japan to facilities near the waterfront, because the construction in Kobe is typical of Japan. The same observations, to various degrees, apply worldwide.

Ports

The Port of Kobe, much of which was new, was devastated by widespread and severe liquefaction and/or permanent ground deformation, which destroyed more than 90% of the port's 187 berths and damaged or destroyed most large cranes. Damage is estimated at more than U.S.$11 billion. Shipping will be disrupted for many months, with major losses to the local economy and a strain on alternative transportation modes.

Ports all along the western United States are particularly susceptible to effects like those seen in the Kobe Earthquake. The ports of Los Angeles and Long Beach, serving the second-largest urban area of the United States, are on or near the Newport-Inglewood and Palos Verdes faults, while the Port of Oakland (significantly damaged in the 1989 Loma Prieta Earthquake) is only a few kilometers from the Hayward Fault. New data on faults in the Seattle, Washington, and Vancouver, British Columbia, port areas are only now emerging. Significant sections of these ports were built before modern geotechnical practice permitted mitigation of liquefaction risk. The real possibility exists that a large portion of the West Coast's shipping capacity could be crippled by a major earthquake.

Transportation

Bridges and Expressways

The Hanshin Expressway, built in the 1960s and primarily of nonductile, reinforced concrete construction, was virtually destroyed over more than 20 kilometers. The almost completed Wangan Expressway, which is largely composed of steel superstructures, had many spans lose their bearing connections, damaging the superstructures and closing the route indefinitely. A number of major bridges of very modern design were severely damaged, resulting in some coming close to collapse.

There are no significant new lessons from the collapse and damage of the older unretrofitted bridges and elevated structures. Some of the upgrade details observed in older retrofitted structures, such as steel column jacketing, are now widely used in California for strengthening. The apparent good performance of these details in Kobe is important to ongoing U.S. programs and needs to be studied in detail.

The damage to the new Wangan Expressway is disturbing and needs to be studied in detail. Possibly cumulative displacements greater than 2 meters were observed on the deck of the expressway. These displacements and the resulting forces probably exceed existing criteria for new structures in the United States (and other countries). The failures of many bearings, and other details, were dramatic and also require detailed investigation.

Further, the performance of the large new bridges, including cable-tied arch, braced arch, and cable-stayed bridges, should be studied extensively because this is by far the strongest earthquake to affect such bridges. The lessons are invaluable, for both new designs and the retrofit of existing large bridges worldwide. Much of the damage observed in these structures has not been seen before. This earthquake also dramatically illustrates the need to speed up the ongoing strengthening program of bridges such as the Golden Gate and San Francisco-Oakland Bay bridges, before a strong event causes even more costly damage and larger economic disruptions than those observed in the Kobe region.

Rail Systems

The narrow Kobe transportation corridor is almost the only rail link between central and southern Japan. It was entirely severed by the earthquake. A number of stations, elevated rail structures, and bridges failed. Several kilometers of elevated structures, including the main north-to-south Bullet Train line, were severely damaged. The structural and foundation details that caused the damage have been observed in numerous prior earthquakes, and the damage was predictable.

While some differences do exist, these rail structures are similar in many respects to U.S. construction. Japanese commuters rely much more on rail lines than do U.S. commuters, but the United States is increasingly emphasizing mass transit. The San Francisco Bay Area relies heavily on the Bay Area Rapid Transit (BART) rail line, and the Los Angeles region is in the midst of a major commuter rail construction program. The damage to elevated structures and the large displacements observed in soft soils, as discussed above, suggest that a review of current design standards, as well as a reevaluation of existing public rail systems such as San Francisco's BART system, should be conducted.

Other Infrastructure

Gas

The gas system in Kobe had major damage, generally caused by ground or building failure, which contributed significantly to the fire problem. Additionally, loss of the system for several months has been a major hardship on the population and has caused a long period of business interruption for many companies. The earthquake once again points out that in high-seismic-intensity areas, gas system damage can contribute significantly to the overall level of damage and long-term socioeconomic impact. Further efforts are required by suppliers to review gas systems in seismic areas for potential damage and to investigate high-technology methods for automatic system control at the meter and upstream as part of their emergency preparedness planning.

Electric Power and Telecommunications

The electrical and telecommunications systems in Kobe and surrounding areas performed as expected based on experience from previous earthquakes. Facilities near the epicenter were damaged but the systems' resiliency prevented widespread service interruption. Long term power outages were limited to the most heavily damaged areas.

Electrical generation facilities (power plants) had limited damage, with the exception of failures related to displacement of suspended boilers and soil failures. The electrical transmission system performed well, with most of the major transmission lines skirting the heavily damaged region of Kobe. The results may have been substantially different had the epicenter been located closer to the 500-kV transmission system.

Although the power systems performed well operationally during the earthquake, there were substantial financial losses. Foundation repairs or replacement, and boiler repairs at generation facilities will take many months. Expensive, extra high-voltage substation equipment must be replaced, and the distribution network must be essentially rebuilt within heavily damaged areas of Kobe. The transmission and distribution components have been shown in past earthquakes to be one of the more earthquake-vulnerable portions of the electrical power industry, a finding further emphasized in the aftermath of the Kobe Earthquake.

Efforts are required to review electric and telecommunications systems in seismic areas for potential damage and emergency preparedness, and to investigate methods for reducing damage.

Water

Generally, ground or building failure was the cause of the severe damage to Kobe's water system. The resulting lack of water contributed significantly to the fire problem and will be a major hardship on the population for several months.

Earthquake improvements had been developed for the system, including the use of seismic shutoff valves at reservoirs. However, three major deficiencies were observed.

First, while seismic shutoffs existed at the reservoirs, none existed within the distribution system, so that even a few breaks could severely lower pressure and impair the system. During the earthquake Kobe's system sustained perhaps 2,000 breaks. The system needed a series of seismic shutoff valves at key locations, placed so as to isolate areas of likely failure and thus maintain a "backbone" system. These valves needed to be remotely operable.

Second, cisterns for backup fire water supply were plentiful in Kobe—nearly a thousand; however, these typically provided only a 10-minute fire-fighting supply. In the United States, comparable cisterns provide a 1-hour supply, making them much more useful.

Third, the emergency response capabilities of the water department were very limited, and the fire department's 65-millimeter hose proved insufficient for relaying adequate amounts of water. Kobe needed a large-diameter hose, portable water supply system, such as that employed by the San

Francisco Fire Department in the 1989 earthquake. Only a few cities in the United States, and none in Japan, have such a system.

Fire Following Earthquake

More than 150 fires occurred in Kobe and surrounding areas in the hours after the earthquake. These resulted in several large fires, and fire fighters were for the most part unable to combat them because of streets being blocked by collapsed buildings and building debris, traffic congestion, and severe water system damage. Fortuitous calm wind conditions prevented conflagrations.

The United States and Japan have both sustained the largest peacetime urban conflagrations in this century's history—because of earthquakes. Fire following earthquake is a potential major agent of damage, of possibly holocaust proportions, for both the United States and Japan. This is verified by major non-earthquake conflagrations in Southern and Northern California in recent years. Should a major earthquake occur in the United States or Japan under unfavorable meteorological conditions, loss of major parts of a city is quite likely.

Further efforts are required to increase efforts to analyze post-earthquake conflagration risk; increase awareness for the fire service and the public; and begin research and development for improved post-earthquake fire-fighting response, such as increased training of citizen fire brigades, alternative water supplies, and "smart" control of gas and water systems.

Preparedness and Response

While data are not yet complete, preliminary observations suggest that preparedness and emergency response efforts in Kobe were less than satisfactory. The immediate urban search and rescue effort was inadequate for the thousands of buildings destroyed in this event. The problem would have been further compounded had the earthquake occurred during the day, when thousands more people would have been trapped in major derailments and office building collapses.

Preparedness and emergency response are often the most affordable, if not the only possible, mitigation techniques available to many regions. U.S. preparedness and response have often been satisfactory, but lapses have occurred (e.g., the immediate response following Hurricane Andrew). No matter what structural retrofitting may precede an event, it can never entirely mitigate the problem, so that a large, prepared emergency response capability will always be required.

Efforts are needed to (1) continue and increase support for emergency preparedness and response, at all levels, public and private; (2) encourage development of innovative techniques for improved response such as automated, rapid post-event damage assessment and decision-making using geographic information system-based tools; and (3) investigate enhanced response through development of citizen cadres for disaster assistance.

Summary

The Kobe Earthquake is a terribly striking example of what earthquakes can do to a modern industrialized society. The loss of nearly 5,500 lives and the hardships of hundreds of thousands of Kobe's residents are tragic. Similar or larger earthquakes are going to occur in Tokyo, Los Angeles, San Francisco, Wellington (New Zealand), and other major cities. We have been "lucky" in the 1989 San Francisco, 1994 Los Angeles, and even the Kobe earthquakes when we consider conditions of time-of-day, wind, and other factors that influence mortality, conflagrations, and the other earthquake consequences that we seek to reduce. The catastrophic loss of more than 140,000 lives in Tokyo in 1923 is an example of what can occur.

We have made the point that there are relatively few new lessons to be learned from the Kobe Earthquake from an engineering viewpoint. The real lesson is that we must motivate our societies to act—to replace or strengthen deficient structures and systems, and improve our planning and preparedness.

阪神大震災

EQE International
44 Montgomery Street, Suite 3200
San Francisco, CA 94104 USA