Water and Sewer Systems

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1.0 Introduction

This report describes the water and sewer lifeline systems that were affected by the Hyogo-Ken Nanbu (Kobe) earthquake of January 17, 1995. This moment magnitude M_w 6.9 (JMA magnitude 7.2) earthquake is the most disruptive earthquake on these types of lifeline systems in recent history. In almost every category, lifeline disruptions were on the order of ten-fold larger than observed in recent U.S. urban earthquakes (1994 Northridge, 1989 Loma Prieta).

To develop this report, the authors conducted reconnaissance investigations of the affected water systems in the Kobe - Osaka area. Detailed information received was obtained through meetings with officials of the following agencies: City of Kobe - Department of Public Works, Water Department; City of Kobe - Department of Public Works, Wastewater Department; City of Ashiya - Department of Public Works, Water Department. Assistance in organizing the reconnaissance efforts was provided by Professor of Civil Engineering Shiro Takada of Kobe University, which was greatly appreciated. Also supporting the reconnaissance effort were the excellent efforts of Mr. Junichi Ueno, Mr. Fred Cardenas and Mr. Nemat Hassini. The reconnaissance trips were in part sponsored by ASCE - TCLEE, NCEER, and NIST, whose support is greatfully acknowledged. It must be recognized, however, that the observations and conclusions made in this report are the responsibility of the report's authors, alone.

As with any post-earthquake investigation, it is not always possible to get all the information strictly correct. We hope that this report does not contain such errors, but it is recognized that mis-interpretations or incomplete information is always possible. We apologize for any inconvenience this may cause the reader.

2.0 Geotechnical Considerations

The earthquake occurred January 17, 1995 at 5:46 am. The epicenter of the earthquake was on Awaji Island, west southwest of Kobe. The trend of the faulting was east

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northeast, running directly beneath Kobe; however, no faulting actually reached the surface in Kobe. (There was some surface faulting in the largely rural island of Awaji, about 1.3 m horizontally, 0.5m vertically, but apparently not in the vicinity of buried lifelines).

Figure 1 shows an aerial view of the Kobe area, with north being towards the top of the page. The thick straight line approximates the direction of the inferred faulting. This has been corroborated with aftershock records. The thick lines that enclose area of Kobe show the areas with the highest damage ratios in terms of structures.

The geography and geology of the Kobe area can be described as follows. To the south of Kobe is Osaka Bay and the port area. As can be seen in Figure 1, there are two large man-made islands that jut into Osaka Bay, named Port Island and Rokko Island. Rokko Island was completed just three years ago. Along the original waterfront are numerous smaller man-made areas, with six smaller islands built into the Bay (these islands are not shown in Figure 1, and are located eastwards of Rokko Island).

The City of Kobe urban area is located in a gently sloping plain, from sea level in the south to about 90 m elevation in the north. The width of the plain ranges from 1.5 km to 6 km. The mountainous areas to the north of Kobe reach up to 1,500 m elevation, with urbanized areas generally reaching up to about 200 m above sea level.

The soils of the Kobe plain range in depth from about 10 m (near the mountainous areas) to about 50 m or more (near the shoreline). Most of the older built environment shown in Figure 1 is on this plain, having soils of varying depth. Most structures have been built since 1945.

The newest area of Kobe is Rokko Island. Suburban areas to the north of Figure 1 were located at some distance from the strongest levels of shaking, and were not heavily damaged.

The highest recorded PGA from this earthquake was 0.83 g. Along the line drawn in Figure 1, which is all alluvial soils, the motions generally ranged in the 0.6g to 0.8g range (five recordings from 561 gal to 833 gal). By using the Joyner & Boore attenuation relationship for soft soils, surface PGAs on Port and Rokko Islands would be projected to be about 400 gal (nearest to the mainland) to 300 gal (furthest from the mainland); one recording on the mainland side of Port Island was 393 gal, which is consistent with the attenuation relationship. In the hill areas north of Kobe, ground motions would be generally between 200 gal and 300 gal.

Table 1. Ground Motions in Kobe - Osaka Area

Location	Conditions	PGA (gal)
Himeji LNG Terminal	Distant from fault	189
Fukiai Supply Station	Near fault, rock Site	833
Nishinomiya Supply Station	Near fault	792
Senboku LNG Terminal II	South of Osaka, distant	240
Osaka Area	20 - 40 km from fault	126 - 263 gal, avg 173 gal
Kobe University	In foothills near fault	306
Motoyama	Near fault, Kobe area	774

Extensive liquefaction occurred in many places in Port and Rokko Islands. Rokko Island is 580 hectares and 12 km perimeter, while Port Island is 436 hectares and 16 km perimeter. These man-made islands were built by placing granular fills on soft clay with the perimeter of each island protected by a long stretch of breakwaters and quay walls. The breakwaters are made of large concrete caissons, 10 to 14 m wide, with a concrete retaining wall on the top and the foundation of the caisson consists of sand and cobble fill which were placed by completely excavating the soft clay in the sea bed [1]. The water depth around the islands generally varies from 10 to 15 m.

Liquefaction of reclaimed ground occurred extensively in these islands and coastal reclaimed areas. Ground settled about 50 to 60 cm in Port Island. Although the ground settled, few structures were damaged, as they were founded on piles, the settlement was rather uniform, and the buildings were located quite a distance from the sea shore (concrete caissons and quay walls), usually at least one hundred meters.

The concrete caissons suffered large lateral movements, up to 2 m, as well as settlements, leaving large settlements and lateral spreads behind them. The right sides of Photos 1 and 2 show the tilting of the caissons (Rokko Island), with the settlements behind the caissons (left sides of Photos). Photo 3 shows typical cracks in the ground as a result of lateral spreading towards the shoreline to the right (Rokko Island).

Due to the large motions, the port cranes which line the edges of these islands were universally heavily damaged. As of late March, 1995 (12 weeks after the earthquake), the reconnaissance teams saw no evidence of earthwork reconstruction, in the approximately 50% of the port inspected; at that time, all damaged cranes had been removed from their rail sections, and placed on temporary supports about 50 m from the sea shore. No business activity was ongoing at Rokko Island. Very little business activity was ongoing in Port Island.

Several large warehouse facilities located near the waterfront (within 10 - 20 m) were observed to be heavily damaged. This was also the case for the Higashinada wastewater treatment plant, to be discussed in detail later in this report.

Although there was widespread liquefaction along the waterfront, there are very few water and just limited wastewater pipes located in these locations. Therefore, damage was not excessive to these systems at these locations. However, as will be discussed in this report, there was extensive pipeline damage to both the water and wastewater systems, mostly located well away from the shorelines. It is in these areas well away from the bay front, that modest soil failures and strong ground shaking motions caused most of the damage to the water and wastewater buried pipeline systems. Some observations are made:

- In many areas of Kobe are vicinity, sidewalk damage is evident (Photo 4). It was understood by the reconnaissance team that the ground water level in these areas is quite deep; yet, 1 cm to 5 cm of ground motion was evident at various locations in perhaps 15% of all urbanized areas away from the sea shore. This could be explained by a number of factors, including: soil failures, lurching, settlements, etc.

- One relatively “unique” condition which may have led to excessive soil movements in areas not normally prone to liquefaction was that many of the streets in the urban areas included open-cut storm gutters, one on each side of the street. These gutters were about 0.5 to 0.75 m wide, and 0.75 to 1 m deep. Sometimes, they are covered by steel grates or concrete covers, but often on less busy streets they are kept open.

This leads to the potential of soil movements perpendicular to the traffic direction of the street, as there is no shear resistance for the top 0.75 m to 1 m of the street to withstand the large lateral motions imposed by the earthquake. Often, we observed that these gutters had moved, as evidenced by displaced steel and concrete hatches, or obvious large ground deformations (Photo 5). The movement of these gutters would then presumably result, at least some of the time, in permanent offset movements at depth in the street, where the main underground utilities are located.

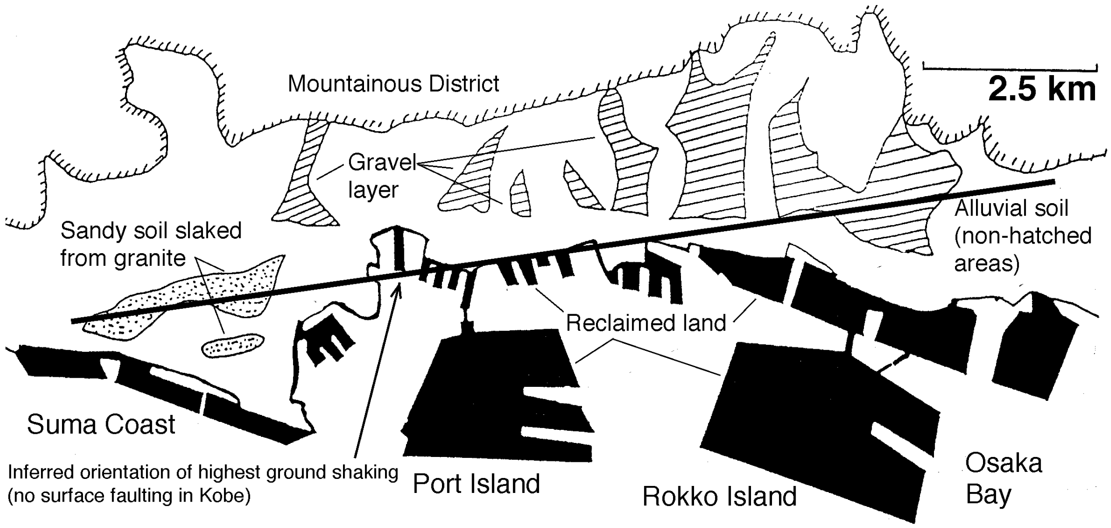

Figure 1. Kobe Area Showing Geologic Features (M. Nasu, J. R. Research Inst.)

3.0 Water Systems That Were Affected by the Earthquake

The Hyogo-Ken Nanbu (Kobe) earthquake of January 17, 1995 affected several cities in the Kobe - Osaka area. As in many U.S. cities, "urban sprawl" has manifested itself in this region, and the 30 km distance between Kobe (population about 1,500,000) and Osaka is completely urbanized, with a number of smaller cities. Roughly in the order of the most damaged to the least damaged water systems are as follows:

- Kobe
- Ashiya (adjacent and east of Kobe)
- Nishinomiya (adjacent and east of Ashiya)
- Takarazuka (adjacent and north of Nishinomiya)
- Itami (east of Nishinomiya)
- Kawanishi
- Toyonaka (east of Itami)
- Amagasaki (southeast of Nishinomiya)

The facilities of the main treated water purveyor, the Hanshin Water Supply Authority, serving Kobe, Ashiya, Amagasaki and Nishinomiya, were also damaged.

In the following sections, we described the key features of three of the water systems: Kobe, Hanshin and Ashiya.

3.1 City of Kobe Water System

The City of Kobe system serves 608,844 households including 1.5 million people. The system was started in 1900, being the 7th modern water system in Japan. The City area is 547 square km; 245 square km has water service. The Kobe Water Department has over 1,000 employees. Figure 2 shows a schematic of the Kobe Water system.

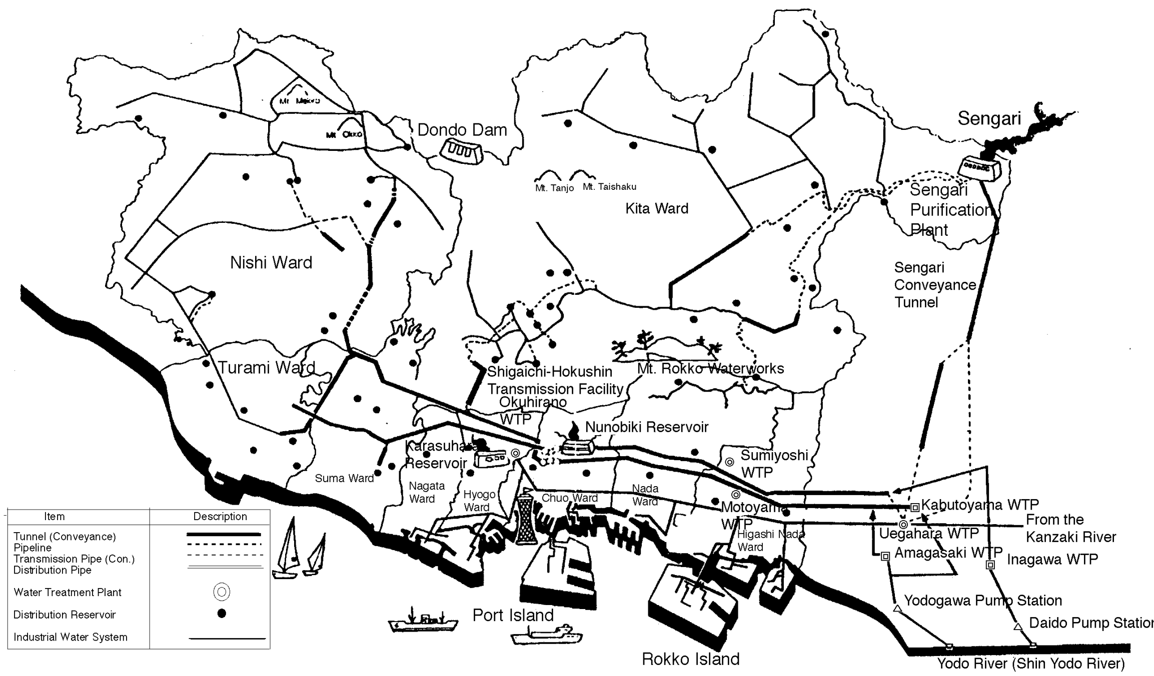

Figure 2. City of Kobe Water system

The system is divided by Mt. Rokko into two service areas, Hokushin (basically, the area north of the Rokko mountains) and Shigaichi (basically the area south of the Rokko mountains, to the sea, and the area hard hit by the earthquake). The Hokushin area is served by Sengari Reservoir located in the northeast of the area. The mountainous area makes up less than 10 percent of the water demand, and has been developed primarily since the 1960s.

The Shigaichi area, the Kobe urban and western parts, is served by Yodo River. The area is approximately 30 km long, east to west, and 1.5 to 6 km wide, running between the shoreline and the mountains. Over 90 percent of the water demand is from this region. Water to this area is supplied primarily from the east from the Hanshin Water System; it takes up to 12 hours for the water to traverse the distance from east to west.

Water for the area is pumped up to the water treatment plants, and runs by gravity to the west at an elevation starting at 90 m above sea level through Kobe's tunnel system. The tunnel system operates in the open channel flow or low pressure regime. Water used at an elevation above 90 meters (approximately 15 percent of the demand) is pumped from the tunnel system. Figure 3 shows the general layout of the pressure zones for the City of Kobe water system.

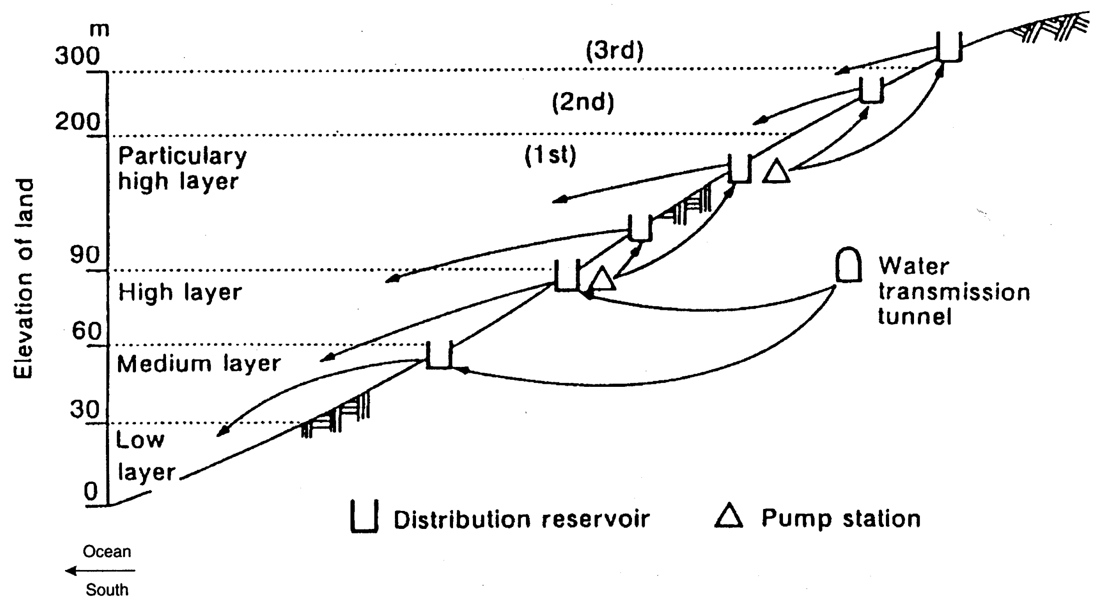

Figure 3. Schematic Profile of Kobe Water Delivery System

The Kobe potable water system is designed to provide both water for drinking and fire protection. There is no dedicated water system for fire suppression, although one was under consideration in 1993. Fire fighting is the responsibility of the fire department.

3.1.1 Raw Water Supply

Nearly all Kobe's water comes from surface water supplies. Nearly three-quarters of Kobe's water supply comes from the east with primary sources including Lake Biwa and the Yodo River. Table 2 summarizes these sources. Figure 2 shows where many of these sources are located.

Table 2. Raw Water Supplies

Source and Comments	Percent of Total Supply	Supply in 1,000 m^3 per day
Lake Biwa via Yodo River (includes Hanshin Water Supply Authority (Yodo River is 30 km east of Kobe)	73.9%	606
Sengari (constructed in 1919)	13.8	113
Karasuhara Reservoir (constructed in 1905)	4.4	36
Rivers in Kobe City area - Sumiyoshi, Sanyo Shinkansen Tunnel	3.8	31
Nunobiki Reservoir, 420,000 m^3 capacity, constructed in 1900; oldest gravity concrete dam in Japan	2.4	20
Dondo Dam	1.7	14
Total	100.0	820

3.1.2 Water Treatment Plants

All Kobe's water is treated before it is distributed. There are eight water treatment plants treating potable water for Kobe, and one treating water for industrial use. The three largest plants are Uegahara, Hanshin, and Sengari. The Uegahara and Hanshin plants are immediately adjacent to one another, and are located to the east of Kobe. The Sengari plant is located north/northeast of Kobe. Table 2 summarizes the water treatment plant information.

Table 3. Water Treatment Plants

Filter Plant	Date Constructed	Raw Water Source	Filter Basins	Capacity (m^3 per day)
Hanshin [1]		Yodo River		144,000
Uegahara [2] potable	1917	Sengari Reservoir	8 slow 8 rapid	127,700
Uegahara - industrial	1964	Yodo River (Kanzaki Riv)		150,000
Okuhirano [3]	1900	Nonobiki, Karasuhara Reservoirs	4 rapid	60,000
Motoyama		Sumiyoshi River	4 rapid	8,000
Sumiyoshi			5 rapid	5,500
Sengari	1967	Sengari Reservoir	8 rapid	108,000
Arima			1 slow	300
Mt. Rokko			1 rapid	1,000

Notes: 1. Municipal corporation including Kobe, Ashiya, Nishinomiya, and Amagasaki.
2. The Hanshin Water Authority Water Treatment Plant is immediately adjacent to the Uegahara Water Purification Plant.
3. Also houses control center

Figure 4 and Figure 5 show schematics of two of the water treatment plants that were damaged in the earthquake, Uegahara and Motoyama.

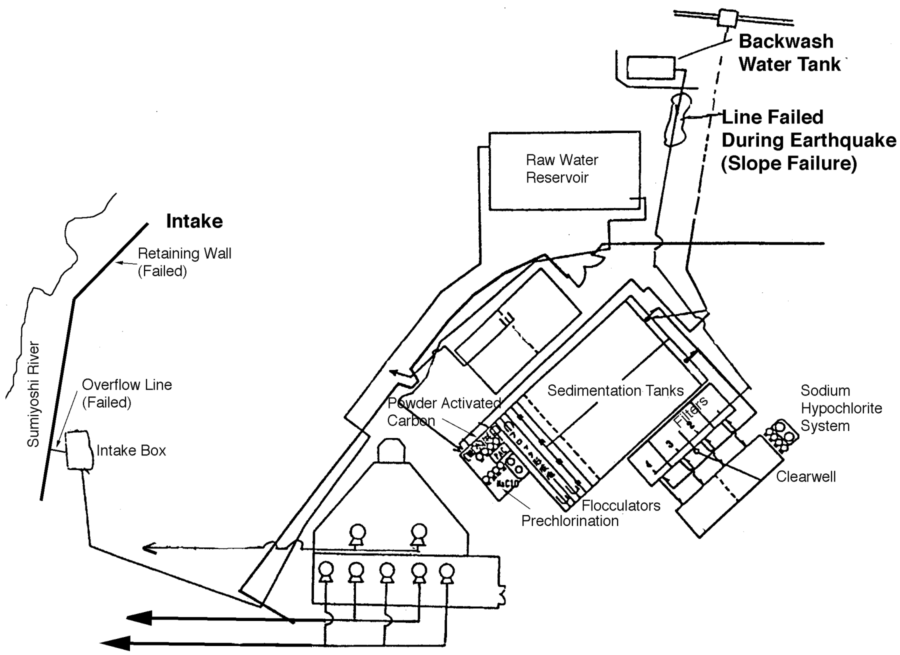

Figure 4. Motogama Water Treatment Plant

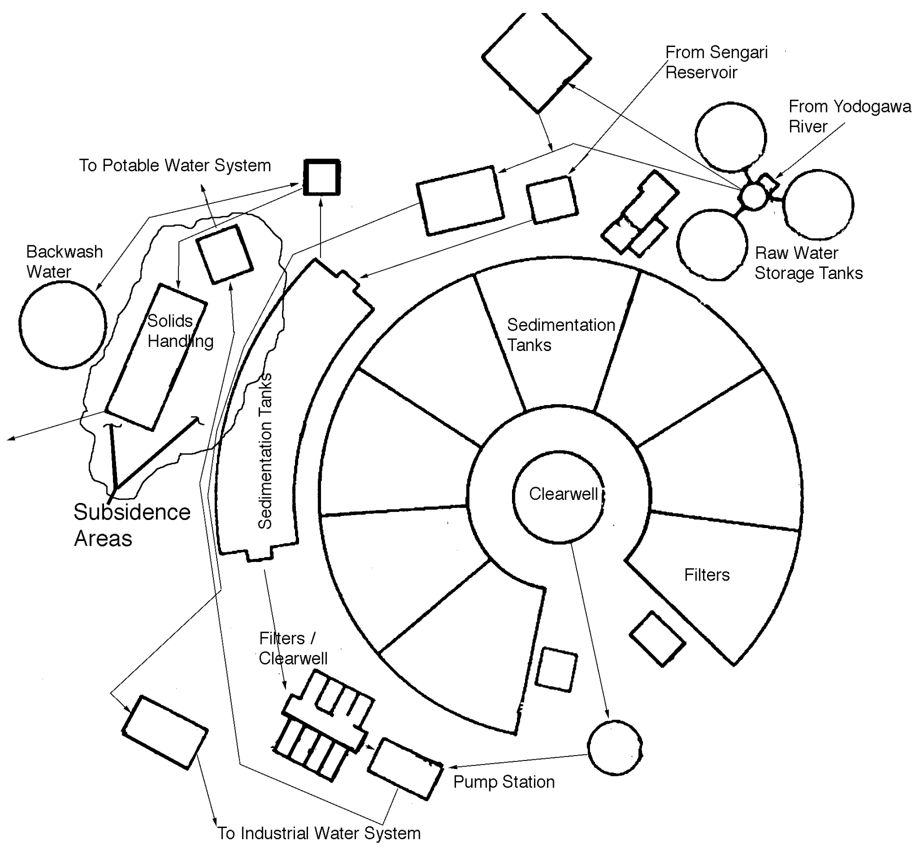

Figure 5. Uegahara Water Treatment Plant

3.1.3 City of Kobe Distribution System

The City of Kobe’s distribution system includes a total of 3,963.1 km of pipe (75 mm and greater). The breakdown of this length of pipe, by material and joint type, is provided in Table 4.

Approximately 6% of that pipe employs special seismic joints as depicted in Figure 6. These joints, per Japan Water Works Association, JWWA, Standard G113 and 114, are specially designed to allow some longitudinal extension and compression but are restrained before they separate. All new pipelines greater than 400 mm in diameter and all pipelines in reclaimed and landslide areas are required to be constructed with this seismic resistant pipe. All large diameter pipelines in Rokko Island are constructed with one of these special seismic resistant joints. (These joints are not used on smaller diameter pipe, owing to their extra cost - a 30% to 40% premium over regularly joined pipe).

Table 4. City of Kobe - Water Distribution System (as of April 1994)

Pipe Material	Joint Type	Length (km)	Percent	Remarks
Ductile Iron Pipe	Special Earthquake Resistant Joint (S, SII) (Photo 6)	237.3	6.0	All trunk mains > 400 mm diam.; ≥ 300 mm in reclaimed land and landslide areas
	Mechanical Joint (K) (Photo 6)	3,180.2	80.2	For 300 mm
	Tyton Joint (T)			For 75mm - 200 mm distribution pipe
Steel Pipe	Welded Joint	103.3	2.6	High pressure pipe
Cast Iron Pipe	Mechanical Joint (A)	308.9	7.8	Replacement in progress
	Leaded Joint	7.0	0.2	
Polyvinyl Chloride Pipe	TS Joint	126.4	3.1	Replacement in progress
Asbestos Cement Pipe		0	0	Replacement complete in 1987
Total		3,963.1	100.0	

Kobe has had an aggressive pipeline replacement program beginning in 1964. Table 5 and Table 6 summarize those programs covering both general renewal and earthquake specific upgrade.

The results of Kobe's aggressive pipeline replacement program were evident in a leakage survey of their system undertaken in 1990. The Kobe system had 93.5 percent effective use of their water compared to Tokyo which had 87.8 percent and Osaka which had 92.7 percent. Effective use is calculated by dividing the amount of water delivered to customers (through meters) divided by the amount of water taken from the source. Meter accuracy and system leakage are the two elements that can dramatically affect the results.

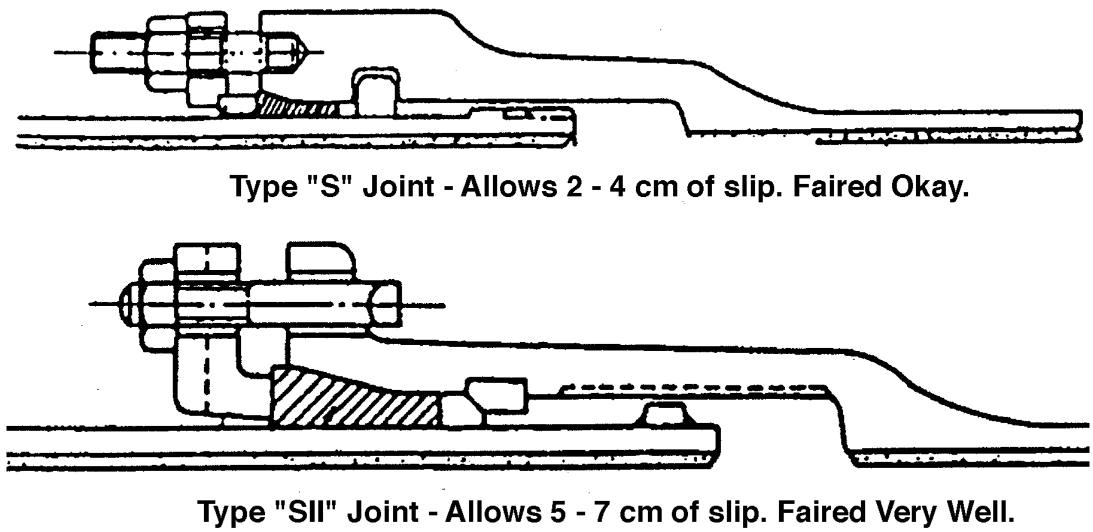

Figure 6. Special "S" and "S-II" Joints Used on Key Pipelines. Type “S” have 2-4 cm of flexibility (500 - 2600 mm diameter); type “S-II” have 5-7 cm of flexibility (100 - 450 mm diameter). Type “S” were used until 1980, type “S-II” since 1980.

In addition to potable water pipelines, Kobe has an industrial water pipeline system. Water is treated at Uegahara Water Purification Plant in a separate treatment system delivering a lower grade water quality, and distributed to Rokko and Port Islands, and along industrial area along the shoreline. That system includes the following pipe:

- Conveyance 21 km
- Transmission 13 km
- Distribution 62 km

Table 5. City of Kobe - Pipe Replacement Program

Year	Cost (yen)	Diameter (mm)	Length (km)
1982 - 1986	10,480,000,000	100 - 700	139
1986 - 1988	4,000,000,000	150 - 800	20
1989 - 1991	4,000,000,000	150 - 800	27

Table 6. City of Kobe - Types of Pipes Replaced

	Cast Iron Pipe	Polyvinyl Chloride Pipe	High-Pressure Pipe Network	Total
Length (km)	84	3	20	107
Cost (yen)	9,100,000,000	200,000,000	2,200,000,000	11,500,000,000

3.1.4 City of Kobe - Distribution Reservoirs

The Kobe Water distribution system includes 119 reservoirs. These include primarily buried cast-in-place reinforced concrete tanks, and some on ground circular precast concrete and welded steel tanks. The reservoirs range in capacity from 40 to 20,000 m^3. About 100 of these reservoirs are buried concrete rectangular tanks. Many of the tanks have interior partition walls, allowing part of the tank to be out of service. Table 7 summarizes the location of these reservoirs by elevation, and Table 8 by area.

Table 7. City of Kobe - Pressure Zones

Elevation	Altitude Above Sea Level	Pressure Zones	% Consumption	Reservoir Sites
1	0 - 30 m	10	53	10
2	31 - 60 m	10	20	13
3	61 - 90 m	14	13	17
4	91 - 180 m	31	11	79 (includes layers 5 and 6)
5	181 - 280m	8	3	
6	> 280 m	1	<1	
Total		74	100	119

Table 8. City of Kobe - Water System Facilities

Block Name		Urban	Western	Northern	Total
Service Reservoirs	Sites	71	8	30	109
	Reservoirs	147	14	54	215
Pumps	Sites	25	5	12	42
	Pumps	132	18	50	200
	Lines	50	9	17	76
Population (1,000s)		1,117	103	174	1,394
Population Served (1,000s)		1,116	86	174	1,377

Kobe Water has had a program to advance the design of reservoirs to meet the wide range of requirements including general structural performance, earthquake performance and corrosion resistance. At the Okuhirano Water Treatment Plant site, Kobe constructed two reservoirs at about the same time, one using a special welded steel design system and the other using a precast concrete design system. The objective was to be able to evaluate the relative performance of both designs. Figure 7 shows a section of the specially-designed steel reservoir. It is designed to accommodate radial expansion during filling. Inherent in the design is damping of compressive earthquake loading on the steel shell. Neither tank at this location was damaged in the earthquake.

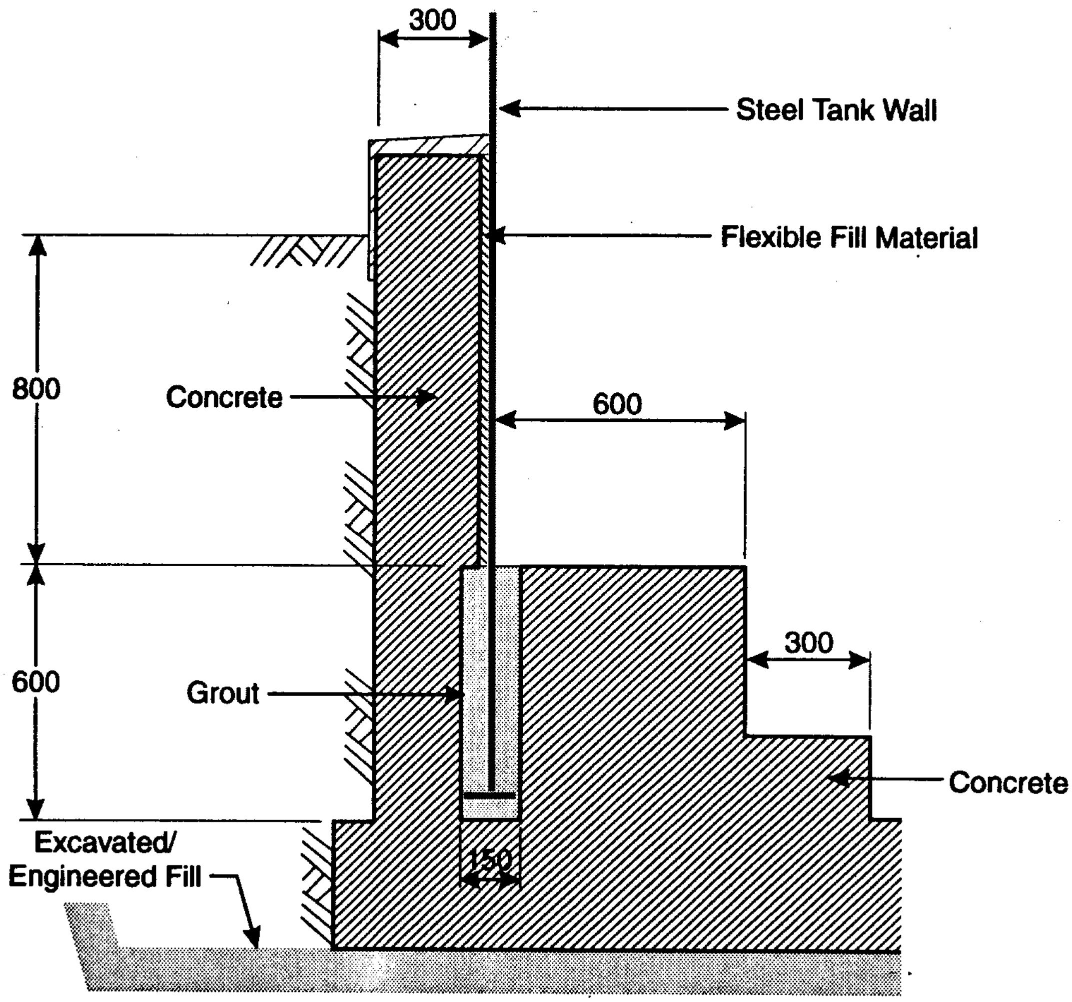

Figure 7. Steel Tank Seismic Design

3.1.5 City of Kobe SCADA System

The Kobe Water Control Center (SCADA System) is located at the Okuhirano Water Treatment Plant. It was built in 1977. It is a Fujitsu 400 MHz UHF-multidirectional multiplex broadcasting system. It monitors over 2,000 points including reservoir level; tunnel level; tunnel, transmission, and distribution flow; pump status; and access alarms. It controls 469 components including pump on/off, rate-of-flow controllers, valve controls, and control selection.

The Control Center communicates with distributed facilities through a repeater station on the International Trade Center Building. That repeater serves much of the urban area as well as the Uegahara Water Treatment Plant directly and also transmits secondary repeaters at:

- Mt. Rokko (serving Northern Service Area, Sengari Water Treatment Plant)
- Mt. Takao (serving Western Area)

Figure 8 presents a schematic of the communication/repeater system.

The SCADA system also incorporates a earthquake monitoring and control system. The function of this system is to isolate water in selected reservoirs from the system and to maintain that water for drinking following earthquake. With this system in place, the typical scenario is that pipe damage in the system would result in quickly draining the service reservoirs. The system is not designed to necessarily maintain water for fire suppression. There is no automated system to isolate major lines crossing vulnerable areas such as lines to the reclaimed land areas.

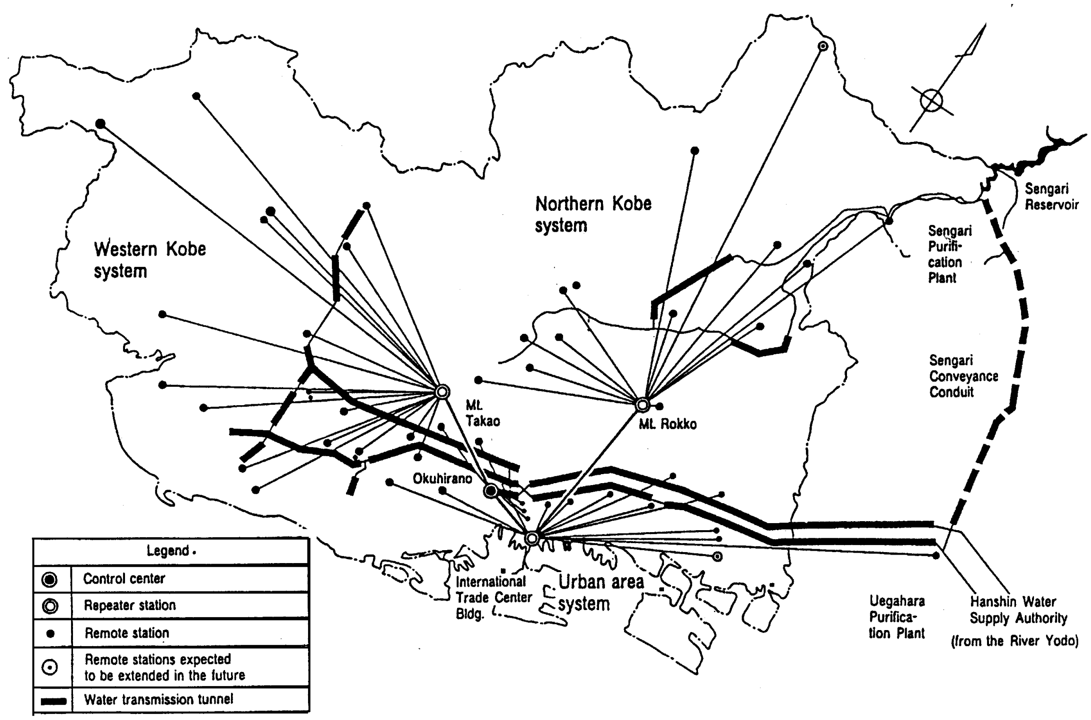

Figure 8. Kobe Water System - Communication Network

The system consists of an earthquake monitoring system at the Okuhirano Control Center, a control panel, the communication system (as described above), and reservoirs with earthquake isolation valves at 21 locations (planned for 31 locations).

The seismograph at the Control Center measures ground motion, and provides input into the earthquake control system (see Figure 9). The earthquake control system allows both automated and manual control of isolation valves on service reservoirs. The decision logic is as follows:

1. 40 gal - manual alarm
2. 80 gal - automatic shut down when combined with excessive rate of change of flow
3. 250 gal - automatic shut down

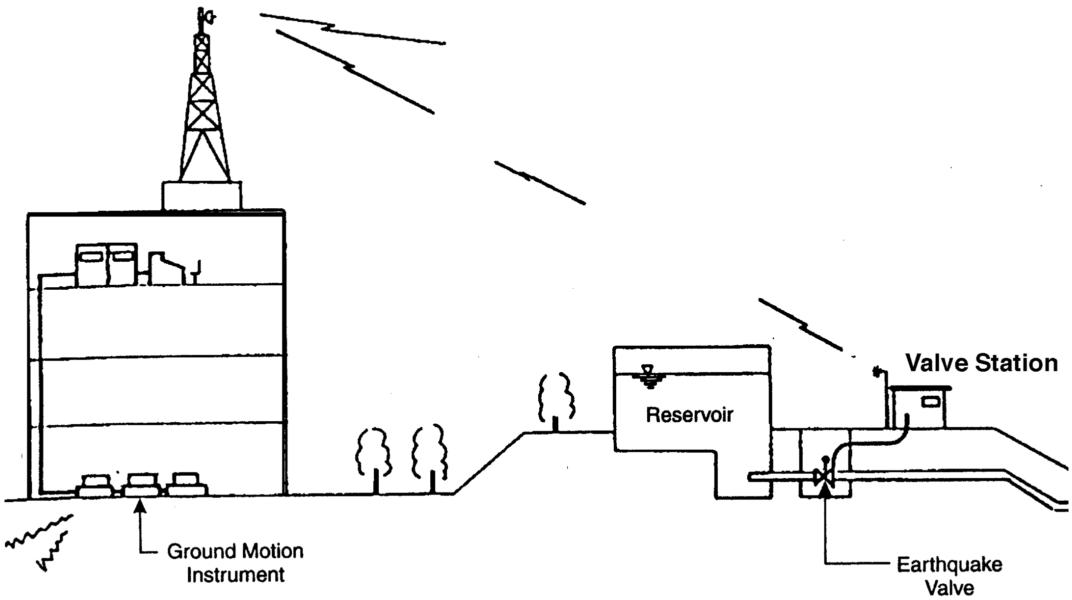

Figure 9. Kobe Water System - Valve Isolation System

At the time of the earthquake, there were 21 reservoir sites that had already been outfitted with remotely controlled isolation valves. At each site, one compartment of a multi-compartment tank, or one tank of two tanks at the site had an isolation valve that can be controlled following an earthquake; (the remaining comparment or tank had no remotely operated valve). This concept allows shutdown of one compartment / tank while maintaining service should an inadvertent shutdown signal be received. If the system can keep up with system leakage, the isolated compartment / tank can be put back on line from the Control Center. If the system can not keep up with the demand, the compartment / tank remains isolated.

Each isolation valve was installed with its own battery backup power supply, which is needed since loss of offsite power after an earthquake is likely.

Emergency planners determined the number of locations and capacities of isolated reservoirs based on being able to serve the population 3 liters/day for drinking for 7 days. Planners estimated that it would take up to 7 days to repair the system. It was calculated that 31 reservoirs would provide adequate storage to meet this criteria. (As will be explained later, the actual time to repair the system reached 60 days, and this required a different strategy to provide water to citizens than had been planned for). Figure 10 shows the locations of the isolated tanks within the system. Isolated tanks were selected so that each would serve an area approximately 4 km in diameter. Figure 11 shows a schematic of the local post-earthquake water distribution spigot system at each reservoir, geared to allow many people to simultaneously fill up containers of water.

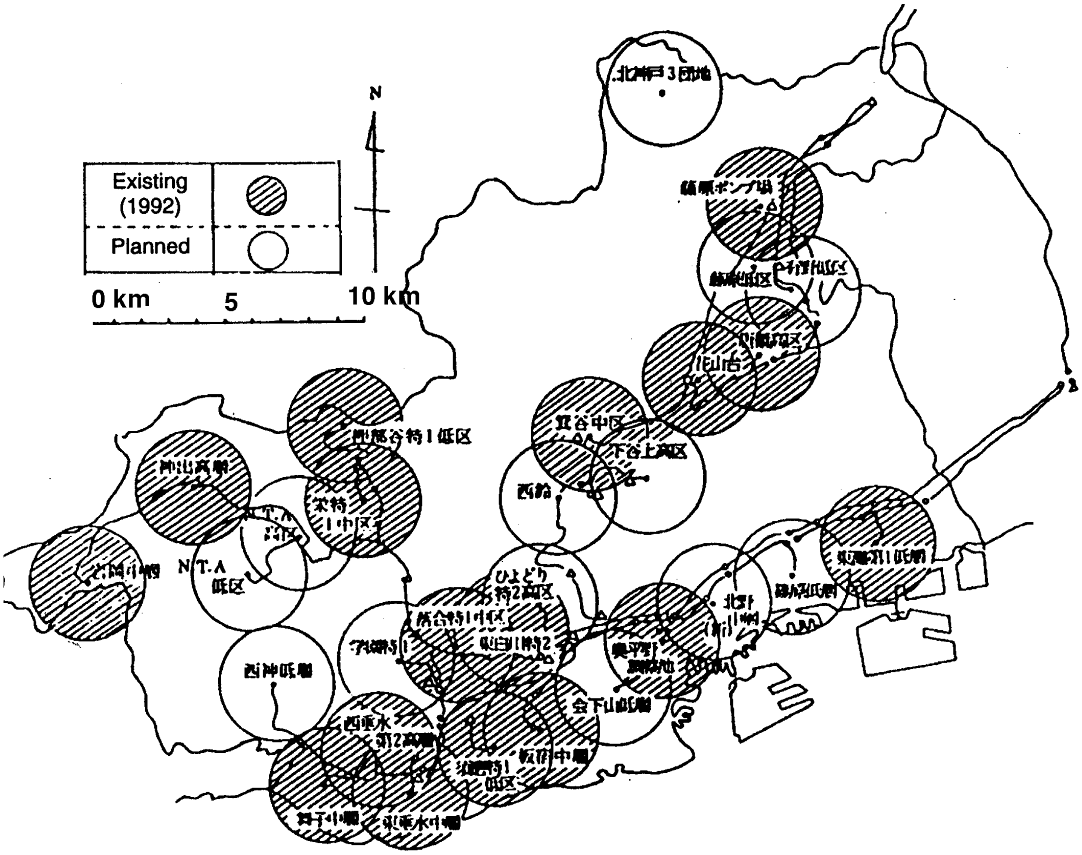

Figure 10. Location of Tanks with Remotely-Operated Isolation Valves

Figure 11 below shows a close up schematic of the typical spigot assembly for water distribution directly to citizens.

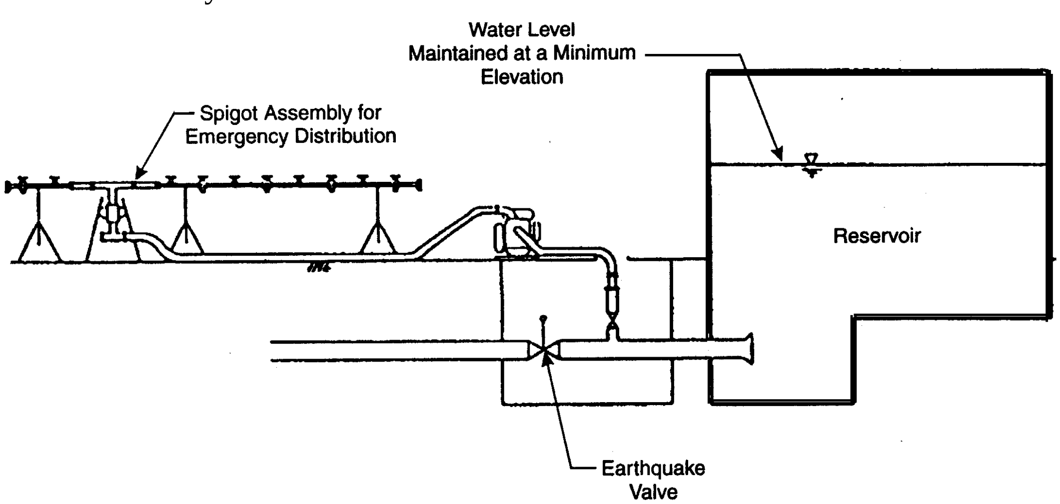

Figure 11. Reservoir Post-Earthquake Water Distribution Spigot System

3.2 Hanshin Water Supply Authority

Figure 12 shows a schematics of the Hanshin Water Supply Authority, as well as points of major pipeline damage in this transmission system.

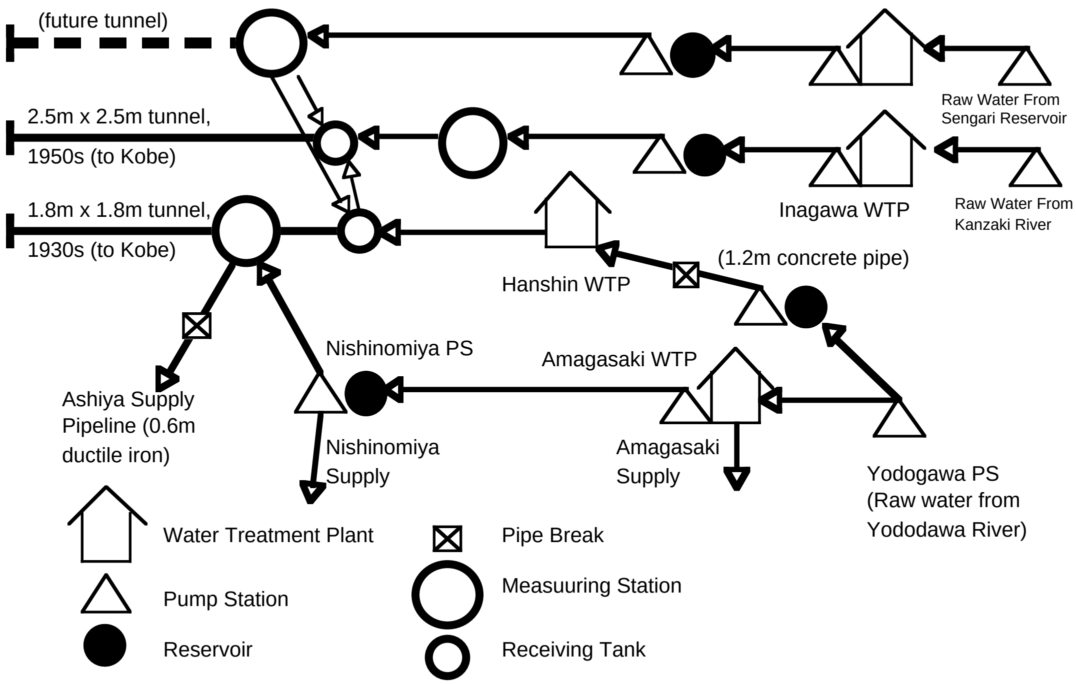

Figure 12. Hanshin Water Supply Authority

3.3 Ashiya Water System

The City of Ashiya's water system is smaller than that of Kobe, but over 90% of its service area was very near (within 2 km) of the inferred fault trace. Thus, although the total damage to the Ashiya system was less than that of Kobe's, the rate of damage was higher.

The Ashiya water system serves a population of about 90,000 people. Like Kobe's water system, most of its customers are located south of the tunnels that run east-west through the Rokko mountains. The Ashiya water system receives its potable water from the Hanshin Water Supply Authority. Below the tunnel elevation, the Ashiya water system is divided into 5 pressure zones. (Above the tunnel elevation, the Ashiya water system serves a small community, Okuske, using an alternate water supply).

The Ashiya water system includes 11 reservoir sites. As with Kobe, at some of the sites there are two tanks. One of these underground rectangular concrete tanks was damaged, leaked and lost its water contents.

Tables 9 - 12 provide the statistics for Ashiya's water distribution system. It should be noted that of the ductile iron pipe in use, 43% are new ductile cast iron pipe, and 57% are older forged cast iron pipe.

Table 9. City of Ashiya Water Distribution Pipe (Includes Transmission Lines)

Diameter (mm)	Length (km)	Percent of Total
700	2.94	1.5
500	3.95	2.0
450	2.94	1.5
400	3.00	1.6
350	1.50	0.8
300	4.10	2.1
250	5.10	2.6
200	12.74	6.6
150	32.00	16.5
125	5.10	2.6
100	62.60	32.3
75	56.87	29.4
Total	192.84	100.0

Table 10. City of Ashiya - Pipe Materials

Material	Diameter (mm)	Length (km)	Percent of Total
Ductile + Cast Iron*	75 - 700	167.7	87 %
PVC	75 - 150	23.1	12
Steel	200 - 250	2.0	1
Asbestos Cement	50 - 75	0.0	0
Total		192.8	100

* 43% Newer Ductile Iron, 57% Older Cast Iron

Table 11. City of Ashiya - Pipe Joint Types

Pipe / Joint Type	Length (km)	Percent of Total	Notes
DI with Mechanical Joints - Bolted	148.3	77 %	
DI with Lead Caulked Slip-On	7.8	4	
PVC	23.1	12	
DI with S and S-II Joints	13.6	7	30% - 40% more expensive
Total	192.8*	100	

* Includes 9 km transmission pipe

Table 12. Distribution Tanks in Ashiya Water System

Tank	Volume (m^3)	High Water Level (m)	Lower Level (m)
1-C	360	580.7	578.2
2-C	55	531.5	527.5
3-C	130	547.7	545.1
4-R	24,000	177.5	170.0
5A-C	2,500	142.08	139.03
5B-C		142.08	135.08
6-C	450	188.0	184.0
7-C	300	1,201.4	1,198.4
8-C	2,500	77.0	69.0
9-C	7,000	53.65	47.45
10-R	2,000	64.0	60.8
11A (failed) R	1,540	79.0	74.0
11B R		79.0	75.0
TOTAL	40,835		

Note: R = rectangular; C = circular

4.0 Conditions Following the Earthquake

In terms of all the cities with water systems affected by the earthquake (there were nine such cities, total), Tables 13 and 14 provide the breakdown of the number of customers without water after the earthquake:

Table 13. Water Customers Without Water - All Cities

Date	Customers Without Water
1/17/95	920,000
1/18	
1/19	
1/20	840,000
1/21	800,000
1/22	660,000
1/23	650,000
1/24	630,000
1/25	620,000
1/26	600,000
1/27	580,000
1/28	550,000
1/29	524,000
1/30	
1/31	495,000
2/1	394,000
2/2	392,000

Table 14. Number of Customers, By City

Water System	Total Number of Customers	Number of Customers Without Water, 1/17/95	Number of Customers Without Water, 2/2/95
Kobe	650,000	580,000	253,600
Amagasaki	192,300	0	0
Nishinomiya	163,000	157,000	113,500
Ashiya	33,700	33,700	20,800
Itami	66,000	66,000	0
Takarazuka	65,000	60,000	3,700
Kawanishi	47,000	10,000	0
Akashi	98,000	68,600	0
Miki	23,000	0	0
Total	1,338,000	920,000	391,600

In terms of repair efforts, peak restoration efforts (all water systems) after the earthquake included 2,090 repair people, often working 12 hour days, 6 days per week.

At the height of the outages, a total of 840 tanker trucks were used to delivery water to people, while the distribution systems were out of service (Figure 13 shows those use in Kobe alone). The heavy effort in organizing tanker truck water deliveries (Figure 14) undoubtedly used personnal resources that could otherwise have been, at least in some cases, been used to repair broken distribution pipe. This poses some question as to the “ideal” method to get limited amounts of water to citizens after a major earthquake. In many areas of Kobe, free water distribution points using small spigot assemblies attached to hydrant locations were in use, even 2.5 months after the earthquake (see Photo 7). A program to rapidly set up such distribution points could be part of emergency planning effort, which could ultimately result in effective manpower use after the earthquake.

Starting January 18, water restoration in Kobe began. Leaks were identified and repaired with the following priorities:

1. Damaged areas, medical facilities, areas with large populations
2. Broken pipes, minor leakage areas.
3. Broken pipes, major leakage areas.
4. Shelters and areas in danger of landslides.

As can be seen in Figure 15, in Kobe the major effort to repair damaged distribution pipes did not get substantially underway until about 7 days after the earthquake. This must be in part accounted for in that many relief workers were first assinged to the distribution of water (tanker trucks, etc.), as well as general mobilization issues.

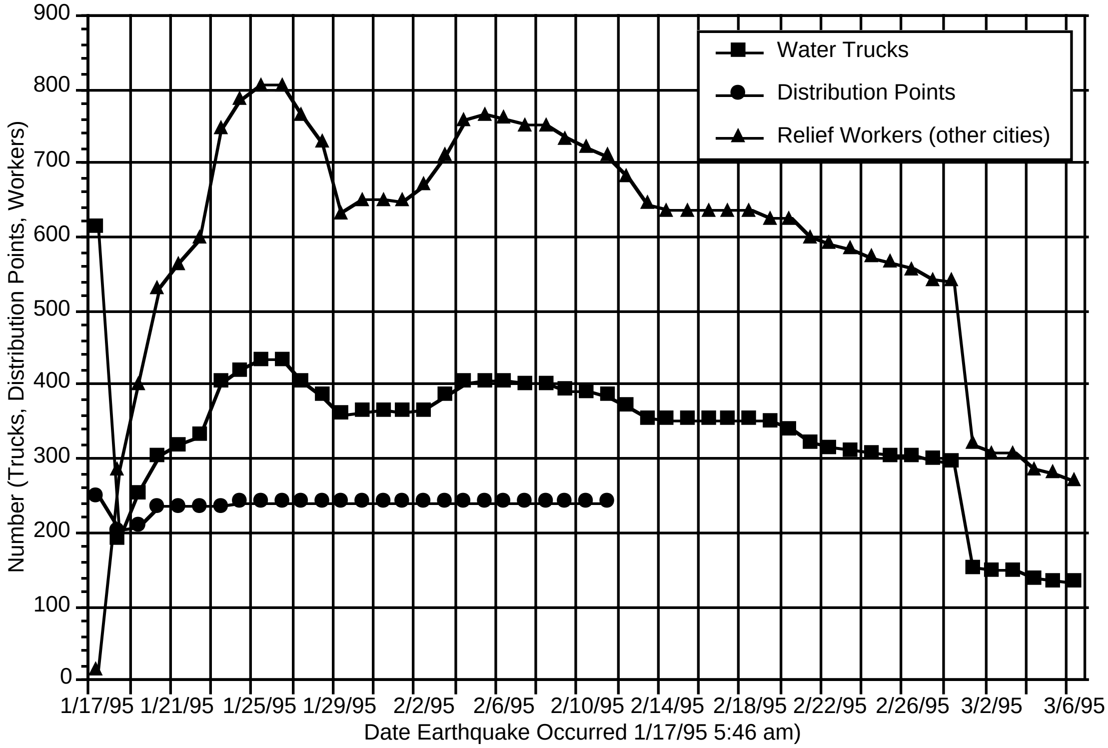

Figure 13. City of Kobe Emergency System Response - Emergency Water Deliveries

Figure 13 shows the status of emergency water supply in the days following the earthquake. As is evidenced, the distribution points set up at 18 reservoirs were insufficient to meet the total city's needs in the distribution of potable water after the earthquake (note the over 200 distribution points). It should be noted that distribution points were later set up at potable hydrant locations throughout the city (see Photo 7).

Emergency water supply tank trucks (Photo 8) were initiated on the evening of January 17. Later, water supply aid came from other cities and from the Self Defense Forces. Regular water supply points were established and increased in numbers as time went on.

Figure 14 shows the number of utilities that provided mutual aid to the City of Kobe, reaching a peak of 29 about one month after the earthquake.

Based on the information provided by the Kobe Water Department in these tables, it appears that the bulk of the restoration effort in the first week following the earthquake was devoted to the distribution of potable water to people using water trucks. About one week after the earthquake, a large effort was devoted to the repair of broken distribution pipe. Areas of the system noted in Figures 13 - 16 can be identified on Figure 2.

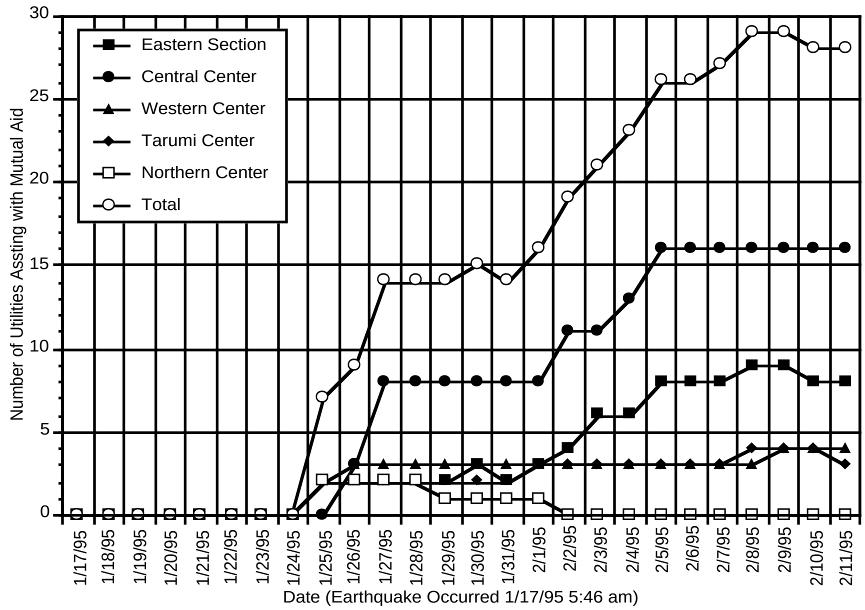

Figure 14. City of Kobe - Mutual Aid

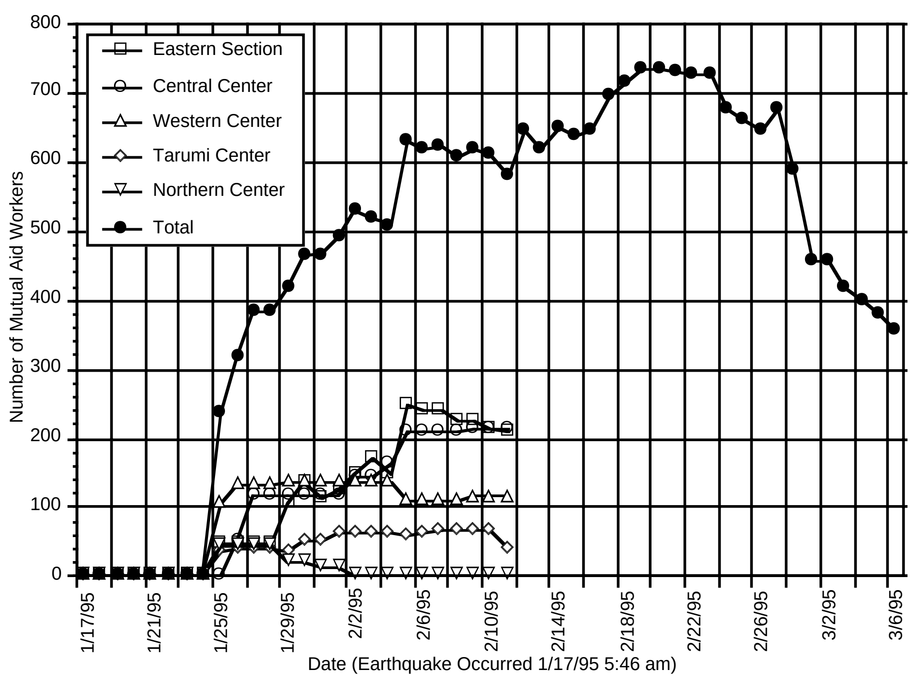

Figure 15. Number of Workers in Each Area of Kobe, Distribution Pipe Repairs

Figure 16 shows the effort devoted to repairs of service line connections, in the City of Kobe:

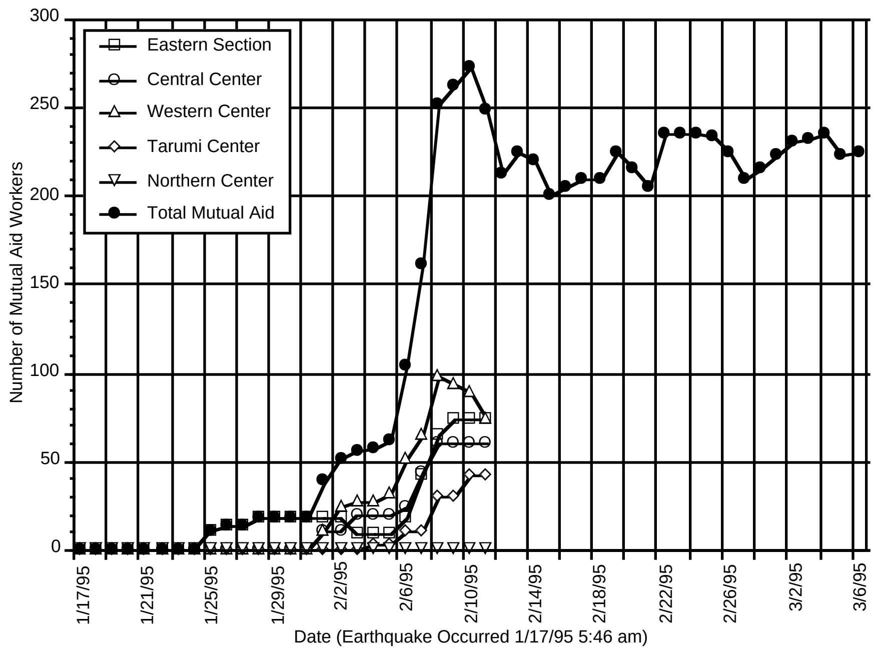

Figure 16. City of Kobe. Number of Workers, Service Line Pipe Repairs

Figure 17 shows the status of system restoration by area, through March 18. Based on the information in this table, approximately three-quarters of this system was initially without service. The western area of the system was the most severely impacted, while the northern part of the system had the least damage. Other parts of the system appear to be equally hard hit.

Water supplied by Hanshin Water Supply Authority's system dropped from 6,000 m^3 to 1,000 m^3 per hour (38 MGD to 6.3 MGD) immediately following the earthquake, but recovered by evening. This was probably caused by loss of power to the Yodo River Pump Station for 15 hours after the earthquake. It was reported that there was damage to the Yodo River supply pipelines, but the exact nature of such damage was not ascertained by the reconnaissance team.

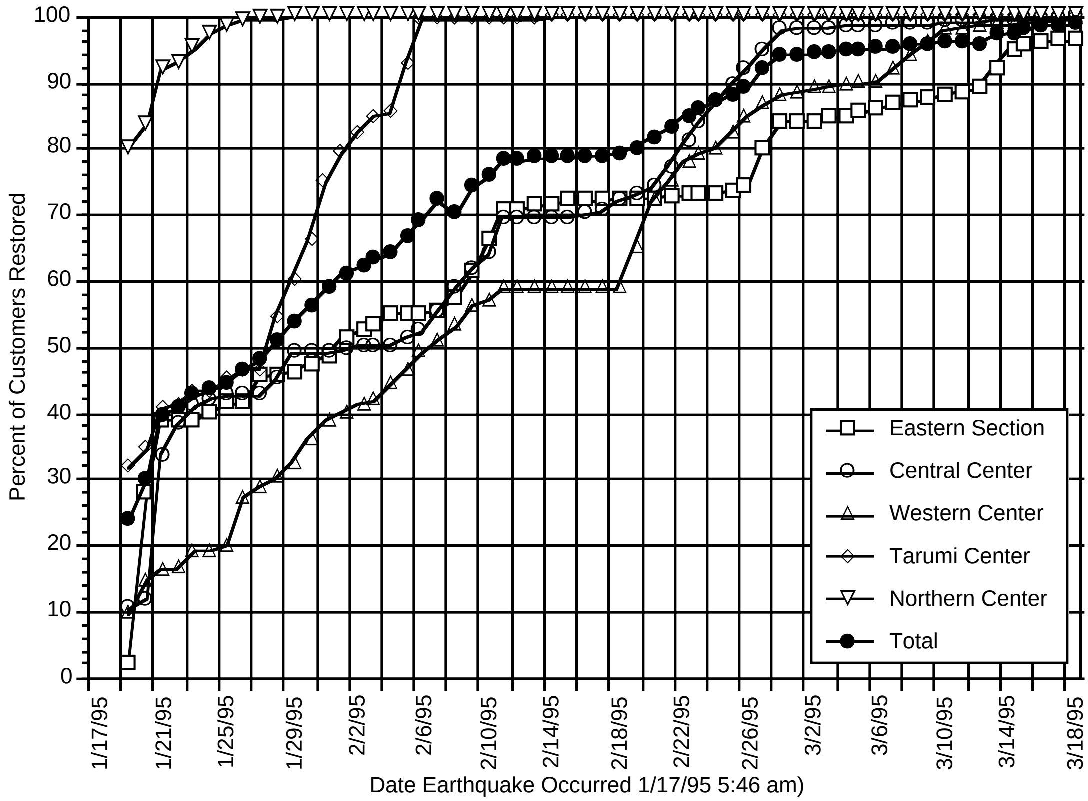

Figure 17. City of Kobe Water Restoration

The remotely-operated earthquake isolation valves successfully operated at 18 of the 21 locations following the earthquake. The 3 remaining valves failed for the following reasons: mechanical or electrical problems (twice); valve closed, but tank lost all water due to tank damage anyway (once). At the 18 reservoirs which were isolated, at total of 33,800 m^3 (9.1 million gallons) of water was held for customer emergency consumption. Actual reservoir storage before earthquake (1/17 - 5:05 am) was 338,455 m^3 (91 MG). Minimum storage after the earthquake (1/18 -6:01 am) was 94,908 m^3 (25 MG).

Service reservoirs serving the urban area without earthquake valves quickly emptied as shown in Table 15.

Table 15. City of Kobe - Empty Reservoirs After Earthquake

Time following earthquake (hours)	Number of Sites with Empty Reservoirs
< 1 hour	6
1 - 2 hours	13
2 - 6 hours	38
> 6 hours	29
Total	86

The number of distribution system pipe repairs in the Kobe water system is not precisely known at the time of writing this report. Latest compiled figures show at least

1,800 pipe repairs (as of March 25, 1995) (this number includes distribution pipe repairs, but exclude service line connection repairs). Table 16 provides statistics only for distribution system pipe repairs made as of mid-February, 1995 (for example, note the total of 964 repairs made in mid-February, versus the 1,800 repairs made by the end of March). The final number of distribution pipe repairs for the Kobe water system is likely to be in excess of 2,000.

It was also reported that as of late March, water supplied into Kobe was 140% of normal for that time of year, indicating a continuing high leak rate, indicating unidentified leaking pipes still were to be repaired.

With regards to service line connection repairs, the total number damaged was not exactly known; however, water company estimates suggested a total exceeding 50,000 repairs in Kobe, if one includes houses that were collapsed. Outside Kobe, in the City of Ashiya alone (total number of structures about 35,000, of which about 2,500 collapsed and a similar number were heavily damaged), it was estimated that about 10,000 to 15,000 structures suffered some type of service line / interior pipe line damage.

Table 16. Kobe Water System Damage Rates (As of 2/28/95)

Diameter (mm)	Length (km)	Repairs Made (2/28)	Repair Rate per km	Repair Type A	Repair Type B	Repair Type C
50	63.1	15	0.24	6	9	0
75	165.1	40	0.24	7	30	3
100	790.3	197	0.25	43	127	27
150	1455.1	301	0.21	55	206	40
200	744.7	138	0.19	23	104	11
250	39.7	6	0.15	3	3	0
300	386.6	139	0.36	20	96	23
350	18.2	5	0.27	0	4	1
400	79.7	30	0.38	4	17	9
450	3.1	0	0	0	0	0
500	88.5	24	0.27	2	7	15
600	45.2	13	0.29	2	3	8
700	46.9	24	0.51	1	7	16
800	10.3	9	0.88	3	5	1
900	26.1	21	0.80	1	6	14
1000	0.5	2	4.02	0	0	2
Total	3963.1	964**	0.24*	170**	624**	170**

Notes. A = Broken; B = Separated; C = other (air valves, hydrants)

* The average repair rate as of mid-March was up to 1,800 repairs / 3963 km = 0.45 / km. The forecasted final repair rate will be likely in the 0.50 to 0.60 / km range, once all repairs are made.

** The total number of repairs tabulated as of March 25 1995 was 1,800.

Figure 18 shows the water service restoration effort for the City of Ashiya. For the first 8 days after the earthquake, there was zero water available to Ashiya, as the transmission system failed. For this reason, no pipe repairs could be made during this time, as there was no water to find the leaks.

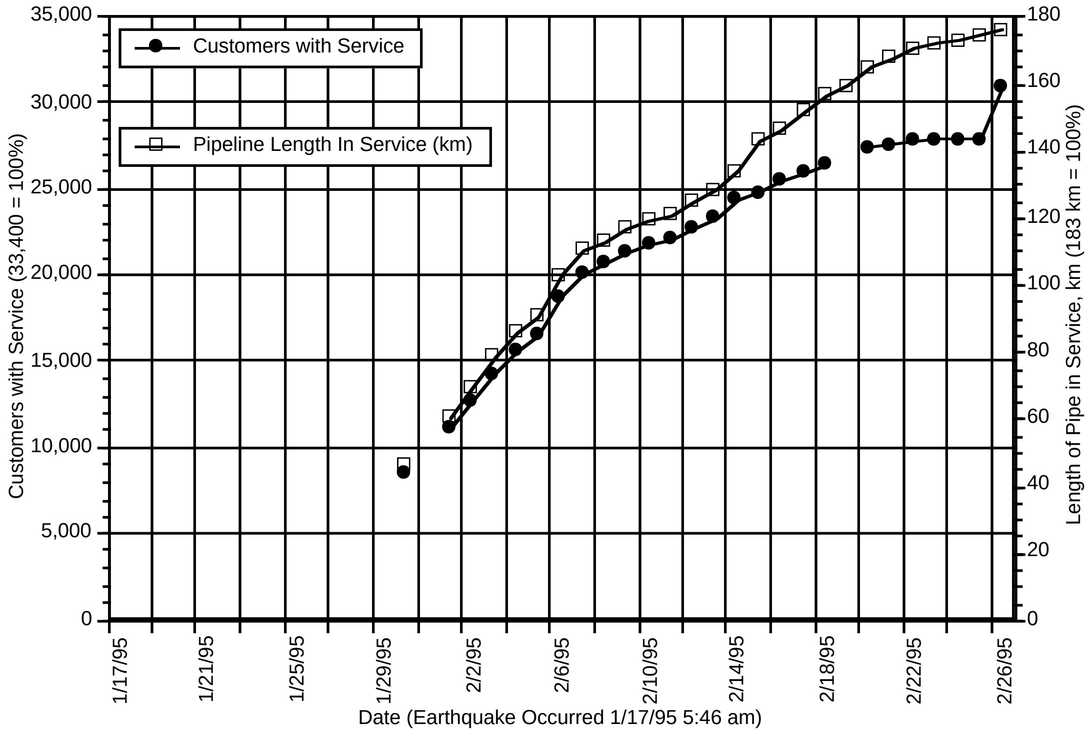

Figure 18. City of Ashiya Water System Restoration

Once the transmission system pipes were repaired, the repair of all distribution pipe breaks proceeded using a staff of 50 Ashiya Public Works Department staff, augmented by an additional 30 staff from other water agencies. The repair process took 32 days once begun. At no time did the water department issue a "boil water" alert, as they considered all water that they introduced into the distribution system to be treated.

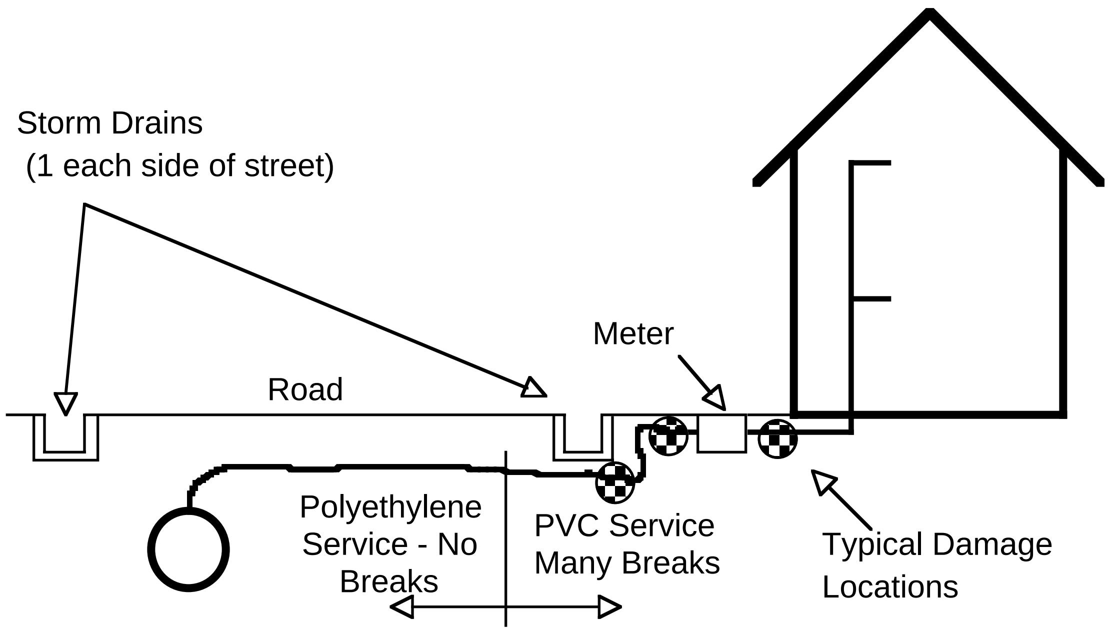

Figure 19. Service Line Connection Failure Locations

4.1 Damage to Water Treatment Plants

This section describes damage to the Uegahara, Hanshin and Motoyama water treatment plants. The Sengari, Okuhirano, and Sumiyoshi water treatment plants had little damage. Information is not available on the other plants.

<u>Uegahara Water Treatment Plant</u>

On the west side of the plant (see Figure 5 and Photo 9), fill behind a retaining wall subsided when the retaining wall moved outward resulting in separating pipeline joints on three treated water lines each 1.2 m diameter reinforced concrete. The lines were 1) Uegahara potable water, 2) Uegahara industrial water, and 3) Hanshin potable pipelines. The Hanshin line was operating as of 2/11/95.

Photo 9 - Aerial view of Kobe’s Uegahara Water Purification Plant (lower left) with the Hanshin Water Purification Plant immediately adjacent (upper right). The landslide that undercut the Hanshin Plant's solids handling building is evident. In addition, the area at about 10:00 o'clock outside the circular basin settled approximately 30 cm, separating joints on three 1.2 meter diameter pipelines over a length of approximately 100 meters, and damaging the solids handling building.

Photo 10 - Repair of one of three 1.2 meter treated water lines leaving the Uegahara/Hanshin Plant sites.

Same subsidence occurred under the sludge thickener building. The floor settled differentially. There was subsidence around pile supported foundation of sludge hoppers. Electrical equipment toppled in sludge thickener building. Apparently the building and adjacent sludge hoppers were pile supported, so the cross section of the slope/retaining/fill is unclear.

Photo 11 - Subsidence (approximately 30 cm) around pile-supported sludge hoppers at Uegahara Plant.

This same subsidence also probably led to the following damage:

- Muddy water and increased water volume in water passages.
- Clarifiers - damage to expansion joints; water leakage
- Process Tanks - some leakage
- Sludge thickening equipment - extensive damage to piping and equipment
- High Rate Filter Piping - bent and disconnected
- Other - damage to pipe, mechanical, and electrical equipment.

Hanshin Water Authority Water Treatment Plant

The plant was not damaged and operating at 3,000 m^3/hr as of February 12. There was a major landslide in back of (NE of) the treatment plant, undercutting the wastewater treatment building, and taking out tennis court and a sludge drying bed. The slide killed 36 people in a housing development below, and dammed the Nigawa River. The slide is the responsibility of Hyogo Prefecture. The original slope was 18 degrees, much less than the 30 degrees where the code requires mitigation. A university professor suggested a layer of waste could have weakened the soil. They had placed plastic covering area above slide to keep rain off slope monitoring equipment in place, and had started to do borings to further investigate the slide. This is the largest slide in the urban area in the Kobe Earthquake. Damage to buildings in the area appeared to be light, occasional roof damage.

Photo 12 - Landslide; undermined solids handling building at the Hanshin Plant.

Motoyama Water Treatment Plant

The Motoyama Plant had damage to two segments of pipelines and minor cracking in a process tank. Broken lines to and from the backwash water tank failed as a result of slope failure.

Photo 13 - Broken lines to/from backwash tank at the Motoyama Water Treatment Plant.

The retaining wall along side the Sumiyoshi River moved, breaking the intake box overflow line. Water is fed to the intake box through a pipeline connected to a small diversion structure in the river bed. This facility is located upstream of the plant. There was a concern that the cast iron raw water line running from the intake box to the treatment plant may have been damaged as a result of the retaining wall movement, and should be checked before it is put into operation. The property owners, just above the suspect raw water line were uneasy; they do not want a break to undermine their house.

Photo 14 - The retaining wall on the left cracked damaging the overflow line from the Motoyama Plant's intake box. There was a concern that the raw water line running behind the retaining wall might also be damaged. This was compounded by the concern for the house above. If the water line broke, it could undermine the house foundation. Blue tarps were in place to prevent further slope failure from rain.

4.2 Damage to Water Transmission Facilities

The two major lines from the Yodo River were broken in 10 locations. One ductile iron line had a split 30 cm long and 4 cm wide. In Hyogo province, 1 700 mm ductile iron pipe was damaged. In Kobe City, numerous large diameter transmission pipes broke. In Itami City, there were 4 transmission pipe failures. In Takarazuka there were 8 transmission pipe failures. [3]

The transmission line from the Uegahara water treatment plant was damaged in many places (1.2 m diameter and 0.5 m diameter).

The 40 km-long Mt. Rokko Tunnel, carrying water from the Uegahara and Hanshin plants west to be distributed, had no major leakage and only minor damage.

Pumps in Karasuhara mine (spring) were destroyed and put out of service. This was only a minor supply.

4.3 Damage to Reservoirs

No major damage was reported to any of the 10 impoundment dams in the immediate strong shaking area. Similarly, no damage was reported to any of the hydroelectric dams (Kansai Electric), although this was to be expected, as these dams are all located quite a distance away from the strong shaking area.

Of the 119 distribution reservoirs (tanks) in the Kobe water system, there was little reservoir / tank damage. The Egeyama Reservoir did sustain damage due to PGDs, which caused leakage in the connection between the reservoir and the adjoining wall, and a vertical crack in the expansion joint (Photo 15). A 500 mm diameter pipe 10 meters long was replaced.

At the Motoyama water treatment plant, one reinforced concrete tank cracked and the inlet water pipe was damaged.

In Ashiya, there was damage to one buried rectangular concrete reservoir, built in 1937, and reportedly at a site with no permanent ground deformations.

All told, there were 5 concrete tank reservoirs known to be damaged in the earthquake, between the Kobe and Ashiya water distribution systems, and the noted treatment plants. Damage to tanks in other water systems was not ascertained.

4.4 Damage to Distribution Pipes

The reported damage to distribution system pipes in the various affected cities is reported in Table 17. It should be noted that in Table 17, the number of distribution pipe repairs is low due to incomplete reports.

Table 17. Damage to Distribution Pipes - All Cities

Water System	Total Length of Distribution Pipes (km)	Number of Distribution Pipe Repairs Fixed	Damage Rate (Repairs/km)
Kobe	3,921	>1,800	0.46
Amagasaki	823	1,042 *	1.27
Nishinomiya	187	1,172 *	6.27
Ashiya	192	303	1.58
Itami	463	-	-
Takarazuka	521	420 #	0.81 ##
Kawanishi	471	83 #	0.18
Akashi	692	35 #	0.05
Miki	424	60 #	0.14
Total	7,694	4,915 #	

Notes: * includes damage to service connections #incomplete data
about 4.0 repairs/km including service connections

It has also been reported but not confirmed that the “S” and “S-II” connection used in Nishinomiya suffered significant amounts of damage; the “S” joints had damage in Ashiya; the “S-II” joints had no reported damage in Ashiya or Kobe. Photo 16 shows a pulled apart mechanical joint connection on a 300 mm ductile iron pipeline. Photo 17 shows a pulled apart joint on a 600 mm steel pipeline. Photo 18 shows a body failure on a 800 mm cast iron pipe. Photo 19 shows a damaged 200 mm “T” joint on ductile iron pipe. Photo 20 shows a failure of a “K” mechanical joint on a 800 mm ductile iron pipe.

Damage to air valves was not unusual, owing to lateral movement of pipeline causing high bending moments / shears at the air valve stem, causing the valve to break off. (See Photo 21).

Residential area leakage (service connections) at 21,458 sites, of which repairs at 18,823 are complete as of mid February. It is estimated that indoor and outdoor supply pipe leakage sites will number several tens of thousands, out of a total city water supply region of 650,000 homes.

Pipelines hung on the Kobe, Rokko, Mikage, and Fukae bridges were damaged, in some cases disrupted service to these islands. Given that there were several dozen collapsed or totally damaged bridges, such damage to pipelines hanging from the bridges must be expected.

Photo 22 Pipe hanging from Bridge to Rokko Island (700 mm type SP).

Photo 23 - Pipe repair on approach to bridge to island where the Higashenada wastewater plant was located. Settlement and slight lateral movement (see concrete wall on right) are indicative of the soil movements that caused the pipe failure.

Photo 24 - Kyoto Water Department truck and crew was making repair shown in Photo 23. They indicated that they were directed to make the repairs as quickly as possible, even though they might be temporary. They said the materials they used in Kyoto (and had with them) were completely different than those used by Kobe Water.

Photo 25 - Differential Settlement at building in mid-Rokko Island. Most modern buildings on the island were pile supported and were not damaged. Differential settlement required repair of utility connections as shown in Photo 26.

Photo 27 - Differential settlement of approximately 1 meter along the front of pile supported ferry terminal on Port Island connecting Kobe to Kansai International Airport. Utility connections were left hanging.

The pipe repairs for the City of Ashiya's water system are summarized in Table 18.

Table 18. City of Ashiya Pipeline Repairs

Diameter (mm)	Number of Repairs	Percentage
700	1	0.3 %
450	2	0.7
350	1	0.3
250	2	0.7
200	12	4.0
150	50	16.5
125	13	4.3
100	65	21.4
75	97	32.0
50	60	19.8
Total	303	100.0 %

Some observations on problems encountered during the pipe repair process. In many areas, there was insufficient water pressure in the pipeline system to be able to locate the pipeline breaks easily. Damage to houses (and resulting debris in roads and streets), as well as numerous collapsed highways made it difficult to bring in equipment ot perform repairs. Concurrent pipe repairs to the gas system resulted in some additional pipeline breaks in the water system. In most cases, water pipe repairs incorporated complete flushing and disinfection, which slowed doen the restoration effort; although as noted, it was reported that no boil water alerts were given after the earthquake.

4.5 Water Department Buildings

Water Department Main Office (City Hall Building 2 (City Hall Annex), 6th Floor collapsed (Photo 28). Distribution pipe maps, facility charts, etc. were destroyed. The water department was relocated into rental office space a few blocks away. The wastewater department (on the 5th floor of the same building) was relocated into rental office space across town. The reason for the collapse of the upper floors of this building was reportedly due to a change in column type (concrete to steel) at this location, reflecting an addition made in previous years. It should be noted that this type of mid-height building collapse damage was not uncommon in many other buildings in the area. In addition, the Western Center partially burnt. Undoubtedly, the loss of regular office space hampered the water system reconstruction efforts in Kobe after the earthquake.

4.6 Monitoring and Control System

The control system to isolate reservoirs for drinking worked as planned at 18 of 21 reservoir sites, and water was saved for drinking. Failure at the three remaining sites was attributed to equipment damage (mechanical and electrical, two times) amd to reservoir failure (the valve worked, but the reservoir was damaged and lost its water contents anyway). As previously discussed, the amount of water retained in the 18 reservoirs was far too little to meet but a small portion of post-earthquake demand for drinking water, and had to be supplemented with several hundred water tanker trucks. Three repeater stations were undamaged.

5.0 Fire Following Earthquake

The City of Kobe has 11 fire stations, 15 branch stations, and a staff of 1,298 uniformed personnel. Equipment includes 2 helicopters, 2 fireboats and 196 vehicles. Other equipment includes 72 portable pumps [2].

Due to water shortages in most of the areas having fire ignitions, the initial fire ignitions spread in many cases, even though there was essentially no wind on January 17, 1995.

According to citizens, the fire boats were not effective in fighting fires away from the waterfront, due to the long distances involved (often over 1 km), and modest elevation gains (30 m or so).

The fire department has installed 968 cisterns, typically 40,000 liters and some up to 100,000 liters in size. This is usually sufficient to control a fire if reached to within a few minutes, but was insufficient in many cases after the earthquake, owing to the much longer response times, leading to much larger fires by the time response started. Conceptually, the cisterns are laid out in a grid covering the city, with one cistern every 400 m by 400 m grid. Within each grid, on average, would also be 4 hydrants from the potable water distribution system.

Photos 29 and 30 show a typical cistern location sign (to assist fire department in finding the cistern), and a atypical cistern valve access system, respectively. Most cisterns use simple valve access through manholes in the streets.

There is one special radio system for communication between the water and fire departments during emergency response situations.

By January 17 at 7:30 pm, 234 fire sites (ignitions) had been counted. It was difficult to the fires because of lack of water supply, congestion of traffic hampering access by fire fighters, and probably a lack of sufficient number of fire fighters. By one count, approximately 100 fires broke out within minutes after the earthquake. By another count, there were 142 fires on January 17.

In Ashiya, there were 11 fire ignitions, 9 of which were alerted by 7:30 am January 17. The fire ignitions started within about 1 km of the inferred fault line.

A few of the initial fires spread into large fires. About 8 fires spread into very large fires, most of which had no fire fighter response during the afternoon of January 17, 1995.

Based on the evidence, it is clear that most fires stopped on their own, even with very small fire breaks (many streets are 10 m wide). The fact that fires did not spread as much as otherwise is attributed to the lack of wind (most important); and common use of stucco exteriors and tile roofs over wood frame houses).

Finally, a total of 419 fires were counted in Kobe City (some counts peg this at about 350 fires). These initial ignitions led to about 1,000,000 m^2 area lost to fire. This loss of buildings represents about 100 years of loss of building stock from fire, under non-earthquake conditions.

About 70% of the structures in the Kobe area had been outfitted with automatic (PGA and pressure-drop) shut-off valves. Reportedly, most of these worked as intended. Figure 20 shows the typical installation.

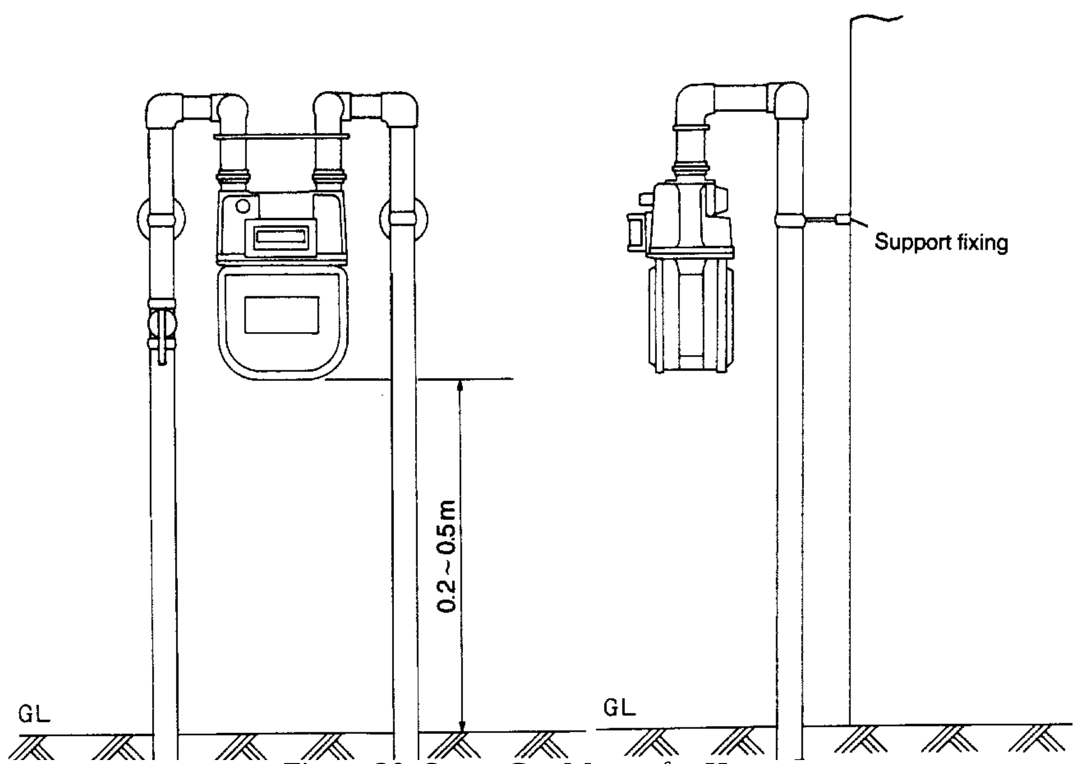

Figure 20. Smart Gas Meters for Homes

However, in cases where the underground gas main leaked (thousands); or collapsed houses breaking the main-side connection of the meter (likely hundreds - see Photo 31) there was ample opportunity for gas to supply fuel for fires.

According to some early studies of about 70 ignitions, about 1/3 each were attributed to electricity, gas (propane or natural) or other factors. It should be noted that the natural gas supply was cut-off to the most devastated areas about 7 hours after the earthquake.

Table 19. Damaged Houses, Burnt Area, Dead, Injured (After National Police Agency, 2/3/95)

District	Damaged Houses	Burnt Houses	Burnt Area (m^2)	Dead	Injured
Kobe City	54,943	4,528	910,065	3,696	13,310
Higashinada Ward	10,800	89	39,215	1,216	3,383
Nada Ward	9,220	176	27,600	819	1,112
Chuo Ward	6,544	30	21,700	206	2,413
Hyougo Ward	4,373	145	12,420	403	1,755
Nagata Ward	15,994	3,089	503,350	712	533
Suma Ward	7,811	993	305,600	333	637
Tarumi Ward	193	5	50	2	1,020
Nishi Ward	0	0	70	3	1,640
Kita Ward	8	1	60	2	817
Ashiya City	4,062	5	5,600	405	2,759
Nishinomiya City	13,931	48	9,600	938	2,987
Amagasaki City	1,478	76	3,372	27	61
Itami City	887	7	295	10	923
Takarazuka City	5,057	2	148	86	1,100
Kawanishi City	1,523	3	0	1	178
Awaji City	5,451	1	120	56	1,080
Akashi City	535	5	100	5	965
Miki City	138	0	13	2	17
Osaka City	2,342	0	2,310	14	2,124
Other Areas	17,263	0	0	3	1,300
Total	107,610	4,675	931,623	5,243	23,804

Note: the number of surveyed damage houses increased to over 188,000 by 2/13/95; dead increased to 5,318, injured increased to 34,553.

6.0 Wastewater System

The City of Kobe is served by seven wastewater treatment plants and one sludge center. In addition, the City of Kobe has 3,315 km of wastewater collection pipes, and 484 km of storm water collection pipes.

Table 20. Kobe City Wastewater Treatment Plants

Wastewater Treatment Plant	Capacity (m^3 per day)	Post-Earthquake Status
Higashinada	225,000	At shoreline. Heavy damage. Emergency settling basin direct to Osaka Bay for 3.5 months; 2-3 years to rebuild.
Chubu	77,900	At shoreline. Moderate damage, repaired in 1 week
Seibu	161,500	At shoreline. Repaired in 1 day
Tarumi	133,890	At shoreline
Tamatsu	75,000	1 km from shoreline
Port Island	20,300	On Port Island
Suzurandai	43,825	10 km inland
Myodani	12,000	10 km inland
Total	737,315 m^3 per day	
Tobu Sludge Center	150 tons per day	on Rokko Island

Table 21. Kobe City Wastewater Collection System

Treatment Area	Wastewater Sewer Length - km	Storm Water Sewer Length - km
Higashinada	719	76
Chubu + Seibu	790	109
Tarumi	619	108
Tamatsu	570	103
Port Island	28	4
Suzurandai	186	33
Inland Areas	406	49
Total	3318	482

About 70% of the sewers are concrete, 20% is PVC and 10% are clay or other materials.

Three of the wastewater treatment plants were heavily damaged: the Higashinada, Chubu and Nishibu treatment plants, which were reduced in capacity to 0%, 50% and 20%, respectively. Outside of Kobe, there was damage to wastewater treatments plants as follows: Amagasaki - 3 plants; Akashi - 3 plants; Nishinomiya - 3 plants; Ashiya - 1 plant.

6.1 Higashinada Wastewater Treatment Plant

This section describes the Higashinada Wastewater Treatment Plant, and its performance in the earthquake. The Higashinada Wastewater Treatment Plant is the City of Kobe's largest plant providing one-third of the city's treatment capacity. It is located on Uozaki Hama Machi (Island), just east of the bridge to Rokko Island.

The plant has an average daily flow of 162,000 m^3/day of which 23% is industrial. Some sewage is from a combined sanitary/storm collection system. The plant capacity is 225,000 m^3/day, and is being expanded to 350,000 m^3/day.

Photo 32 - Aerial view of Higashinada Wastewater Treatment Plant. As a result of liquefaction related lateral spread the embankment along the inlet between the island and mainland moved north (towards the water) 2 to 3 meters.

The facility was heavily damaged when the retaining wall along the north side of the plant adjacent to the waterway moved two to three meters towards the water as a result of liquefaction. As a result of the movement, much of the site settled an average of one meter. Figure 21 shows the plant layout and notes damage locations.

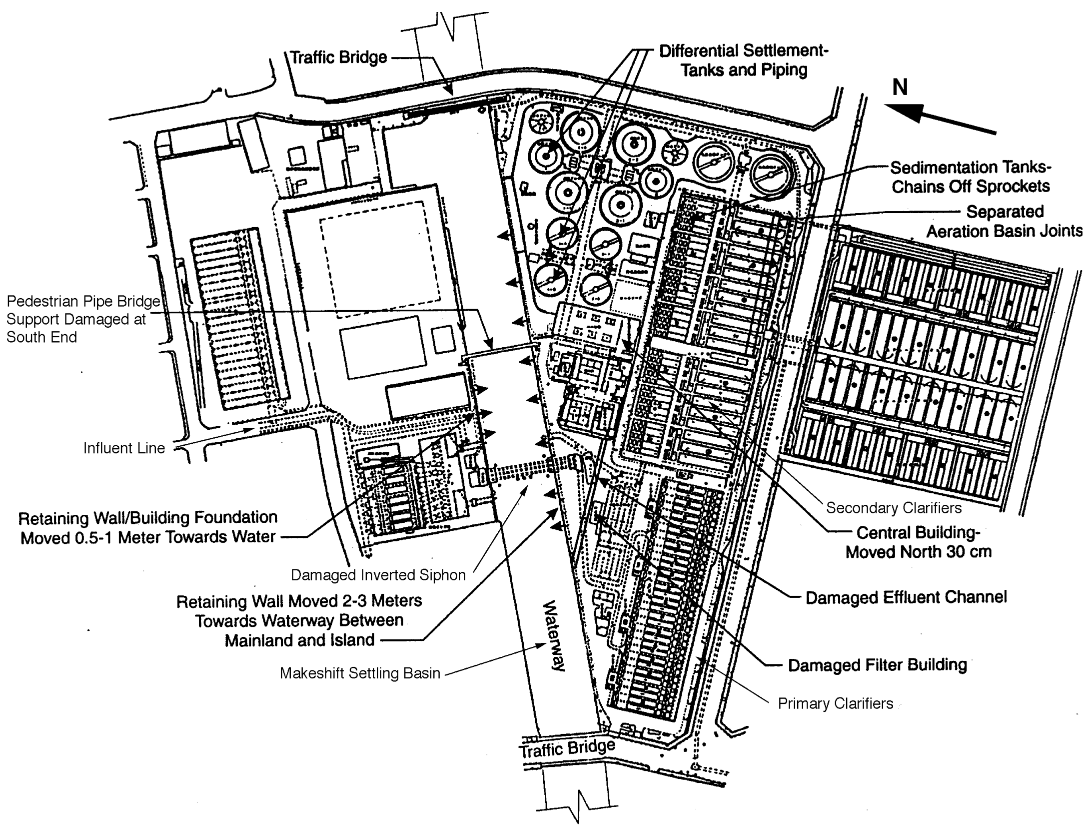

Figure 21. Higashinada Wastewater Treatment Plant

Photo 33 shows the retaining wall along the channel between the mainland and the treatment. This wall moved laterally towards the water about 2 - 3 m, allowing much of the nearby site behind the wall to settle 1 m. Photo 34 shows ground cracking behind the retaining wall shown in Photo 33 (which is off to the right).

Lateral spreading caused severe damage to underground structures as well as facilities on spread footings. Photo 35 shows that the effluent channel, 2m x 2m, separated due to 1 m of lateral spreading, in 4 places. The pipe rack distorted due to ground deformations of about 1 m (Photo 36).

Plant damage included the following:

- Aeration basin joint separation (Photos 37, 38). This basin (rectangular concrete tank) is pile supported. Photo 38 shows a closeup of a torn water stop.
- Sludge scraper chains came off their sprockets in the sedimentation tanks (Photo 39).
- Photo 40 shows flexible bellows that connect the tank on the left (on piles) to ground supported pipe on the right. Two and a half months after the earthquake, this tank was emptied and out of service.
- Differential settlement of about 0.6 m relative to the pile supported filter building occurred as shown in Photo 41.
- Photo 42 shows piping distorted as a result of differential settlements. Photos 43, 44 and 45 show piping and equipment distorted as a result of subsidence of their foundations. The welded steel tee, about 300 mm diameter, cracked at the weld between the leg and the run as seen in Photo 45.
- Photo 46 shows a welded steel pipe, about 200 mm diameter, folded where the foot pipe bridge support was distorted from lateral spread.

The operating status as of February 10 was primary treatment with chlorination using a bypass "shipping canal" as an emergency settling basin. To set up this emergency settling basin, several fences were installed in the canal to control the floating solids and to provide a longer retention time, by January 25.

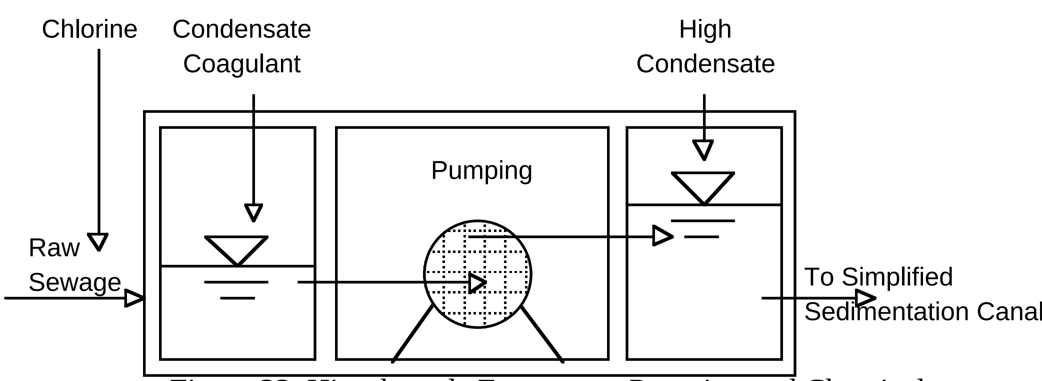

Figure 22. Higashenada Emergency Pumping and Chemicals

Once the flow is treated with chemicals (Figure 22), the flow is pumped into the shipping canal (Figure 23).

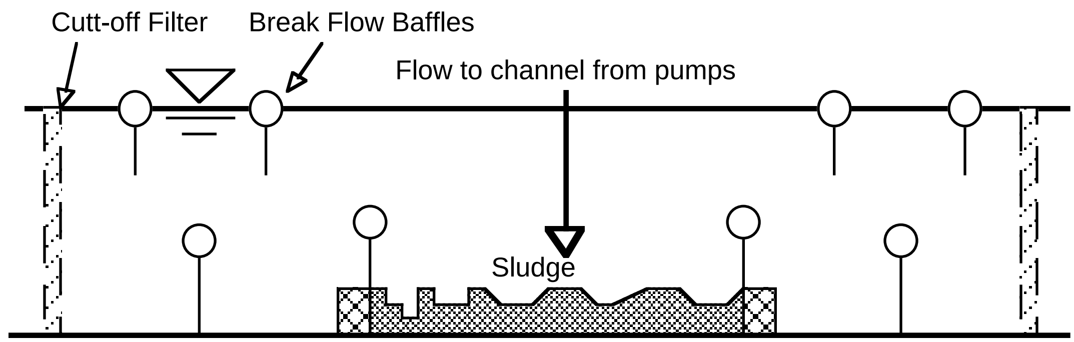

Figure 23. Makeshift Settling Basin Using Shipping Canal

This temporary set-up is being used through April, at which time the wastewater agency hoped to be able to restore use of some of its regular settling basins after installation of a new temprary retaining wall with H piles and sheet piles. Photo 47 shows the shipping canal with the cut-off filters and baffles indicated by the floating fences. In Photo 47, the pump station is on the left, pumping the chemically-treated sewage into the canal in mid-picture; the baffles are shown both in the foreground and in the background.

6.2 Wastewater Collection System

The City of Kobe's wastewater collection system was heavily damaged. The dominant damage modes were uplift or settlement of manholes, road surfaces, balked, inflow and accumulation of soil and sand.

In Port Island, there was severe damage to concrete culverts due to liquefaction.

After the earthquake, the basic process for sewer line damage assessment and recovery was as follows:

- First, the sewers were visually inspected from manhole to manhole for flow. If ponding of water was evident, then:
- Cameras were sent through the sewers from manhole locations to assess damage. A total of 37 cameras were used in this operation (many from contractors and mutual aid sources).
- Repair crews are sent into sewers to perform repairs as needed.
- There was only one location where wastewater backed up and flowed onto public access areas. This was rapidly isolated, and there was not effect on public health. (It should be recognized that the lack of water coming into the area probably lowered the wastewater flows, thereby limiting the public health threat).
- It is expected that it will take over 2 years to perform complete restoration of the complete sewer network.

Of the trunk sewer lines, 4.2 km were found to be seriously damaged, and 61.9 km had some minor amount of damage, out of an inventory of 83.9 km.

Table 22. Kobe Waste and Storm Water Collection System Damage

Type of Damage	Wastewater (through 1/24)	Storm Water (through 1/24)	Total
Manholes	672	138	810
Road Surfaces	314	58	372
Pipes Clogged	76	57	133
Flood	0	0	0
Soil in Pipes	41	4	45
Other	44	10	54
Total	1,147	267	1,414

In other cities, the number of wastewater sewer repairs were as follows: Amagasaki: 30; Akashi: 5; Nishinomiya: 50; Ashiya: 75; Itami: 3; Takarazuka: 64; Kawanishi: 9.

In areas where flow needed to be maintained, and the sewers were badly damaged, temporary pumping of the sewage was performed. Photo 48 shows a temporary setup (apparently in use for many weeks) situated near the Higashenada treatment plant. The raw sewage is being pumped out of a manhole in the foreground (not seen), into the fixed pipes and reinforced flex hose (in the middle of the picture), which is then delivered about 100 m distant (to the right of the photo).

In Kobe City, out of 15 wastewater lift stations and 11 stormwater lift stations, there was damage to 5 and 1 liftstations, respectively. In other cities, there was lifetstation damage as follows: Amagasaki: 6; Akashi: 6; Nishinomiya: 11; Ashiya: 2.

Wastewater officials described some ideas in terms of being better prepared for future earthquakes: first, the use of deeply buried main interceptors would alleviate damage problems (sewers and tunnels deeply buried have little earthquake vulnerability); second, it would be advisable, although costly, to have interceptor sewers interconnected to two or more treatment plants, which would allow flexibility in post earthquake operations should one treatment plant be heavily damaged; third, water treatment plants must be designed to accommodate the inevitable liquefaction effects associated with areas of poor soils.

Acknowledgement

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