NIST GCR 97-720

A STUDY OF THE PERFORMANCE OF PETROLEUM STORAGE TANKS DURING EARTHQUAKES, 1933-1995

Building and Fire Research Laboratory
Gaithersburg, Maryland 20899

United States Department of Commerce
Technology Administration
National Institute of Standards and Technology

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A report to:

U.S. Department of Commerce
Technology Adminstration
National Institute of Standards and Technology
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Gaithersburg, MD 20899

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U.S. Department of Commerce
William M. Daley, *Secretary*
Technology Adminstration
Gary R. Bachula, *Acting Under Secretary for Technology*
National Institute of Standards and Technology
Robert E. Hebner, *Acting Director*

PREFACE

The Congressional emergency appropriation resulting from the January 17, 1994 Northridge earthquake provided the Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST) an opportunity to increase its activities in earthquake engineering under the National Earthquake Hazard Reduction Program (NEHRP). In addition to the post-Northridge earthquake reconnaissance, BFRL concentrated its efforts primarily in the study of post-earthquake fire and lifelines, and moment resisting steel frames.

BFRL sponsored a post-earthquake fire and lifelines workshop in Long Beach, California in January 1995 to assess technology development and research needs that will be used in developing recommendations to reduce the effects of post-earthquake fires. The workshop participants developed a list of priority project areas where further research, technology development, or information collection and dissemination would serve as a vital step in reducing the losses from post-earthquake fires. NIST funded a number of studies identified by the participants which are listed in NIST Special Publication 889.

BFRL, working with practicing engineers, carried out surveys and assessment of the damaged buildings and partially funded a SAC (Structural Engineers Association of California, Applied Technology Council, California Universities for Research in Earthquake engineering) workshop on seismic performance of steel frame buildings in September 1994. The objectives of the workshop were threefold: 1) to coordinate related interests; 2) focus on the problems observed in the performance of steel buildings; and 3) develop a research plan to solve the problems. NIST funded the research and engineering communities to carry out several of the proposed studies.

This report represents a part of these studies related to post-earthquake fire and lifelines sponsored by NIST as part of the Congressional emergency appropriation.

ABSTRACT

This study is primarily concerned with the performance of petroleum storage tanks during earthquakes. Because of the similarity in construction of water tanks, their performance has also been included where relevant information is available.

The study covers the seismic performance of storage tanks during major earthquakes ranging from the 1933 Long Beach earthquake through the 1995 Hyogoken-Nambu (Kobe) earthquake. The study discusses failures as well as satisfactory performances of the tanks during the more recent earthquakes.

Based on the observations of damage, recommendations to improve the design of storage tanks are provided.

ACKNOWLEDGMENTS

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Dr. Bijan Mohraz provided the inspiration and also ongoing guidance during the development of this report. Individuals who helped significantly with reference materials include Leslie Ann Crockett of the California Institute of Technology Earthquake Engineering Research Library and Charles D. James of the University of California Earthquake Engineering Research Center at Richmond, California.

The author is indebted to the following persons for information on specific events and for the use of materials in their files: Lorin Todd of San Luis Tank, and Jerry Englehardt of Santa Fe Pacific Pipe Line. Allan Porush and Paul Summers of Dames and Moore provided certain information and discussed their experiences. T.P.Wachholz efforts proved invaluable in compiling and editing. Word processing was by Mary Cooper. The patience of Dr. Riley Chung is gratefully acknowledged.

Information on specific earthquakes was provided by the following:

Kern County 1952; R. Haglund, L. Gearhart, F. Lundquist, all of General Petroleum Corp.

Alaska 1964; J. LaMonte, Dames and Moore (Seattle); W. Daniels, UNOCAL.

San Fernando, 1971; R. Lyons, MWD; L. Lund, CLADWP, ret.

Imperial Valley, 1979; J. Abboud, SFPPL.

Coalinga 1983; S. Conley, Chevron Pipe Line.

Loma Prieta 1989; J. Englehardt, A. Howsley, D. Thompson, M. Armer, all of SFPPL; R. Laigo, ARCO; R. Pack, IMTT.

Landers 1992; D. Ostrum, SCE; G. Conner and M. Meeler, Bighorn-Desert View Water Agency; M. Stockstell and J. Brown, Hi-Desert Water Dist; W. Yew, G. Boubel, and S. Fogelberg, ARCO.

Northridge 1994; S. Saria, So. Cal. Water Co.; R. Wheeler, City of Simi; W. Porter, Newhall County Water District; T. Rulla, CLADWP; P. Nyom and B. Depremio, Valencia Water Company.

Kobe 1995; T. Etoh, APL-Kobe; Dr. M. Kawatani, Osaka University.

In this study, as in other earthquake analyses, the availability of Strong Motion records provides one of the bases of sensible investigation. The collection of Strong Motion records by the Corps of Engineers, Utilities, and the California Strong Motion Instrument Program [A. Shakel, M. Huang] is appreciated.

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1. INTRODUCTION

1.1 General

The purpose of this report is to catalog the performance of petroleum storage tanks as affected by earthquakes. Because of the similar construction of water tanks, their performance has also been included for specific later earthquakes where significant and relevant information has been available.

Although the inception of Earthquake Engineering began with the 1923 Tokyo earthquake, the effects on tanks did not become a subject of general interest until the Alaska earthquake of 1964. The author's original intent was to begin the analytical section of this report with the Alaska earthquake. However, our research efforts discovered sufficient information on the Long Beach and Kern County earthquakes to include them in the analytical section. The later earthquakes, (Imperial Valley and forward) are clearly better documented, with more detailed information concerning heights, diameters, wall thickness', and fluid levels at the time of the earthquakes, in addition to more information about the seismological and geological aspects of the earthquakes.

Petroleum storage tanks and water storage tanks are similar but there are some significant differences regarding design criteria. Petroleum Storage tanks are built under American Petroleum Institute (API) Standard 650. Water tanks are usually built under American Water Works Association/American Welding Society (AWWA/AWS) Standard D100. Smaller petroleum (and some water) tanks are also built using Underwriters Laboratories Standard 142. The AWWA/AWS Standard is more conservative than the API Standard, in that lower allowable stress values are used, required course thickness calculations are slightly different, and under the recent AWWA/AWS Standards consideration can be given to vertical earthquake forces. The API Standard 650 cone roof tanks must be built with a frangible roof/shell joint, or a special equivalent joint can be by agreement between the purchaser and the tank manufacturer.

Petroleum storage tanks are of three basic configurations, Cone Roof, Floating Roof, and Cone Roof with an Internal Pan. Figure 1.1 depicts the three tank configurations.

The first API Welded Tank Standard (12C) came out in July 1936. The first AWWA Standard for Riveted Tanks and Standpipes was published in 1935; the first Welded Tank Standard appeared in 1940. The seismic provisions for both codes were included in 1979.

When considering tanks and earthquakes the tank can be rendered non-functional either by tank failure or by connecting piping failure. If the tank suffers structural damage but does not lose its contents the tank is considered to have functioned satisfactorily. If the tank loses its contents because of connecting piping failure, the failure of the piping should be considered and evaluated on its own merits.

1.2 Earthquakes Not Covered

There have been a number of earthquakes where tanks have sustained damage but little detailed information is available. These events are noted below, with what information was readily obtainable concerning the effects of the earthquakes on tanks. Although damage to tanks has been reported in Chilean earthquakes, no discussion of these events has been made in this study.

Tokyo 1923; M 8.3: Tanks at the Yokosuka Naval Station failed, allowing drainage of oil to harbor waters, where the oil caught fire causing considerable damage [1] [2].

El Centro 1940, M 6.9: The water supply tanks for the cities of Holtville and Imperial collapsed. The epicenter of this earthquake was about 10 km from Holtville and 15 km from Imperial. Both cities were about 8 km from the Imperial Fault, on which there was displacement [3].

Nigata 1964, M 7.5: This earthquake caused the collapse of a number of tanks at a local oil refinery; a resulting fire caused extensive damage to the refinery. A tsunami carried the oil offsite where it blanketed a residential area [4] [5].

Miyagi-Ken-Oki (Sendai) 1978, M 7.4: Three large tanks failed, the oil over topped the containment dikes spilling into the refinery and into harbor waters [6].

Costa Rica, 22APR91, M 7.4: This earthquake caused extensive damage and resulted in the failure of some tanks at the RECOPE refinery [7].

Managua Nicaragua, 23DEC72, M 6.5: Water tanks in the city were damaged with elephant foot buckling, but remained in service. A small ESSO oil refinery survived the earthquake with no (or minimal) damage, although accelerations of 0.39 g in EW, 0.34 g in NS, and 0.33 g in vertical directions were experienced at the refinery [8].

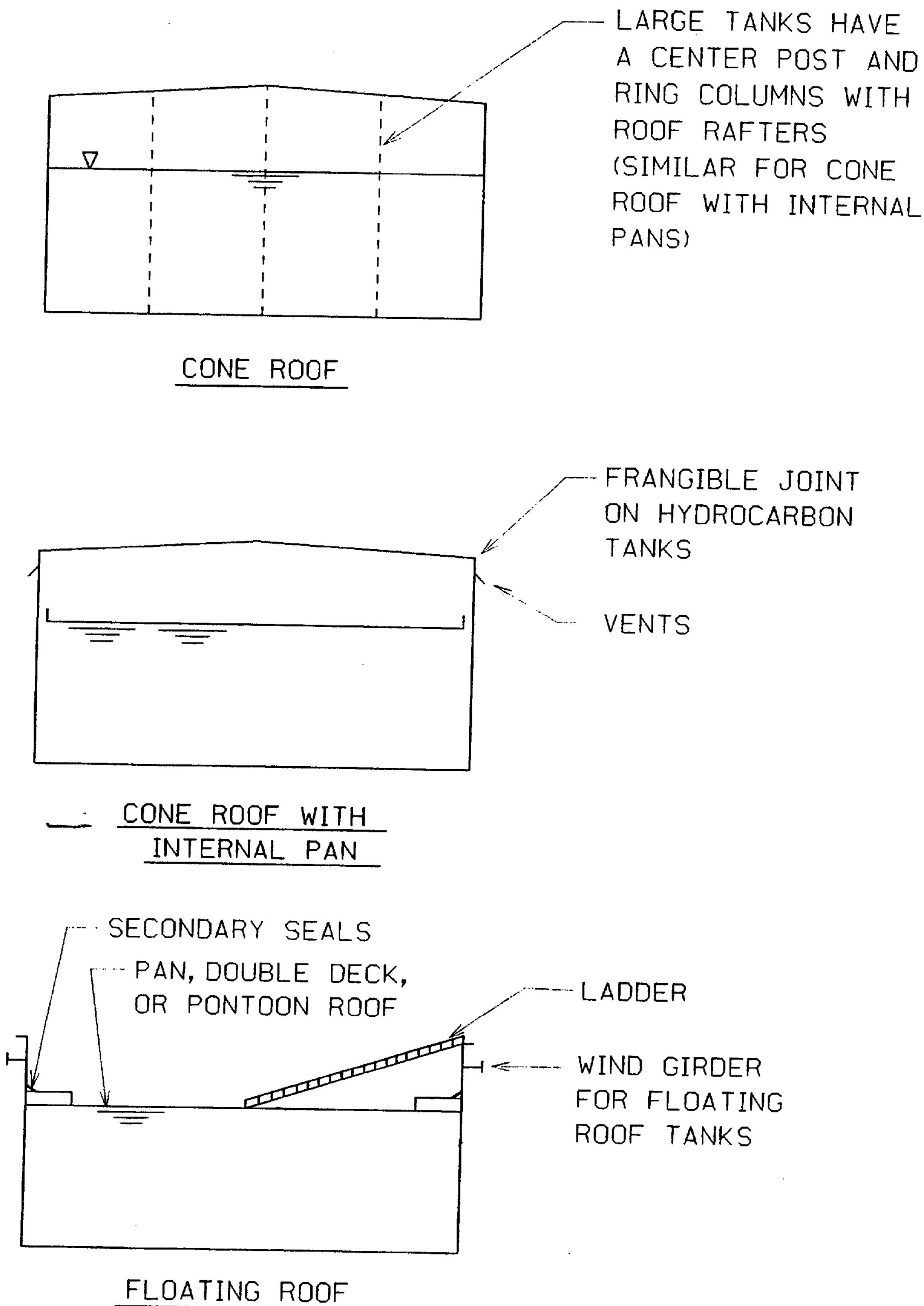

Figure 1.1 **Tank Configurations**

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2. THE 1933 LONG BEACH EARTHQUAKE

This magnitude 6.4 earthquake on March 10, 1933 originated offshore on the Newport-Inglewood fault. Recent work has placed the epicenter on shore. Considering the concentration of oil production, storage, refining, and transport facilities in the affected area, actual failures were few. Tank damage, while not widespread, occurred enough times to warrant attention. All tanks that failed, or sustained damage, were of riveted construction. The failures were in the shell plates and butt or tension straps, and are not comparable to the failures experienced by welded tanks in later earthquakes. The roof/shell damage experienced in this earthquake seems to have its equivalent in later earthquake damage to welded tanks. Sloshing in floating roof tanks also occurred in this earthquake, causing damage to the seals. Only one possible case of elephant foot buckling was noted in one of the reports of the earthquake; this was to a water tank. Examination of the extant damage reports indicates that nearly all tanks reporting damage were full, or nearly full [9] [10]. The general area affected by the earthquake, as well as the locations of some tank failures, is shown in Figure 2.1.

Tank "A" located in Huntington Beach was a spectacular failure. This tank was nearly full (98%), in close proximity to the epicenter (3.5 km) and to the fault (2 km). The tank was in a block with three other tanks which were partially full at the time of the earthquake. These tanks sustained no damage. The failed tank had a diameter of 28.9 m (95.5 ft) and a height of 8.8 m (29.1 ft); its roof was of galvanized iron on wooden supports. Oil splashed to the top of the shell of an adjacent 12.1 m (40 ft) high tank, 15.2 m (50 ft) distant from the failed tank. The released oil traveled over 91.8 m (300 ft), went over a firewall, and broke windows on an adjacent garage. Fortunately, no fire resulted [11].

Tank "B" was a 118,000 bbl tank located 5 km from the fault and 15± km from the epicenter. This tank was at a tank farm with 43 other identical tanks, none of which failed. Few details are available on tank geometry or failure mode, other than it was a total failure with both shell and roof sustaining damage.

Tank "C" was a tank 45.4 m (150 ft) in diameter and 19 m (63 ft) high which had a 14.5 m (48 ft) water depth at the time of the earthquake. This tank had eleven shell courses and the failure was at the top of the fourth shell course. Portions of the tank shell were up to 60 m (200 ft) from the tank after the failure. This tank was 45 km from the epicenter and was probably within 1-2 km of the fault; see Figure 2.2 [10].

There were numerous tanks with cast iron fittings which broke, allowing oil or product to escape. A number of tanks had roof/shell failures; on the basis of the reports, virtually all of the tanks which had roof/shell or floating roof damage had an outage (tank height less depth of fluid) of less than 0.61 m (2 ft). Tanks less than one-half full generally did not have rivet damage and "sweating" at the seams. Damage to roofs (and some of the failures) were generally on the northeast-southwest quadrants of the tanks, perpendicular to the general trend of the Newport-Inglewood fault. This does not hold true for Tank "A" which failed in the northwest quadrant [11].

Roof damage to both floating and cone roof tanks did occur, predominately in tanks which were nearly full. Steel valves and flexible inlet/outlet connections also seemed to fare well, considering the number and severity of inlet/outlet problems and the total number of tanks in the affected area. Two interesting statements in the Joint Report by Six Oil Companies [11] were: 1) "tanks with diameters less than 15 m (50 ft) did not have roof problems", and 2) essentially "that tanks with outages greater than two feet had little problems while those with outages less than two feet had the preponderance of roof problems."

One of the first accelerometer readings was made during this earthquake. For the station in Long Beach, 29 km from the epicenter, the 270° direction the acceleration was 0.17 g, and the vertical acceleration was 0.20 g. (The 90° - 180° value is not available.) At a station in Vernon, outside the seriously shaken area and 51 km from the epicenter (25 km north of Long Beach), the 188° component was .14 g, the 278° component was .16 g, and the vertical component was .16 g [12]. No surface displacement on shore was found in this earthquake.

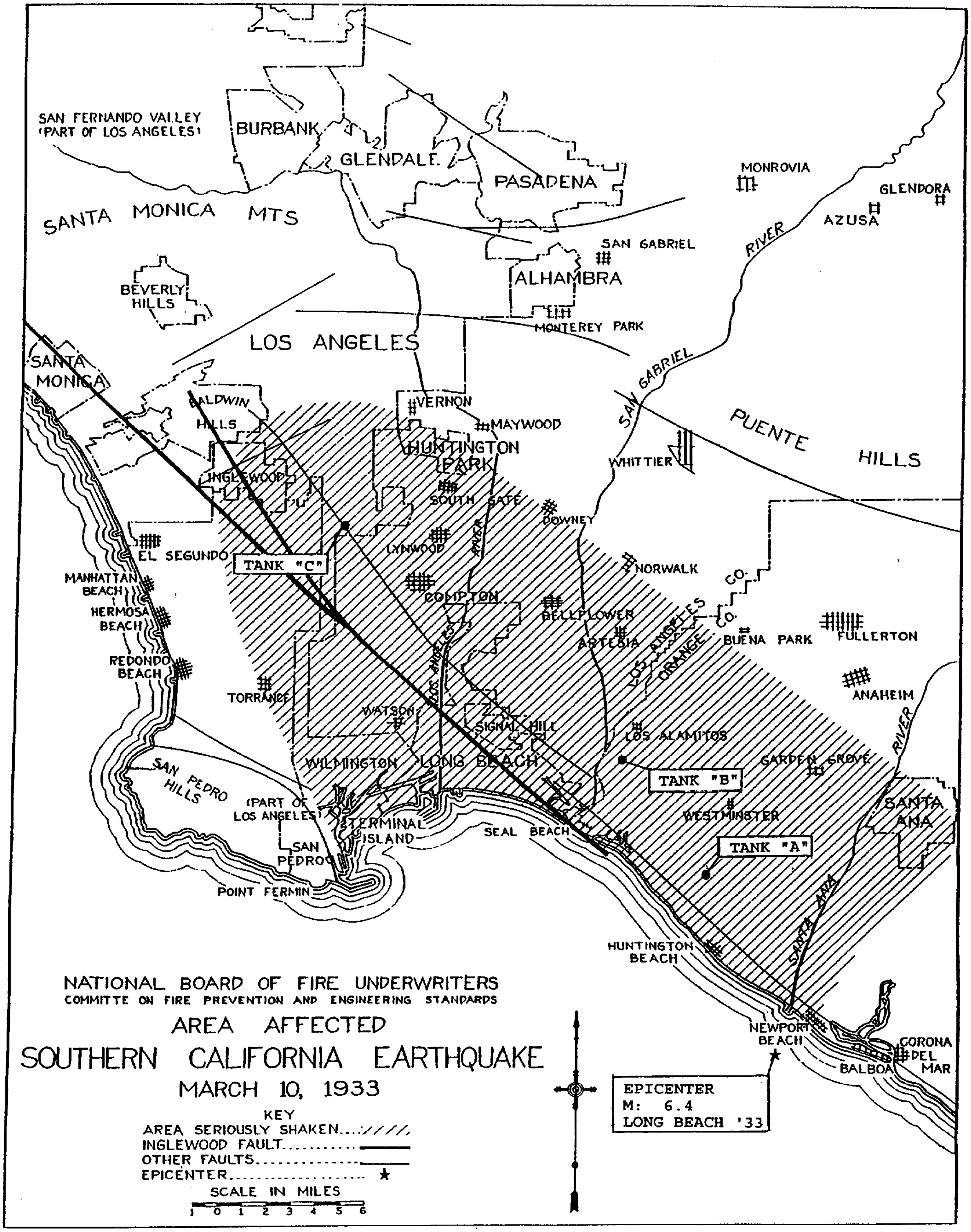

Figure 2.1 1933 Long Beach Earthquake Area Map [10]

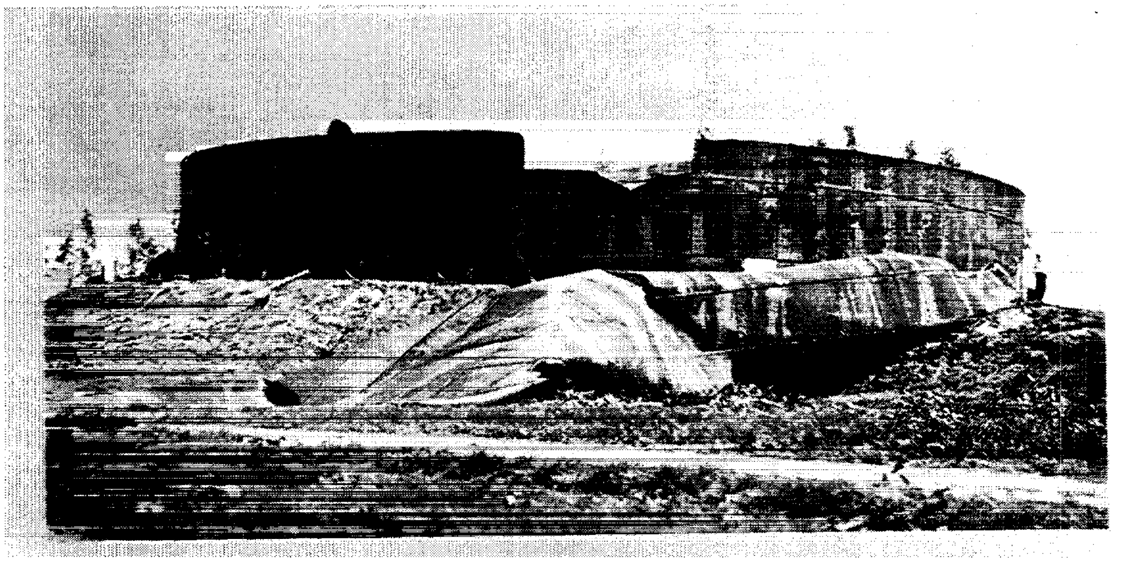

Figure 7-8. The top of this steel tank was thrown about 200 feet due to sloshing liquids. Western Avenue tank of the Los Angeles Water Department after the 1933 Long Beach, California, earthquake.

Figure 2.2 CLADWP Western Avenue Tank. The top of this steel tank was thrown about 200 feet due to sloshing liquids [L. Lund/Steinbrugge Collection at UCB EERC/Richmond].

3. THE 1952 KERN COUNTY EARTHQUAKE

This magnitude 7.5 earthquake occurred on July 21, 1952, and was followed by a series of strong aftershocks in a rather extended area in the northeast direction from the initial epicenter. The initial earthquake occurred in a sparsely populated area, but an area in close proximity to a number of tanks. Table 3.1 [13] lists the damage to the then General Petroleum tanks on their pipeline system from the San Joaquin Valley to the Los Angeles Basin. Figure 3.1 shows the general location of the various facilities affected as well as the epicenter of the initial earthquake. Table 3.2 gives the distance from the epicenter to the specific location of the tanks. Ground displacement occurred generally to the northeast of the epicenter. There were a number of smaller diameter bolted "production" tanks which either failed by elephant foot buckling, or in at least one case, the tank collapsed and fell over. This collapsed tank was nearly full. Adjacent tanks which were not full suffered no damage. Most production tanks have heights and diameters that are approximately equal, and are of bolted shell construction.

TABLE 3.1 GENERAL PETROLEUM STEEL OIL TANKS

(From: Bulletin of Seismological Society Vol. 44, No. 2B,
"An Engineering Study of the Southern California Earthquake of July 21, 1952 and its Aftershocks", by Steinbrugge and Moran)

Location	Tank No.	Diameter d m (ft)	Tank Ht. h m (ft)	d/H	Oil Ht at Time of Shock H'	Per unit Full	Roof Type	Remarks
Pentland	550x81	34.9 (114.5)	9.14 (30)	3.82	4.0	.35	Fixed	Bottom ring bulged 1/4"
	550x82	34.9 (114.5)	9.14 (30)	3.82	19.0	.166	Floating	----
	550x83	34.9 (114.5)	9.11 (29.9)	3.83	2.6	.023	Fixed	Earth imprints by bottom edge
	550x84	34.9 (114.5)	9.14 (30)	3.82	18.1	.158	Floating	Some oil splashed onto top
	550x85	34.9 (114.7)	9.05 (29.7)	3.86	9.4	.082	Fixed	----
	550x86	34.9 (114.5)	9.08 (29.8)	3.84	27.2	.236	Floating	Approx. 15 seals damaged, oil splashed over side, earth imprints by bottom edge
Emidio	37003	28.71 (94.2)	9.2 (30.2)	3.12	8.8	.093	Floating	Oil splashed onto roof
	37014	28.71 (94.2)	9.14 (30)	3.14	18.8	.200	Fixed	----
	550x79	34.99 (114.8)	9.11 (29.9)	3.84	4.6	.040	Floating	----
	800x11	35.72 (117.2)	12.74 (41.8)	2.8	10.1	.103	Fixed	----
Rose	37004	28.71 (94.2)	9.17 (30.1)	3.13	19.8	.210	Floating	Tank settled, lower course bulged, oil splashed on shell
	37015	28.71 (94.2)	9.17 (30.1)	3.13	7.4	.078	Fixed	----
Grapevine	37005	28.71 (94.2)	9.17 (30.1)	3.13	21.3	.225	Floating	Bottom leaked, oil splashed over wind girder
	37016	28.71 (94.2)	9.17 (30.1)	3.13	2.4	.025	Fixed	----
Lebec	37006	28.65 (94)	9.2 (30.2)	3.11	15.8	.168	Floating	Oil splashed onto roof
	370x13	28.93 (94.9)	9.08 (29.8)	3.18	15.8	.168	Floating	Earth imprints by bottom edge
	55021	34.93 (114.6)	9.11 (29.9	3.81	12.4	.108	Fixed	----
	55022	34.93 (114.6)	9.11 (29.9)	3.81	5.5	.048	Fixed	----
	55047	34.93 (114.6)	9.14 (30)	3.82	3.2	.28	Fixed	----
	80105	35.69 (117.1)	12.74 (41.8)	2.8	Empty	----	Fixed	----

TABLE 3.2 DISTANCES FROM TANK SETTINGS TO THE EPICENTER OF THE JULY 21, 1952 EARTHQUAKE, AND LOCAL SOIL TYPE

Location	Distance to Epicenter (km)	Local Soil Type
A. M. Kelly Pump Station	3.2	Rock
Rose Station	7.7	Alluvium
Emidio Station	7.7	Alluvium
Grapevine Station	13	Rock
Lebec Station	20	Rock
Paloma Gasoline Plant	21	Alluvium
Pentland Station	25	Alluvium
Continental Station	38	Alluvium
Weed Patch, Refinery	28	Alluvium
P.G. and E. Kern P. H.	42	Alluvium

Virtually all of the tanks listed in Table 3.1 were riveted tanks, with thick shells to allow for acceptable tensile stresses at the riveted splice between the shell plates. Considering the proximity of the facilities to the epicenter and severity of the earthquake, one would expect more tank damage, especially considering the extensive damage to older buildings from this earthquake. Continental Station, not listed in Table 3.1, sustained no damage. Damage to the tanks at the A.M. Kelly Station was reported not significantly different from that at the General Petroleum Stations listed in Table 3.1. Figure 3.2 shows the elephant foot buckling on a bolted tank at the General Petroleum Emidio Station.

Damage also occurred to tank floating roofs at the Pacific Gas and Electric (PG and E) Kern Power House (Steam Station). The damage was principally to the floating roof seals accompanied by some sloshing and oil spillage. Tank damage at Weed Patch consisted of sloshing in full (or nearly full) cone roof tanks, with the roof/shell weld being broken on two tanks with the consequent spillage of oil by sloshing. See Figure 3.3. Similar damage occurred at two oil refineries closer to Bakersfield. Information on the PG and E tanks is given in Table 3.3 [13]. In most cases where damage to floating roof tanks occurred, there was also rotation of the roof and breakage of the roof anti-rotation guide and/or gage well.

TABLE 3.3 DATA ON TANKS AT THE PG AND E KERN POWER HOUSE

Tank No.	Diameter d m (ft)	Height H m (ft)	d/H	Remarks
1	36.6 (120)	6.25 (20.5)	5.9	Damage to Roof Truss
2	23.8 (78)	8.93 (29.3)	2.7	Damage to Roof Truss
3	23.8 (78)	13.5 (44.3)	1.7	Seal Damage
4	36.6 (120)	8.9 (29.2)	4.1	Damage to Roof Truss

Severe fire damage occurred at the Paloma Gasoline Plant. The principal cause of the damage was the failure of two butane storage spheres. The failure mechanism was the failure of diagonal tension rod bracing between the columns supporting the spheres, allowing the support columns to rotate. This allowed the sphere to roll off of its supports, breaking or opening piping which allowed the butane to escape. The escaping butane caught fire and destroyed the entire facility [14] [15].

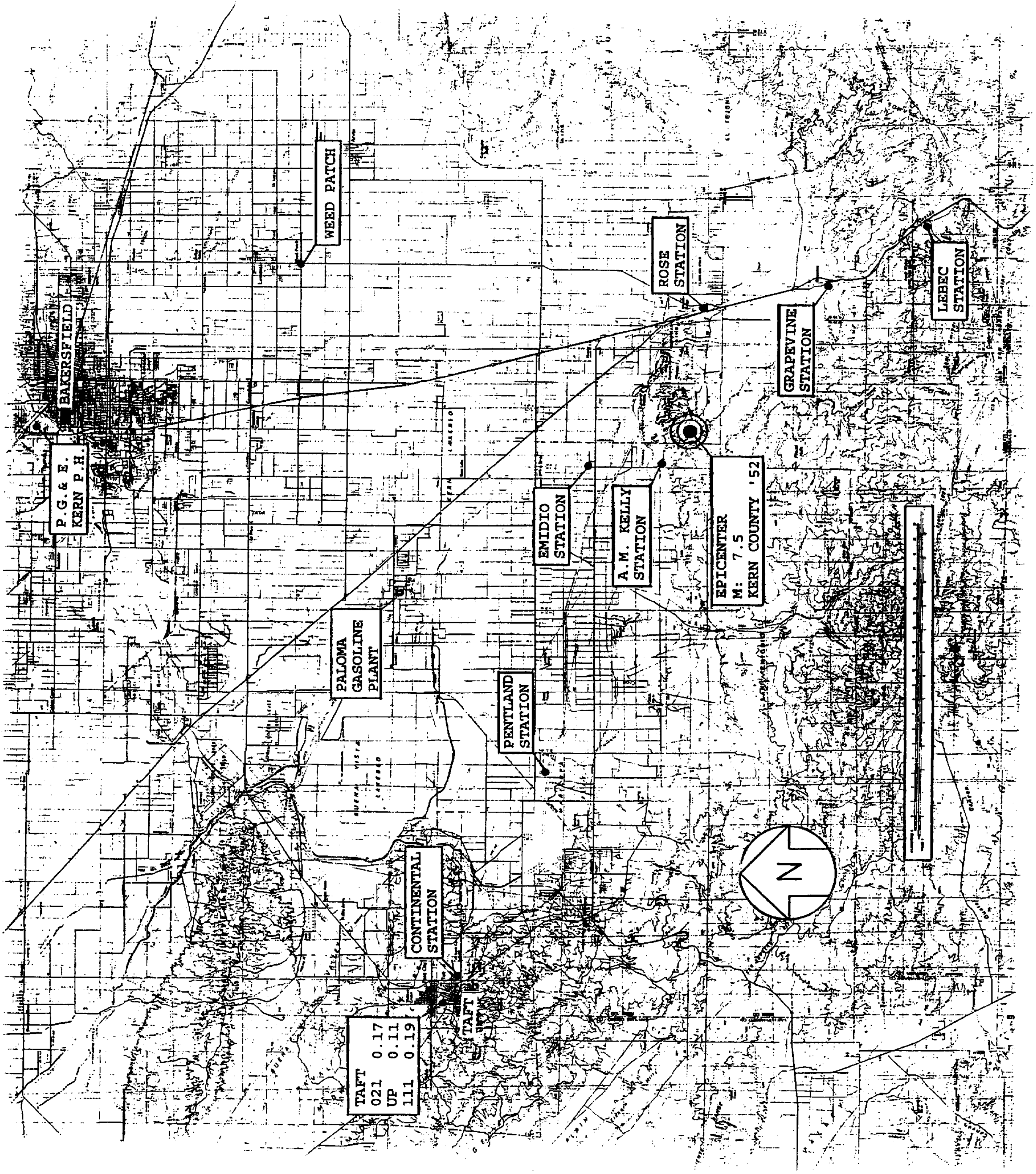

Figure 3.1 1952 Kern County Earthquake Area Map.

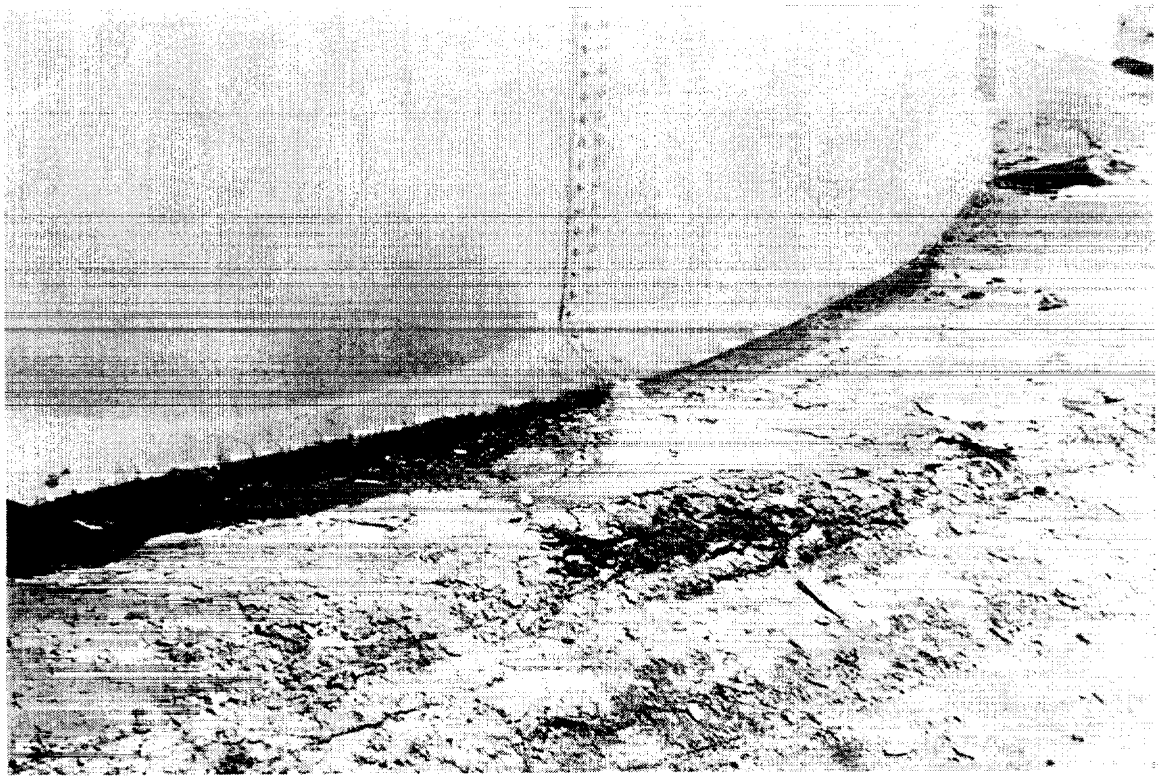

Figure 3.2 Bolted Tank at General Petroleum Emidio Station [Steinbrugge Collection at UCB EERC Richmond]

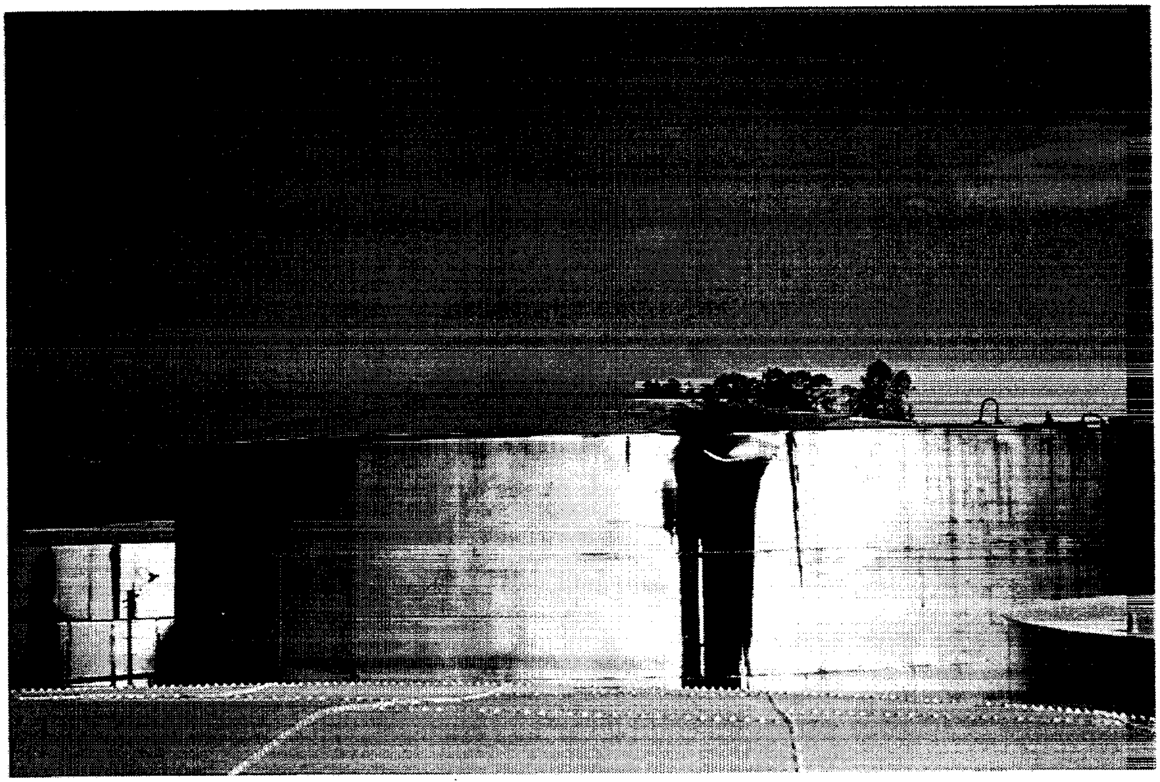

Figure 3.3 Roof/shell buckling and tearing at Weed Patch [Steinbrugge Collection at UCB EERC Richmond]

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4. THE 1964 ALASKA EARTHQUAKE

The Great Alaska magnitude 8.4 earthquake occurred on March 27, 1964. The epicenter of this earthquake was located in or near Prince William Sound. Damage to tanks and other structures in surrounding cities was extensive. This damage was caused not only by the strong shaking and ground failure, but also, for many sites, by the tsunami which followed the earthquake. Although this earthquake provided an impetus to study the effects of earthquakes on tanks, specific definition of damage to tanks from this earthquake is not plentiful. The extent of tank damage which occurred at large distances from the epicenter should cause concern for areas adjacent to faults which can produce earthquakes of equal magnitude. The following describes the damage to tanks in several areas. See Figure 4.1 for a map of the area.

Anchorage

Anchorage is located 130 km from the epicenter. Tanks were located in the dock area, where the military and a number of oil companies had storage tanks, and at the airport. Soils in the dock area consisted of silts and a thick lens of "Bootlegger Clay". Soils away from the shoreline were probably more stable than those close to the shoreline. No specific identifiable data is available on individual tanks; on the basis of photographs, the larger tanks appear to be about 13 - 16 m (40 - 50 ft) high and about 13 - 37 m (40 - 100 ft) in diameter. There appears to be about twenty "tall" (H>1.5d) tanks, and about twenty tanks with the height equal to or less than the diameter.

On the basis of air photos, damage to the larger tanks appeared to be minimal. Damage to smaller tanks appeared more frequently and more severely for those tanks situated closer to the water. The tanks inland from the main entrance road appeared to survive the earthquake reasonably well. Tanks at the airport had approximately H=d, and on the basis of photos and reports suffered sever elephant foot buckling (including loss of product) as well as shell and roof damage [16] [17]. The type of damage is correlated to height and diameter in Table 4.1. Tanks listed in the table were all full or nearly full. Reports on the earthquake noted that tanks less than half-full did not suffer damage. Figures 4.2 and 4.3 show tanks at the Anchorage Airport.

TABLE 4.1 ANCHORAGE TANK PROPERTIES AND DAMAGE [17]

Tank	Diameter d m (ft)	Height H m (ft)	d/H	Damage Observed
A	9.1 (30)	14.6 (48)	0.63	Collapsed, failed
B	30.5 (100)	9.6 (32)	3.1	Damage to roof top shell and columns
C	13.7 (45)	9.6 (32)	1.4	Damage to roof top shell and buckled
D	36.6 (120)	9.6 (32)	3.8	Damage to roof top shell and columns
H	27.4 (90)	9.6 (32)	2.8	No damage except floating suction
I	16.7 (55)	7.0 (23)	1.7	Damage to top shell and rafters
J,K,L	9.1 (30)	12.2 (40)	0.75	Extensive bottom shell buckling
M	8.5 (28)	12.2 (40)	0.70	Collapsed, failed
N	12.8 (42)	12.2 (40)	1.05	Bottom shell buckling
O	6.1 (20)	12.2 (40)	0.50	Bottom shell buckling, broken shell/bottom weld
P	43.9 (144)	17.1 (56)	2.6	Floating roof buckled, large waves
Q	34.1 (112)	17.1 (56)	2.0	Floating roof damaged
R	14.9 (49)	14.6 (48)	1.02	Bottom buckled, 12-in uplift
S	27.4 (90)	14.6 (48)	1.9	3/4 full, roof and roof/shell damage

Valdez

Valdez is 85 km from the epicenter and on Prince William Sound. Two tank farms were severely damaged by the earthquake and by the resulting fire. The ensuing seismic sea wave destroyed the tank farms and spread the fire along the water front. The tank farms were built near the shoreline on what one would anticipate as "poor" soils. The tanks appear to be not large (from aerial photographs) with d/H's from 1 to 2 and diameters not larger than 12 m (40 ft). A submerged landslide occurred close to the tanks, taking out the dock and other local structures closer to the shoreline [18].

Whittier

Whittier was the closest community to the epicenter at 60 km and also on Prince William Sound. Tanks located near the shoreline suffered damage similar to those at Valdez. Tank size and location were similar to Valdez. Seismic sea waves provided most of the destruction (see Figures 4.4 and 4.5). Tanks (eight minimum) setting well back from the shore apparently survived the earthquake with minimal damage (see Figures 4.6 and 4.7) [18].

Seward

Seward is located on the Gulf of Alaska, about 135 km from the epicenter, to the south and approximately 200 km from Valdez to the west. Seward contained two tank farms of size similar to those at Valdez. Seward first felt the shaking of the earthquake, then a seismic sea wave, and finally by a conflagration fueled initially by the destroyed tank farms [19].

Nikiska

Nikiska is 210 km from the epicenter, on the Kenai Peninsula about 105 km southwest of Anchorage on the Cook Inlet. Two oil refineries are presently located there, and it has long served as a terminal for the shipment of LPG's and crude oil. Rinne [17] in the reporting on "Oil Storage Tanks" gives substantial data on tanks at Nikiska. Table 4.2 gives a compilation of his data.

TABLE 4.2 TANK DATA ON NIKISKA AND ANCHORAGE AIRPORT [17]

Tank	Diameter d km (ft)	Height H km (ft)	d/H	Damage Observed
R200	9.1 (30)	14.6 (48)	0.63	Water, full, failed
R162	27.4 (90)	14.6 (48)	1.87	Full, cone roof damage no elephant foot buckling
R163	27.4 (90)	14.6 (48)	1.87	Full, cone roof damage no elephant foot buckling
R100	34.1 (112)	17.1 (56)	2.00	Floating roof, 1/6 full, roof damage
R120	21.3 (70)	14.6 (48)	1.46	Floating roof, 1/3 full, roof damage
R110	43.9 (144)	17.1 (56)	2.57	Floating roof, roof damage, 39 ft level
R140	14.9 (49)	14.6 (48)	1.02	Elephant foot buckling, no failure
AA4	3.2 (10.5)	9.1 (30)	0.35	1/3 full, walked, no damage
AA7	12.1 (40)	13.0 (42.5)	0.94	Severe elephant foot buckling, failed
AA5	8.5 (28)	12.2 (40)	0.70	Failure, collapsed

R designation believed to be Nikiska Refinery; AA is Anchorage Airport

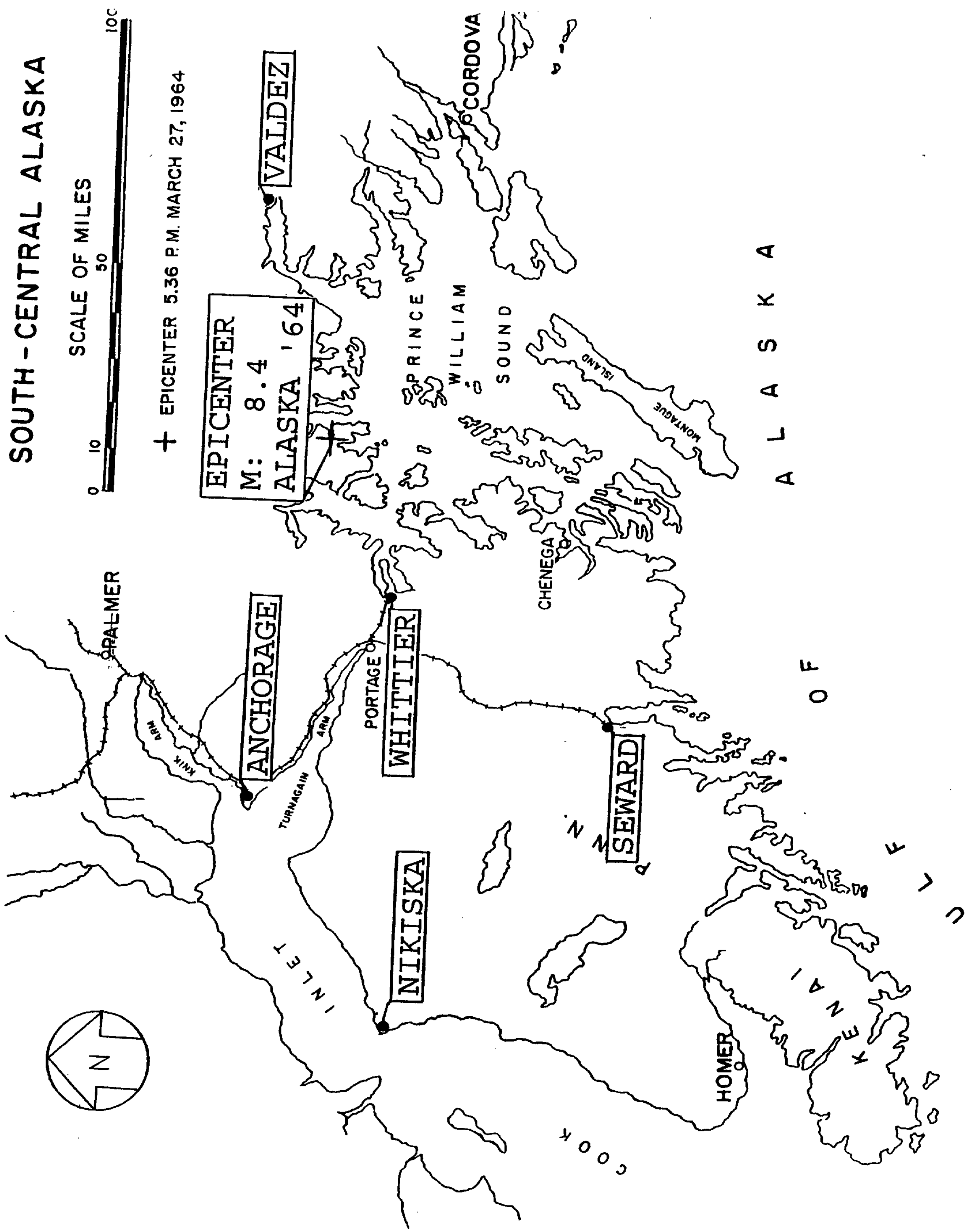

Figure 4.1 1964 Alaska Earthquake Area Map

Figure 4.2 Elephant foot buckling and shell/floor failure [Courtesy G. Housner].

Figure 4.3 Port area, Anchorage [Steinbrugge Collection at UCB EERC Richmond]

Figure 4.4 Whittier tanks near waterfront (Courtesy W. Daniels)

Figure 4.5 Whittier tanks, fire and tsunami damage (Courtesy W. Daniels)

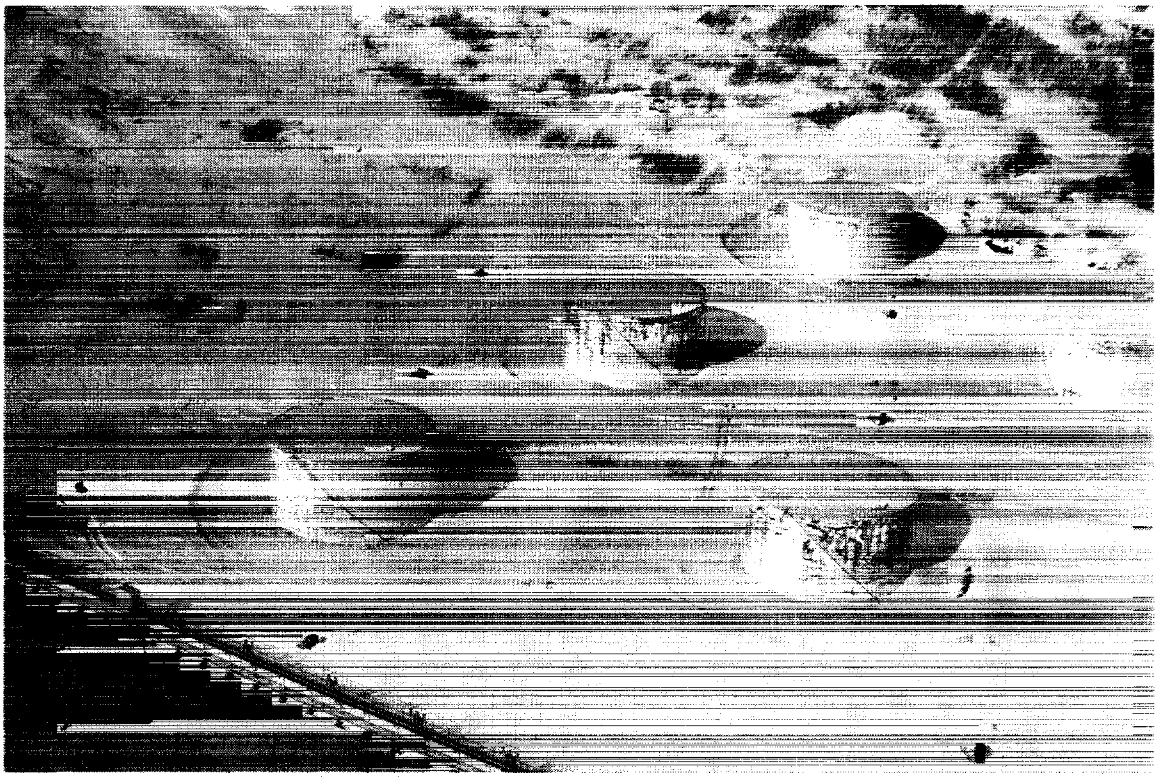

Figure 4.6 Tanks at Whittier which sit well back from the shore [Steinbrugge Collection at UCB EERC Richmond]

Figure 4.7 Whittier tanks which survived both the earthquake and tsunami with minimal damage [Steinbrugge Collection at UCB EERC Richmond]

5. THE 1971 SAN FERNANDO EARTHQUAKE

This magnitude 6.7 earthquake had its epicenter about 21 km north of the City of San Fernando in the mountains north of the San Fernando Valley. There was ground breakage or surface faulting south of the epicenter, in the valley surface. Most of the heavy damage was north of this faulting [20]. Figure 5.1 shows the general area and notes specific features.

Tank damage in this earthquake seems to have been confined to the general area north of where ground breakage occurred. A 31 m (100 ft) diameter by 11 m (36 ft) high water tank at the Metropolitan Water District Jensen Plant, near or on the faulted zone, uplifted at least .33 m (13 in) on the south side based on maximum anchor bolt (d=25.4 mm /1 in) stretch on the south side. The minimum stretch was .035 m (1 3/8 in) on the north side. This tank which sets atop a bluff had roof and upper shell damage but no elephant foot buckling. The tank was one-half to two-thirds full at the time of the earthquake. The tank has a knuckled roof/shell joint. Shell buckling damage was in the upper shell course but not in the knuckle joint and was on the south side of the tank. This tank sat on a ring foundation and had foundations under the nine interior columns. The lowest shell course was 17.5 mm (11/16 in); the upper course (below the knuckle section) was 12.7 mm (1/2 in). The floor plate was 8 mm (5/16 in). The roof was 4.8 mm (3/16 in) [21] [22]. See Figures 5.2 and 5.3.

A welded water tank at the Olive View Hospital suffered elephant foot buckling and also a 3 m (10 ft) floor/shell tear. The inlet/outlet piping was also damaged, allowing the tank to lose its contents. This tank was 17 m (55 ft) diameter by 12 m (40 ft) high, with the bottom course 11.4 mm (.45 in) and the top course 6.4 mm (.25 in). Inside the tank roof rafters buckled and vertical buckling of the floor occurred in several places. The d/H for this tank was 1.4 [23]. See Figures 5.4 and 5.5.

The Veterans Hospital was served by two tanks. The smaller, older tank was of riveted construction and the larger newer tank was of welded construction. The riveted tank was set on and anchored to steel beams which buckled. The anchor bolts stretched or displaced and the inlet/outlet piping sheared. No significant damage to the welded tank was observed. The City of Los Angeles Department of Water and Power (CLADWP) maintained two small tanks (Alta Vista 1 and 2) west of the Veterans Hospital. Alta Vista 1 was of riveted construction, built in 1931. Its diameter was 16.6 m (54 ft) and the height was 8.6 m (28 ft). The bottom shell course was 9.5 mm (0.375 in). Alta Vista 2 was of welded construction, built in 1954. Alta Vista 2 was 29.2 m (95 ft) in diameter and 11.2 m (36.5 ft) high. Reported damage was to cast-iron inlet/outlet fittings with no damage to either tank shell or bottom.[23].

The Newhall County Water District, 13 km west of the epicenter and 8 - 10 km north of the surface faulting, had two tanks which sustained floor plate ruptures and shell buckling. The local Mutual Water Company in the Kagel Canyon area lost all five of their small 6.2 m (20 ft) by 6.2 m (20 ft) bolted tanks.

The CLADWP Sesnon Tank, a 29 m (95 ft) diameter and 13 m (42 ft) high welded steel tank developed a buckle 7.4 m (24 ft) above the bottom on a 150° arc. This tank had a 25.4 mm (1 in) bottom course and a 8 mm (5/16 in) top course, and was built in 1966. This tank was 95% full. This tank had a 12.7 mm (1 in) by 0.9 m (36 in) sketch plate (annular ring), which reportedly lifted from the foundation. This tank was not anchored. This tank had roof beams with a wooden roof which displaced in one area [22] [24]. See Figure 5.6.

The CLADWP Granada High tank, 17 m (55 ft) diameter by 13.8 m (45 ft) high with riveted construction built in 1929 with a wooden roof, suffered roof collapse and shifting [22].

Inquiries revealed that there was no damage to either of the product terminals in the San Fernando Valley, both of which were south of the zone of faulting.

The Newhall refinery was located 12km from the epicenter and 4-5km from the surface faulting. This facility had about 400,000bbls of tank storage. Three 20,000bbl tanks, 18.5m (60ft) in diameter by 12.2m (40ft) high, which were full of Jet Fuel had elephant foot buckling on one side. Two 37m (120ft) in diameter by 12.2m (40ft) high tanks had no damage. There was minor piping damage but no serious problems developed.

Figure 5.1 1971 San Fernando Earthquake Area Map.

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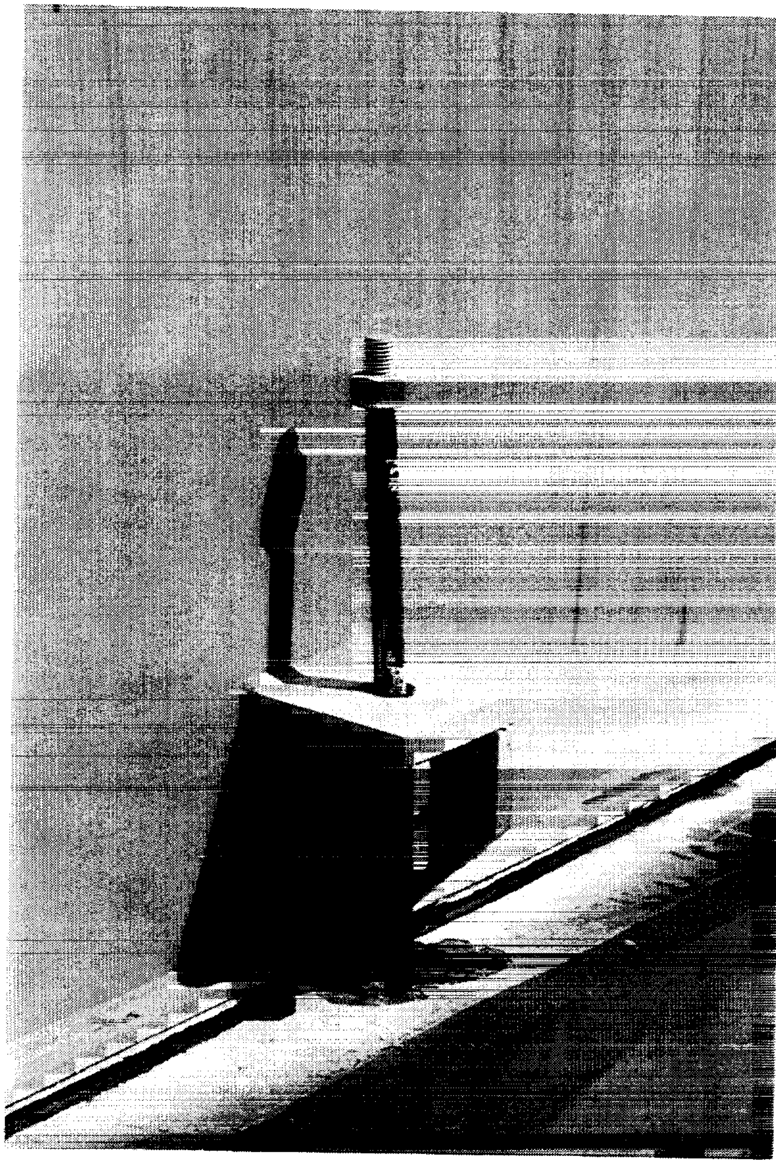

Figure 5.3 Jensen tank, pulled or stretched 1 inch anchor bolt [Steinbrugge Collection at UCB EERC Richmond]

Figure 5.4 Olive View Hospital Tank which had a shell/floor failure [Steinbrugge Collection at UCB EERC Richmond]

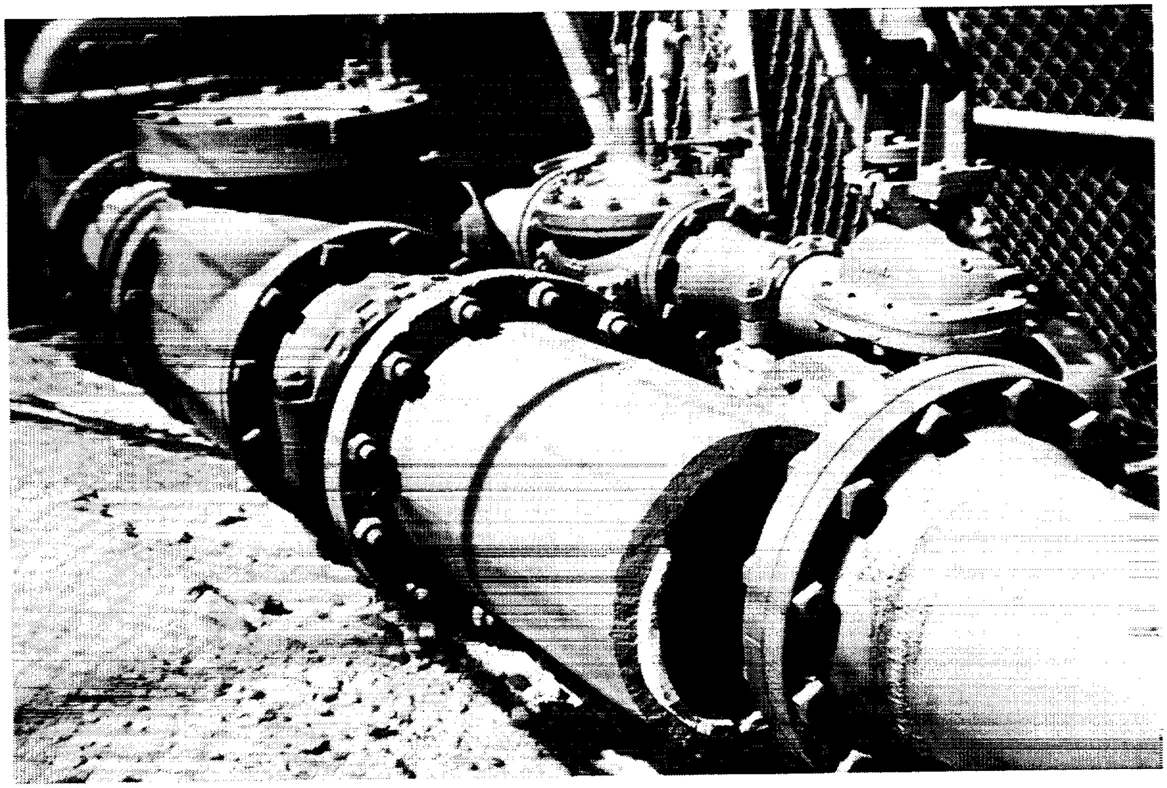

Figure 5.5 Olive View Hospital Tank Piping [Steinbrugge Collection at UCB EERC Richmond]

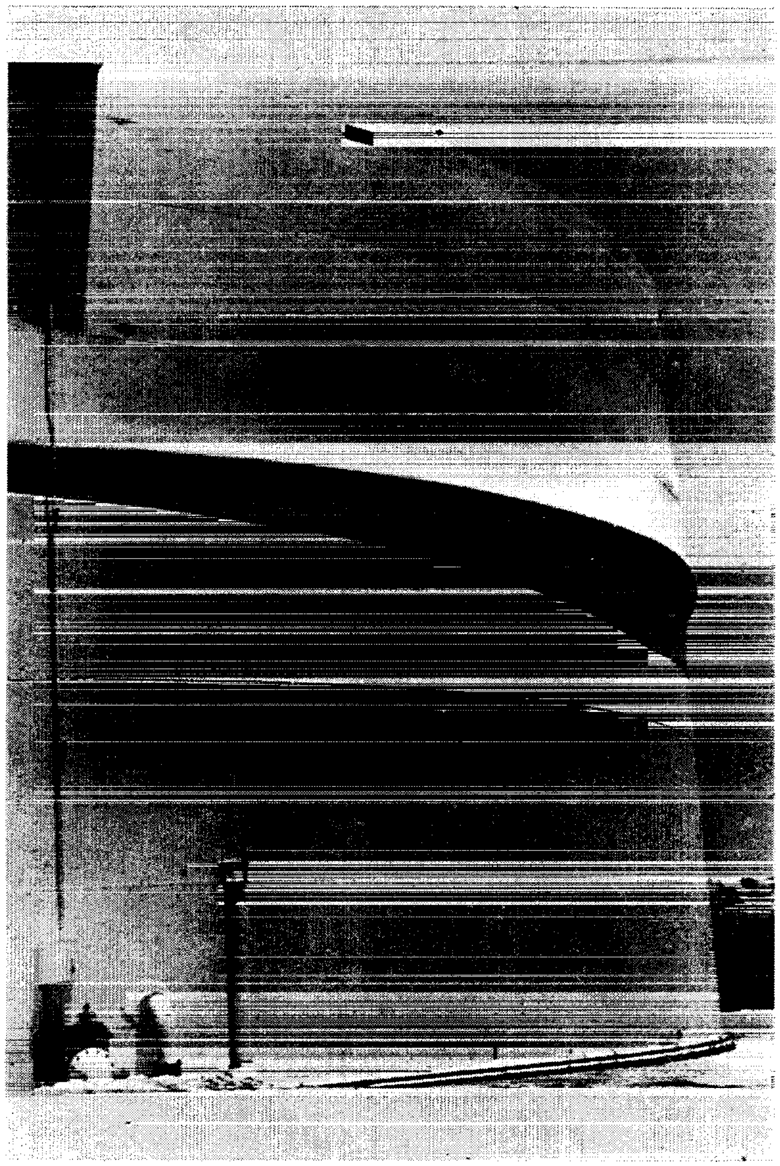

Figure 5.6 Sesnon Tank of CLADWP [Courtesy of G. Housner].

6. THE 1979 IMPERIAL VALLEY EARTHQUAKE

This magnitude 6.5 earthquake provided the opportunity to evaluate the performance of tanks where near ground motions were recorded. Most of the information in this section was obtained from the EERI Reconnaissance Report [25] and the paper by Haroun [26]. Ground-motion was estimated from USGS Professional Paper 1254, The Imperial Valley, California, Earthquake of October 17, 1979 [27]. The epicenter was located about 30 km from the site of the tanks. The tanks were located about 4 - 5 km west of the Imperial fault, where there was surface movement in the vicinity of the tanks.

Damage to two tanks was observed at the Imperial Irrigation District (IID) power plant, about 4 km from the fault. Both tanks were full at the time of the earthquake, and both suffered similar roof damage which consisted of the roof separating from the shell at the roof/shell weld, allowing oil to spill from the tanks. The larger tank, with the most damage, was 41.2 m (135 ft) in diameter and 13.7 m (45 ft) high, with a diameter to height (d/H) ratio of 3.0. The smaller tank was 22.3 m (73 ft) in diameter and 6.1 m (20 ft) high, with a d/H ratio of 3.6. There was no other significant damage to these tanks. There is evidence that the largest tank at this site uplifted from the ground [28]. Four other tanks at this location showed no apparent damage. The oil level in these tanks is not known.

Significant damage at the SPPL terminal (now SFPPL-Santa Fe Pacific Pipelines) was to three tanks. The most severe damage was to tank IP-13. The damage to this tank was elephant foot buckling over a 90^0 arc, and opposite the buckling arc there was a 10 cm (4 in) weld separation at the shell-bottom plate joint. IP-13 has a concrete ringwall foundation and has a cone roof with an internal floating pan. This tank was 70% full at the time of the earthquake. Damage to tank IP-16 was principally elephant foot buckling of the tank shell with no shell/bottom separation. This tank sets on a concrete ringwall foundation, and also has a cone roof with an internal floating pan, and was 83% full.

Damage also occurred to tank IP-5 which sets on an earth foundation and is a cone roof tank (without internal floating pan), and was 73% full. Table 6.1 lists the damaged tanks, with diameters, heights, and fluid heights at the time of the earthquake.

There was a total of 18 tanks at this terminal, some with liquid levels greater than those of the tanks which sustained major damage. Minor damage, which was widespread among the station tanks, consisted of roof seal damage, broken anti-rotation devices, relief piping damage, grounding cable pulled off, settlement, and roof strain and swing line damage. All tanks at this terminal were built to API 650 in effect at the time of construction.

Figure 6.1 shows the location of the tanks relative to the epicenter and displaced sections of the Imperial fault, and gives the USGS accelerometer array readings in the vicinity of the tanks.

Because of the floor/shell plate tear on tank IP-13 the area within 1.6 km of the terminal was evacuated. To stop the gasoline leak plant personnel injected water into the tank. The gasoline then floated on the water until the tank was evacuated of product.

TABLE 6.1 TANK SIZE AND STATUS [25]

TANK NO	DIAMETER d m (ft)	HEIGHT H_{TK} m (ft)	d/H	H_{LIQ} (ft)	PER UNIT FULL	FDN	ROOF
1	24. 4 (80)	14.6 (48)	1.67	(20.3)	.43	E	F
2	24.4 (80)	14.6 (48)	1.67	(23.4)	.49	E	F
3	20.4 (67)	12.3 (40.5)	1.65	(15.7)	.39	E	C
4	14.6 (48)	14.6 (48)	1.0	(25.5)	.53	E	F
5*	14.6 (48)	14.6 (48)	1.0	(34.9)	.73	E	F
6	13.0 (42.5)	12.2 (40)	1.06	(15.2)	.38	C	F
7	13.0 (42.5)	12.2 (40)	1.06	(15.7)	.40	C	C
8	24.7 (81)	14.6 (48)	1.53	(39.4)	.82	C	F
9	13.0 (42.5)	12.2 (40)	1.06	(25.8)	.65	C	F
10	13.0 (42.5)	12.2 (40)	1.06	(30.5)	.76	C	F
11	14.2 (46.5)	12.2 (40)	1.16	(34.4)	.86	C	C
12	13.0 (42.5)	12.2 (40)	1.06	(34.5)	.86	C	F
13*	12.6 (41.25)	14.9 (49)	0.84	(43.5)	.70	C	CIP
14	14.7 (48.2)	14.9 (49)	0.84	(29.9)	.61	C	CIP
15	15.2 (49.8)	14.9 (49)	1.0	(29.8)	.61	C	CIP
16*	14.6 (48)	14.6 (48)	1.0	(39.9)	.83	C	CIP
C-1	6.5 (21.25)	7.3 (24.1)	0.88	(7.1)	.30	E	CIP
C-2	6.5 (21.25)	7.3 (24)	0.88	(9.4)	.39	E	F

FDN: E-ON EARTH (ROCK BASE), C-CONCRETE RINGWALL
ROOF: F-FLOATING ROOF, C-CONE, CIP-CONE/INTERNAL PAN
*: MAJOR DAMAGE

Valley Nitrogen had a facility 20km from the epicenter and 12km from fault displacement. There was no apparent significant damage to the four or five tanks at this location.

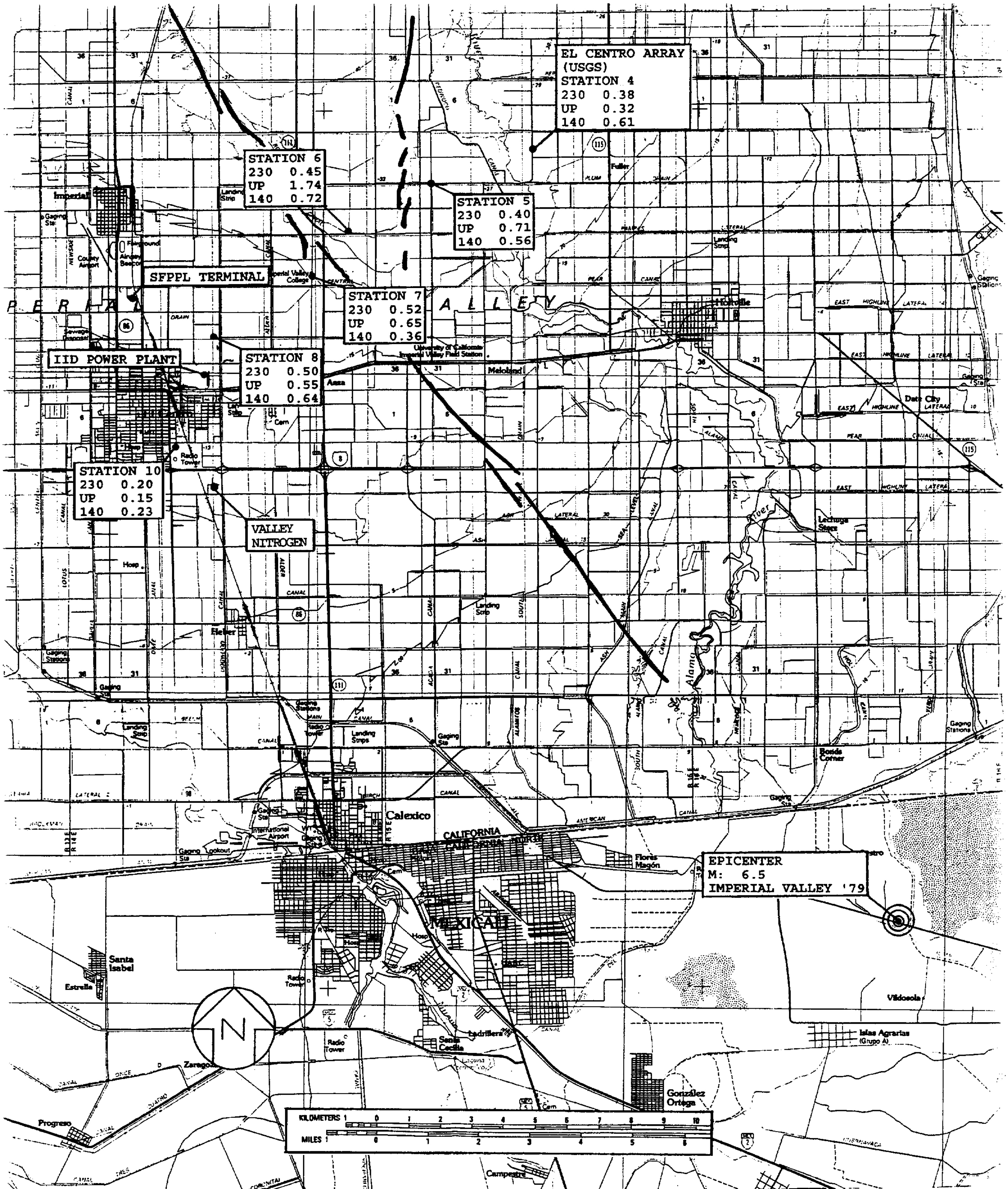

Figure 6.1 1979 Imperial Valley Earthquake Area Map

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7. THE 1983 COALINGA EARTHQUAKE

The Coalinga magnitude 6.7 earthquake on May 2, 1983 presented the opportunity to observe the performance of both large and medium sized tanks when subjected to strong ground motion a relatively short distance from the epicenter. Some of the information contained in this section is from Manos and Clough [29]. Additionally the writer visited the area shortly after the earthquake, when repairs were still being accomplished. The general terrain is rolling hills and valleys, with primarily alluvial soils which are considered good foundation soils. Estimates of the peak acceleration from the initial shock ranged from 0.6 g to 0.82 g [29]. It is believed that there was no surface faulting from this earthquake.

There were a number of large diameter (over 31 m or 100 ft) oil storage tanks within 6.4 km of the epicenter. There also were two large diameter water tanks within 5 km of the epicenter. Most of the large oil storage tanks had floating roofs, and many had seal damage with some having pontoon or roof damage. Figure 7.1 shows a map of the area.

Site "A" was the most distant with major tanks, about 6 km east from the epicenter. This tank farm is about 70 years old, and had nineteen tanks most of which are riveted. The two largest tanks were nearly full and suffered floating roof damage. Other tanks were not full and apparently did not suffer damage.

Site "B" is about 5 km east-northeast of the epicenter and has six identical welded 43 m (120 ft) diameter by 14.8 m (48 ft) high floating roof tanks. These tanks have concrete ring foundations, but also have 1/4 inch bottom plates and are not anchored. They were all constructed to the API Standard 650, and built in 1956. There is a 18.5 m (60 ft) diameter by 12 m (40 ft) high firewater tank at this site, which was full at the time of the earthquake (see. Figure 7.7).

Two of the oil tanks at site "B" were full at the time of the earthquake. There was splashing or top spillage from these full tanks, and also some roof secondary seal damage. There was no settlement as these tanks were on concrete ring foundations. One of the nearly empty tanks at this site also had roof seal damage. Three partially full tanks had no apparent damage. No shell buckling was evident. The firewater tank appeared to have settled uniformly about two inches with no visible damage.

Site "C" is about 4.5 km southwest of the epicenter, and is a mainline pumping station on a major crude pipeline from the southern San Joaquin Valley to the San Francisco Bay area. It has four large 61.5 m (200 ft) diameter by 14.8 m (48 ft) high welded floating roof storage tanks built to the API Standard 650. Two of these tanks (7 and 8) were built in the mid 1960s and have 1/4 inch bottom plates. Two (13 and 14) were built in the late 1970s or early 1980s and have 1/2 inch annular rings. None of the tanks have concrete ring foundations and all are set on gravel pads. This site also had a 37 m (120 ft) diameter by 12 m (40 ft) high riveted shell open top firewater tank with a welded bottom (the 'old' shell was welded to a "new" bottom). This station also had three fired heaters, two gas turbine driven pumps with heat recovery units, electric motor driven pumps, an outdoor power substation, a control building with additional offices, and miscellaneous structures.

Tank 7 contained 10.7 m (35 ft) of crude oil at the time of the earthquake, the other three tanks had about 3 m (10 ft) of crude. All tanks incurred roof seal damage, with the severest damage on a NE-SW axis for all four tanks, and with no seal damage on an NW-SE axis. The seals, which are normally straight, had been bent at some locations 90^0 or more, (see Figures 7.5, 7.6 and 7.8). Tank 7 spilled/splashed oil over the top of the tank and onto the wind girder. Tank 7 "pounded" into the foundation soil about 100 mm (4 in), again on a NE-SW axis, with no "pounding" on the NW-SE axis (see Figure 7.3). On the west side, the tank lifted sufficiently to break a water-draw/bottom plate weld which allowed significant leakage of crude oil. A diagram of the water-draw/bottom plate and the break is shown in Figure 7.2. A pipe support on the west side was also bent, and showed movement of about 100 mm (4 in) each side of the pipe centerline, in a north-south direction. See Figure 7.4. On Tank 8 the flange on the wind girder buckled on the south side.

The 37 m (120 ft) diameter by 12 m (40 ft) high riveted water tank did not appear to be damaged. Cracks in the soil adjacent to the tank may have been induced by settlement, but there was not the differential settlement as noted at Tank 7. This tank appeared to have a bulge in the bottom course but did not have elephant foot buckling. There was minor reparable damage to some of the equipment foundations, and problems with lighting, ceilings, electrical switchgear, and office furniture in the control building.

Site "D" was located about 3.2 m north of the epicenter and contains two old riveted shell tanks, one of which was modified by the addition of a welded ring added at the top of the highest riveted ring. The top welded ring survived the shaking but the top riveted ring failed by buckling. Figure 7.9 shows a bolted tank which pounded into the ground. Figure 7.10 shows roof spillage on a bolted tank; this tank was located about 16km (10 miles) north of the epicenter. Figure 7.11 shows the effect of broken valves/fittings on a tank slightly south (500m) of Site "D".

Site "E" is a gathering station with two bolted "production" tanks. Principal damage at this site was broken cast iron valves and fittings, pulled Dresser Couplings, and a minor soil/tank settlement. Tanks at this site were smaller and had lower diameter/height ratios; they were also set on crushed rock foundations. This site is about 2 km south of the epicenter.

Site "F" contained a 34 m (110 ft) diameter by 12 m (40 ft) high AWWA Standard D100 welded water tank, built in 1971. This tank contained municipal water, to a height of 7.9 m (26 ft) on the day of the visit shortly after the earthquake. No damage was evident to the tank or piping at this site. This site is approximately 3.2 km from the epicenter.

Site "G" was a crude oil treatment facility which had a number of bolted tanks. Two tanks of 17 m (55 ft) diameter by 10 m (32 ft) high suffered elephant foot buckling. Both tanks were about three-quarters full. Other tanks at this site developed leakage at bolt holes, with other minor damage. Most of those other tanks were less than or equal to half-full. This site was about 6.5 km west of the epicenter [29].

Sites "H and I" are located west of Coalinga, about 16 km from the epicenter. Damage was not extensive at these facilities and consisted principally of sloshing losses from tanks and some damage to piping [30].

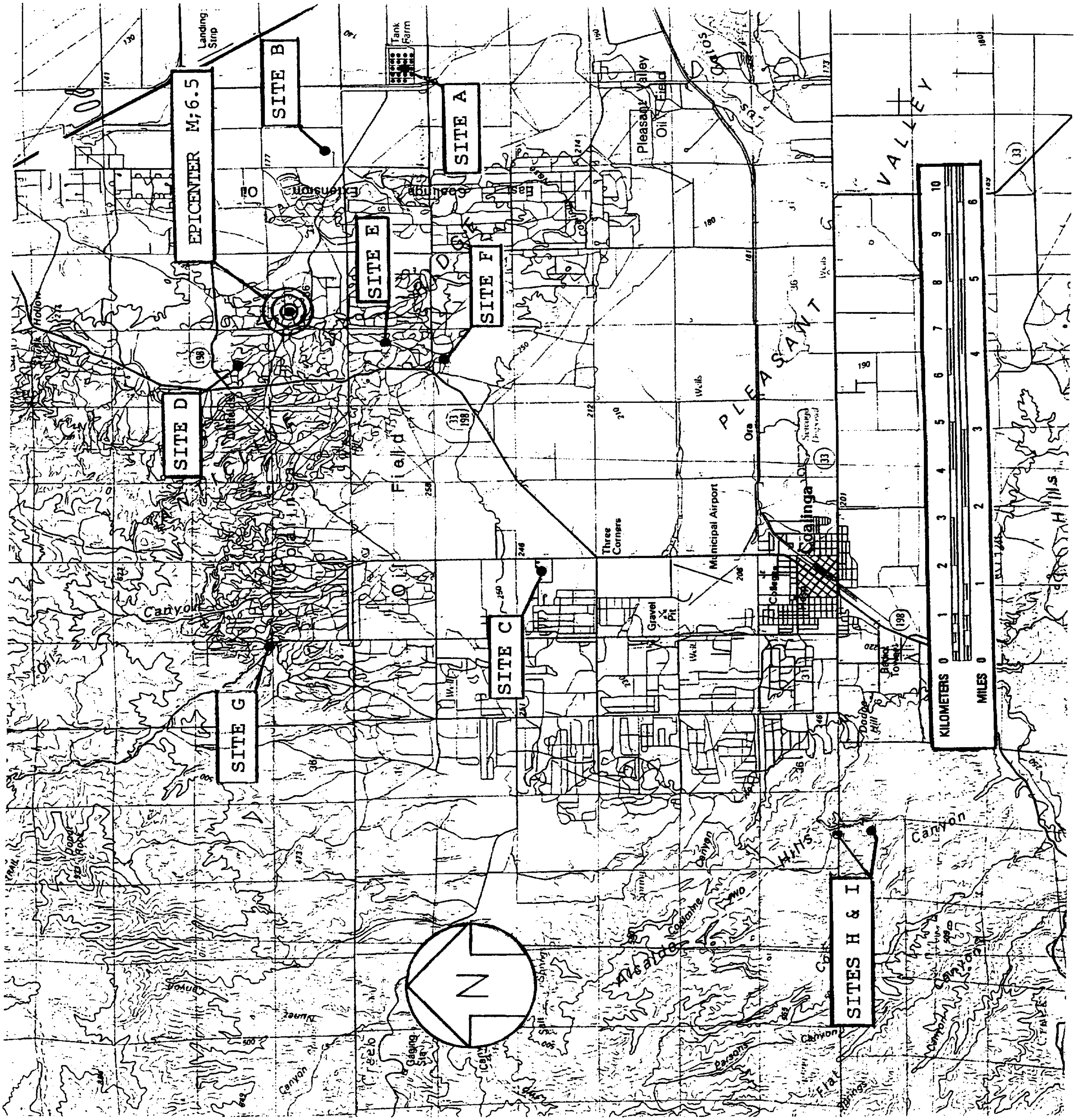

Figure 7.1 1983 Coalinga Earthquake Area Map

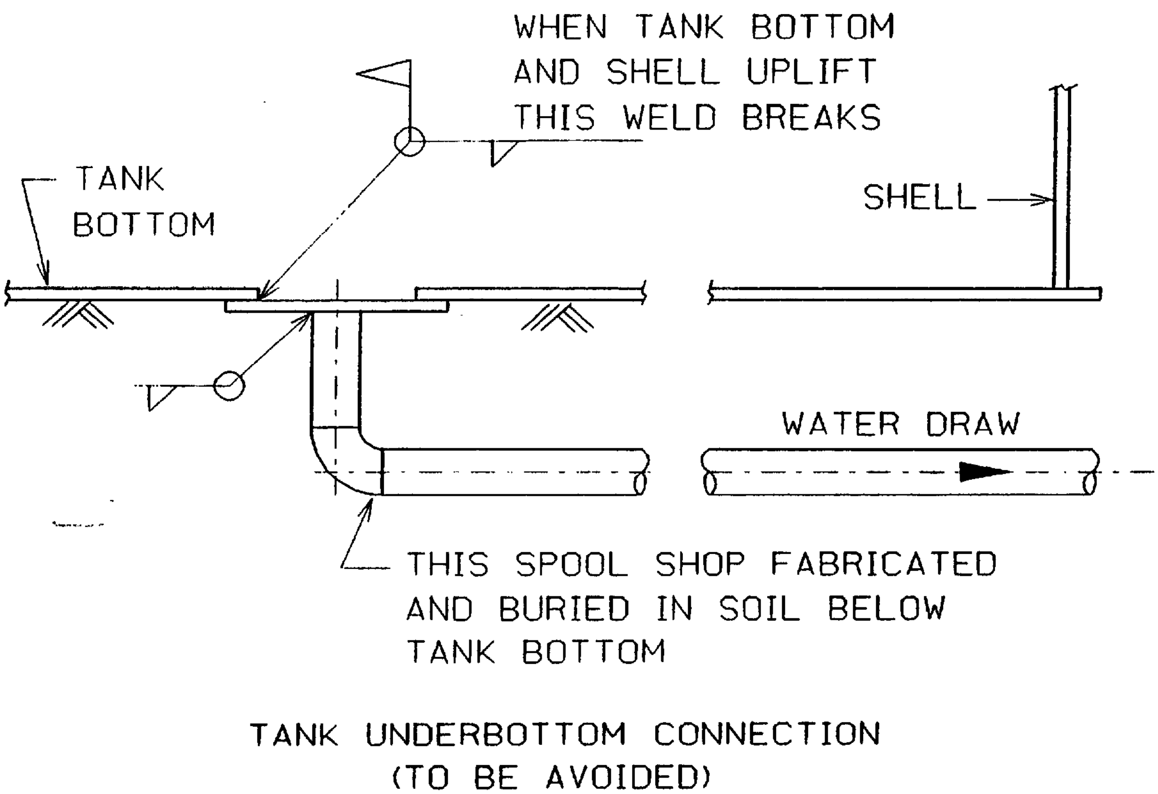

Figure 7.2 Waterdraw piping on Tank 7, Mainline pumping station. Field weld failed, allowing contents to leak.

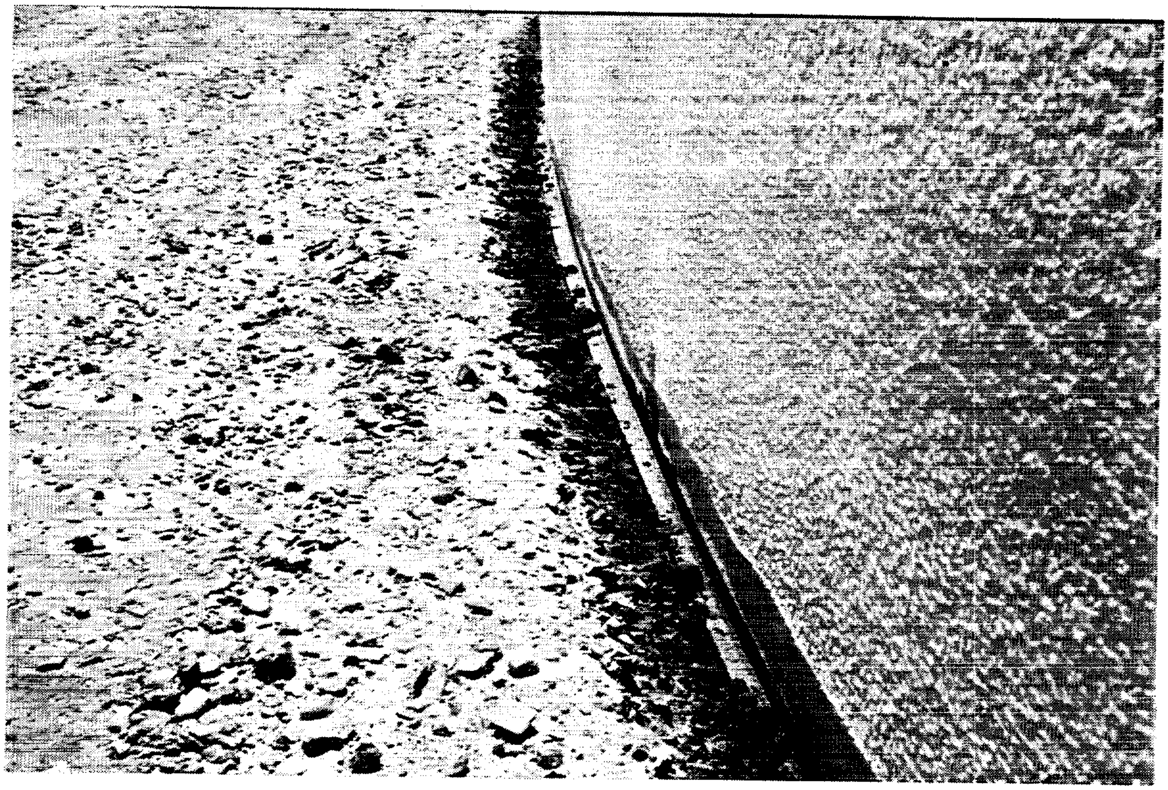

Figure 7.3 Tank 7, 61 m (200 ft) diameter by 14.8 m (48 ft) high with oil pounded into adjacent soil about 10 cm (4 in) in a NE-SW direction. Other tanks with only 3.05 m (10 ft) of oil did not do this.

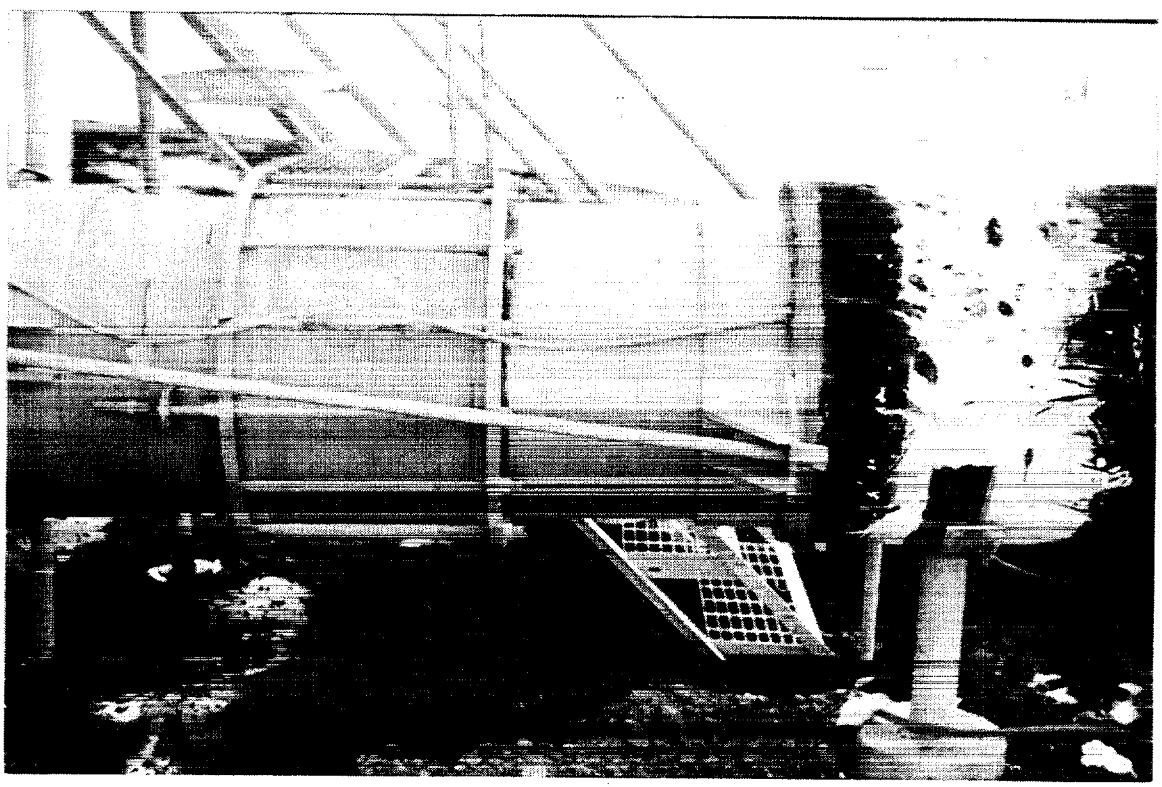

Figure 7.4 Inlet/outlet line on Tank 7, support was battered on both sides of pipe.

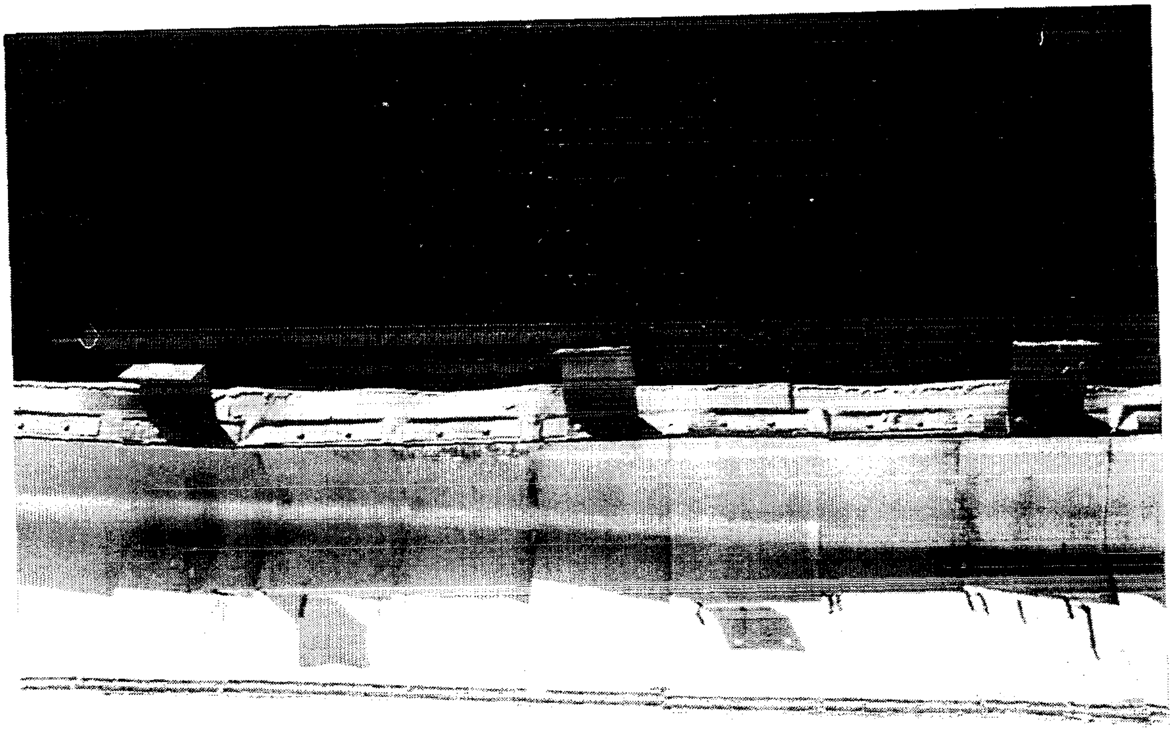

Figure 7.5 Bent secondary seal on Tank 8, this bending was maximum in NE-SW directions.

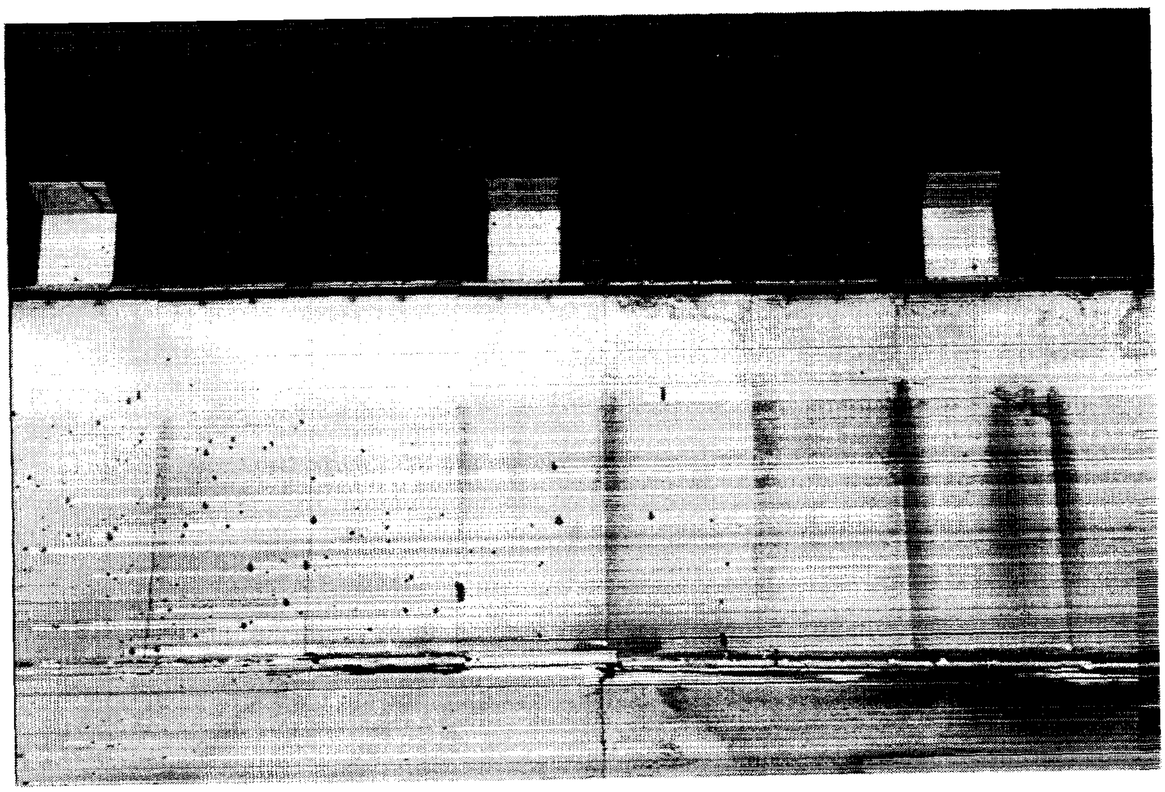

Figure 7.6 Normal unbent seal on Tank 8, seals did not bend in NW-SE direction. This was typical for all tanks at this site.

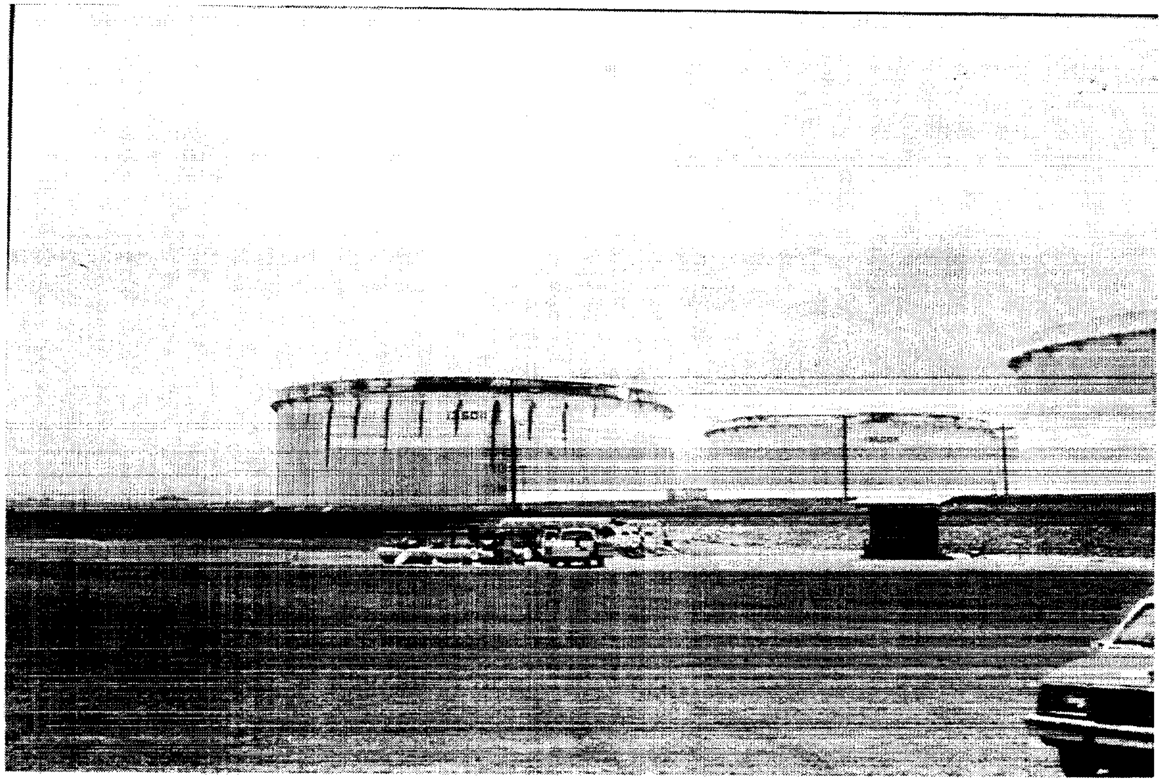

Figure 7.7 These tanks were at Site B and were full.

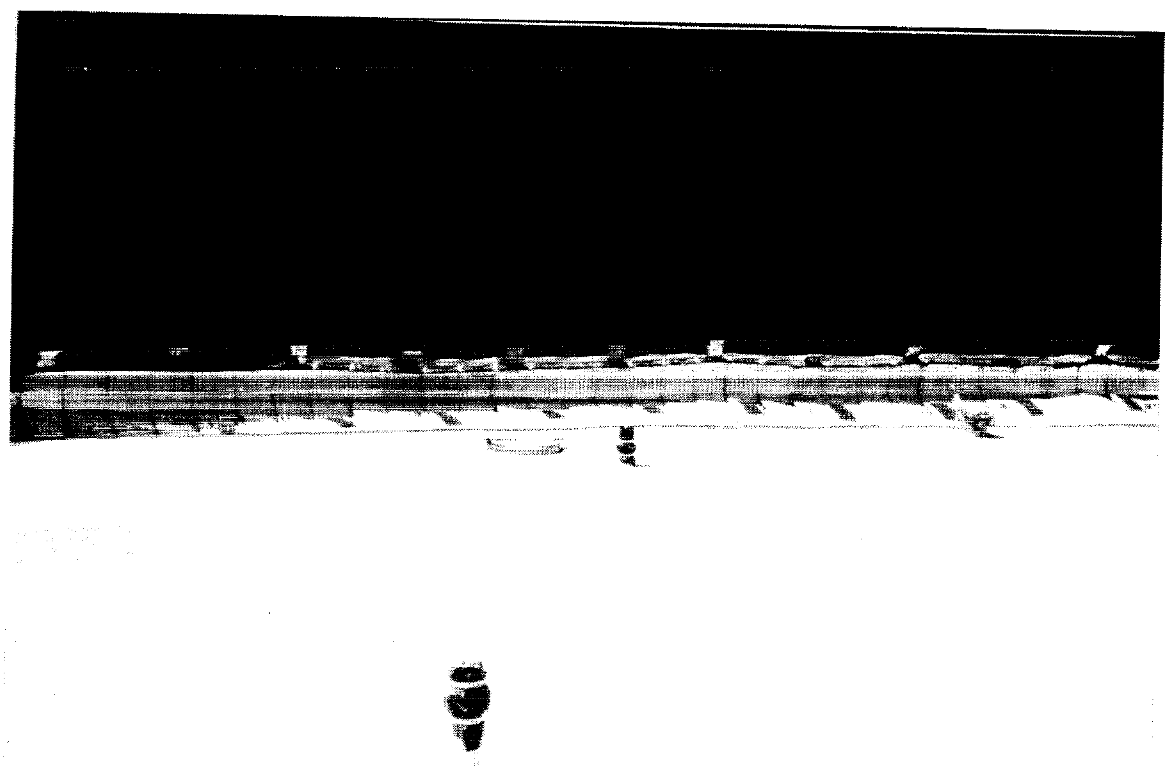

Figure 7.8 Bent seals in Tank 7.

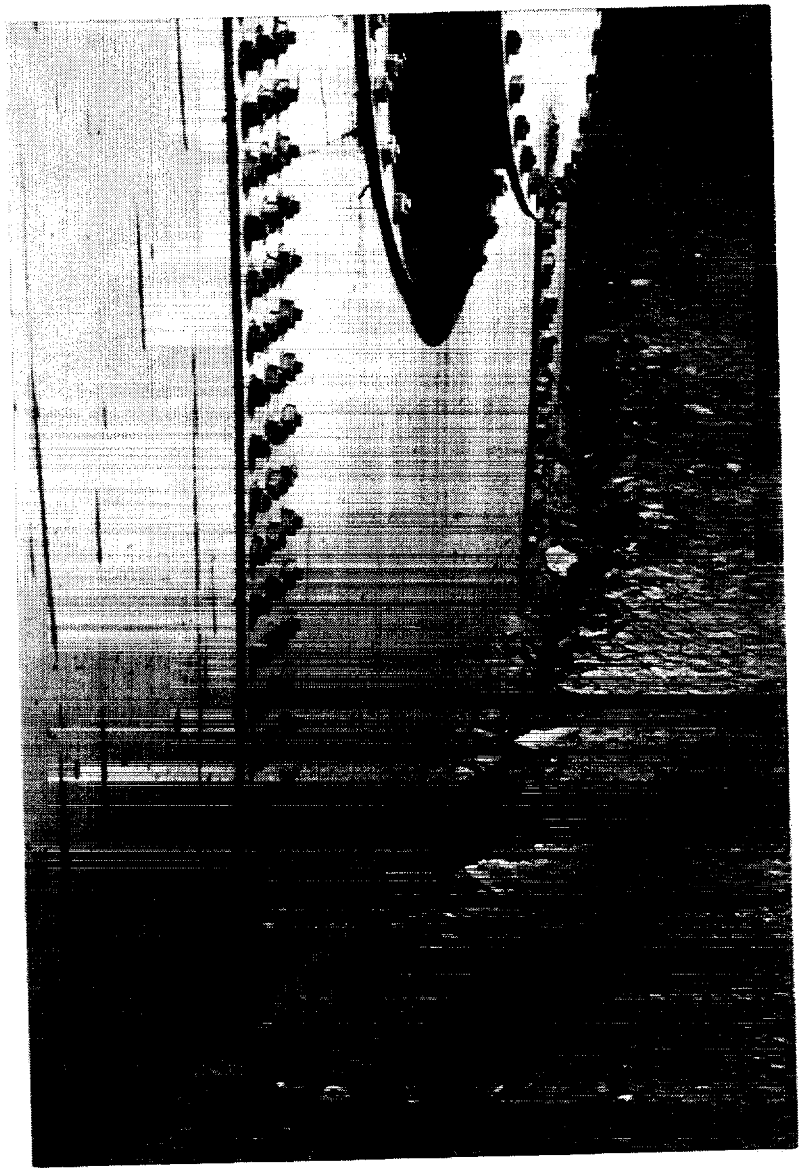

Figure 7.9 Bolted tank which pounded into the ground [Steinbrugge Collection at UCB EERC Richmond].

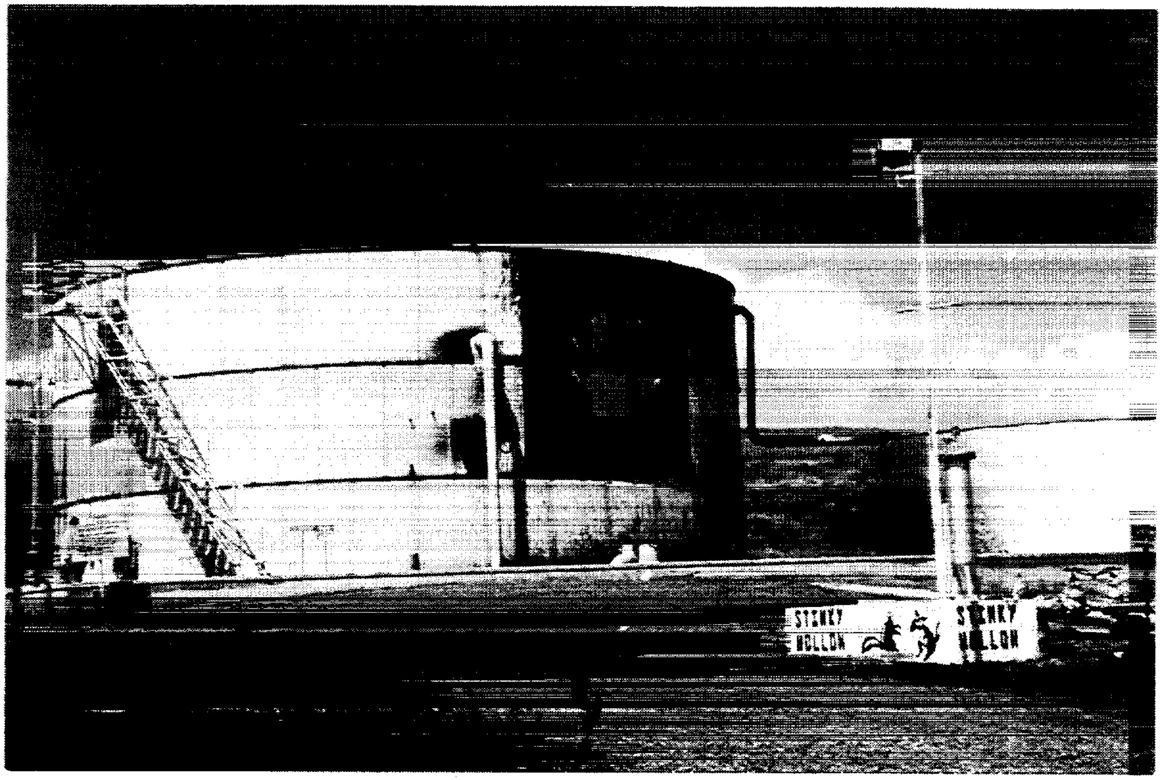

Figure 7.10 Roof spillage on this bolted tank [Steinbrugge Collection at UCB EERC Richmond].

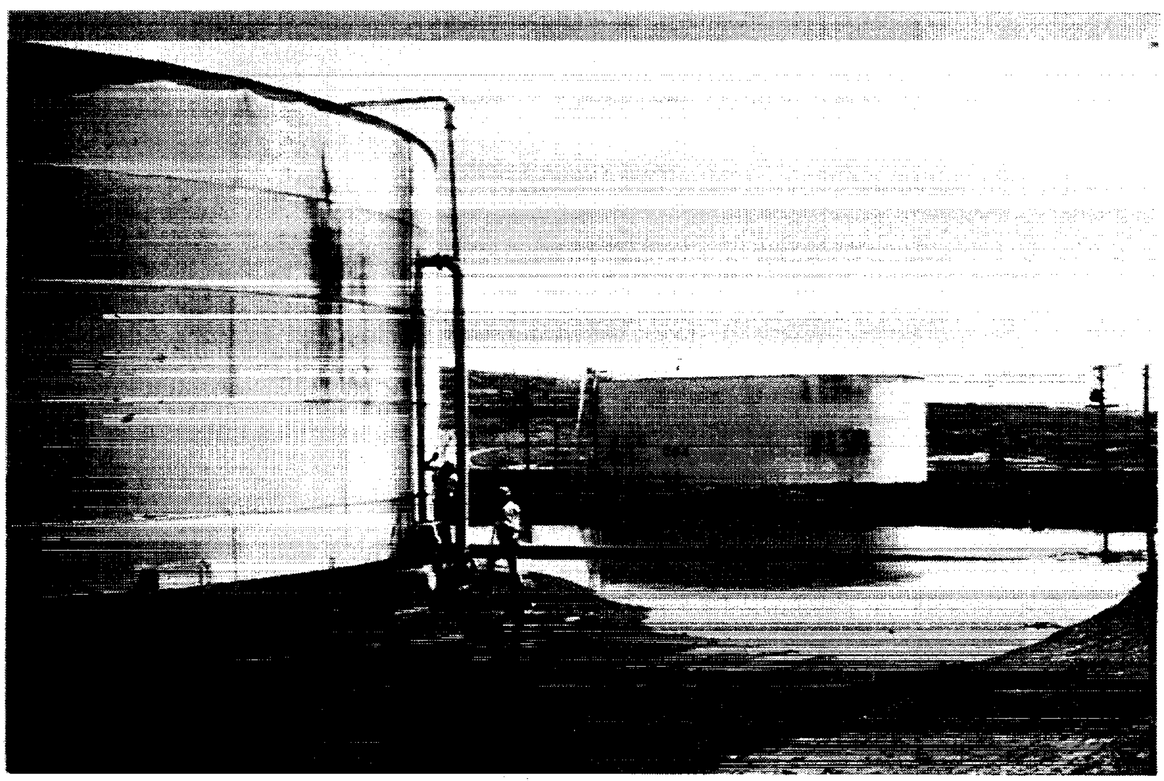

Figure 7.11 Broken valves/fittings caused this spillage [Steinbrugge Collection at UCB EERC Richmond].

8. THE 1989 LOMA PRIETA EARTHQUAKE

The Loma Prieta magnitude 7.0 earthquake of October 17, 1989 caused considerable tank damage; fortunately no catastrophes followed. Some of the most severe damage was at a location far from the epicenter. Three petroleum tank locations are considered in this report. In addition, two specific water tank locations are examined. Figure 8.1 is a map of the area showing five sites and some accelerometer values in the general area.

Richmond Terminal

The location with the most severe tank damage was a terminal located at Richmond, about 108 km from the epicenter. This facility consisted of twenty tanks for the storage of gasoline, diesel fuel, turbine fuel, and heavy fuel oil. The sizes ranged from 34 m (110 ft) in diameter by 14.8 m (48 ft) high to 3.7 m (12 ft) in diameter by 15.4 m (50 ft) high. There were cone roof tanks, cone roof with internal pans, and floating roof tanks. The facility is a marine terminal, located at tidewater with soil conditions which could not be called good. All tanks are on pile foundations with a continuous concrete pile cap. At this location there were cases of elephant foot buckling (five tanks), and pipe supports pulling from the tank shell (pulling out a section of shell in one case). Some small pipe supports tilted, but piping for the most part behaved quite well. Three tanks of 13 m (42 ft) in diameter by 12 m (40 ft) high were nearly full at the time of the earthquake, two of the three tanks suffered elephant foot buckling or incipient buckling. Many of the other tanks at this site were not full so that no conclusive statement can be made considering total performance. It is noted that there was no apparent roof, pan, or floating roof damage at this location.

Also located at this facility was a lubricating oil plant; see Figure 8.2. This facility consisted of about sixty tanks ranging from 3.7 m (12 ft) in diameter by 7.4 m (24 ft) high, 3.7 m (12 ft) in diameter by 15.4 m (50 ft) high, 3.7 m (12 ft) in diameter by 11 m (36 ft) high, 6.5 m (21 ft) in diameter by 12.3 (40 ft) high, and 9.2 m (30 ft) in diameter by 12.3 m (40 ft) high. Of all these tanks the only one to be damaged was a 9.2 m (30 ft) diameter by 12.3 m (40 ft) high floating roof tank which was full and which had elephant foot buckling. The walkway between this tank and another also pulled loose and fell to the ground. Virtually none of the tanks at this lubricating oil plant were anchored. Two of the 3.7 m (12 ft) diameter by 15.4 m (50 ft) high tanks were anchored and there was evidence of the anchor bolts restraining and slightly bending or cupping the bottom plate; see Figure 8.3. The nature of the liquid fuel business dictates that on the average the tanks are about half-full. The nature of the lubricating oil business is such that on the average the tanks are probably less than half-full. This could help to explain the clear lack of damage for tanks which have such small diameter/height ratios. Figures 8.4 and 8.5 show a cutout of an elephant foot buckle. Figures 8.6 and 8.7 show elephant foot buckling on a tank. Figure 8.8

shows where a bracket pulled out, leaving a hole in the tank. Figure 8.9 shows the start of an elephant foot buckle.

Immediately adjacent to the above described facility was a similar products terminal, situated on comparable ground. This facility suffered no damage. A short distance away was a third products terminal on similar poor ground where no significant damage was sustained at this terminal other than a ladder-platform separation at the top of one tank. Inquiries indicated that there were no internal pan problems with the tanks at these locations [31].

In an area behind and uphill from the above described terminals was an additional group of larger floating roof tanks sitting on substantial ground, this facility also suffered no damage.

San Jose Terminal

This terminal is located about 40 km north of the epicenter. It is a products terminal with 32 tanks varying from 38 m (125 ft) in diameter by 14.6 m (48 ft) high to 7.5 m (24.5 ft) in diameter by 9.8 m (32 ft) high. Tank capacities range from 2,500 bbls to 100,000 bbls with a mean size of 32,000 bbls and a median size of 25,000 bbls [18.9 m (62 ft) diameter by 14.6 m (48 ft) high.] Soils at this location are alluvium and would be considered reasonably good foundation soils. Initial construction of this terminal was in 1965.

This terminal was practically free of damage with the exception of two tanks which had their internal pans sink after severe damage to the pans. An internal pan floats on the product inside a regular cone roof tank; the pan greatly diminishes evaporation and is for air pollution control and fire prevention. One damaged tank was a 23.7 m (77 ft) in diameter by 14.8 m (48 ft) high premium gasoline tank, the other was an 27 m (88 ft) in diameter by 14.8 m (48 ft) high turbine fuel tank. Both were full or nearly full at the time of the earthquake. The damage in both tanks was similar and consisted of bending and buckling of the internal pan for about three-quarters of its diameter. The most severe bending was about 30^0 down from the horizontal plane of the pan, with the apex of the bend about 4.5 m - 6.1 m (15 - 20 ft) from the edge of the pan. The mechanism of the damage is surmised to be severe sloshing in the tank, where a segment of the pan is sloshed up and held against the roof while at the same time the fluid support of the pan is lowest in a diagonally opposite segment. After the bending which can cause misalignment, the pan then sinks into the product. No product was lost as the tank shell and floor retained all of the tank contents.

A typical "mean" tank would be 19.8 m (65 ft) diameter by 14.6 m (48 ft) high, giving a d/H ratio of 1.35. Virtually all tanks at this terminal are cone roof with an internal floating pan. Again there was no shell buckling or reported roof/shell damage.

Discussion with operating personnel at this terminal brought forth their ability to detect earthquakes. As part of the instrumentation at these product terminals tank level detection is installed and an alarm is sounded if the fluid level in the tank rises more than 3 mm (1/8 in) (this to assure no product cross-contamination.) When a distant (or close) earthquake occurs, the sloshing in the tanks activates the level alarms. The personnel can tell it is an earthquake because virtually all the alarms activate at the same time with an audible signal. The Northridge earthquake was detected at the San Jose Terminal. Earthquakes in Oregon have been detected at the Sparks (NV) terminal [32].

Brisbane Terminal

This terminal is located about 85 km north-northwest of the epicenter. It is also a products terminal with 17 tanks varying from 30.5 m (100 ft) diameter to 9.1 m (30 ft) diameter and 12.2 m (40 ft) high to 14.8 m (48 ft) high. The tanks at this terminal are located on firm ground in a hillside location with good foundation conditions. The tanks at this location with cone roof, internal pan, and floating roofs were all built before earthquake design considerations were included in the tank design code. No damage was experienced at this station [32].

Gilroy No. 1

A USGS/CDMG CSMIP accelerometer station (Gilroy No. 1) was located approximately 15 m (50 ft) from a water tank which suffered no damage from the earthquake. The site is 28 km east of the epicenter, and the tank and accelerometer settings were on Sandstone. The reported tank capacity is 950,000 gallon with a height of 8 m (26 ft), this gives a diameter of about 24.4 m (80 ft) and a d/H of 3.1. Horizontal accelerations of 0.50 g and 0.43 g, and a vertical acceleration of 0.22 g were recorded at this site. There was no tank damage at this site [33] [34].

Moss Landing

The P.G. and E. Moss Landing Power station is located approximately 22 km south of the epicenter. A 750,000 gallon--est. 17 m (56 ft) diameter by 12.2 m (40 ft) high--water tank failed at the floor/shell connection, where the junction was reportedly corroded. Rapid draining of the tank ostensibly caused inward buckling of the shell in the top course. Other large petroleum storage tanks survived at this location without apparent damage [33].

Other Tankage

Damage to water tanks was confined to the South Bay area generally within 15 km of the epicenter. A 100,000 gallon bolted steel tank in the Los Gatos-San Jose area had elephant foot buckling. The damaged panels were replaced and the tank was returned to service. The inlet/outlet piping underneath a 700,000 gallon welded steel tank built in the 1950's separated from the floor plate. The inlet/outlet line was replaced and the tank was returned to service. In Watsonville a 1,000,000 gallon steel water tank constructed in 1971 buckled on one side at the roof/shell joint but did not experience any leaking. A 600,000 gallon tank constructed to AWWA Standard D100 in 1986 performed excellently [35].

In the Santa Cruz area unanchored 750,000 and 400,000 gallon welded steel tanks with roofs had roof problems but the tanks shells performed well. A 1,250,000 gallon tank constructed to AWWA Standard D100 in 1983 was undamaged [34] Considering the severity of the earthquake and damage to buildings and other facilities, steel tanks did quite well. Overall, the performance of water tanks designed to later AWWA Standards, including seismic loadings, performed well.

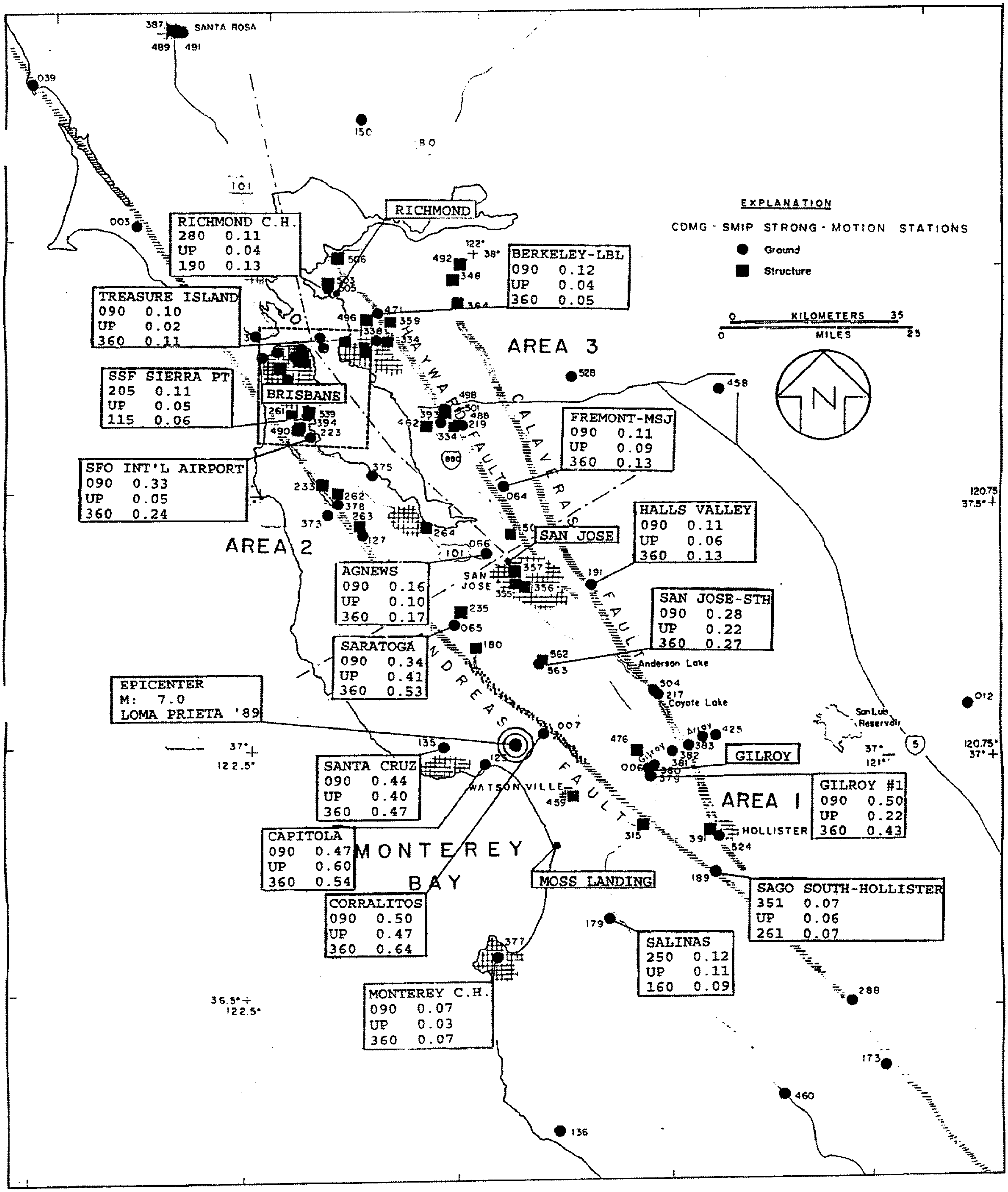

Figure 8.1 1989 Loma Prieta Earthquake Area Map [34]

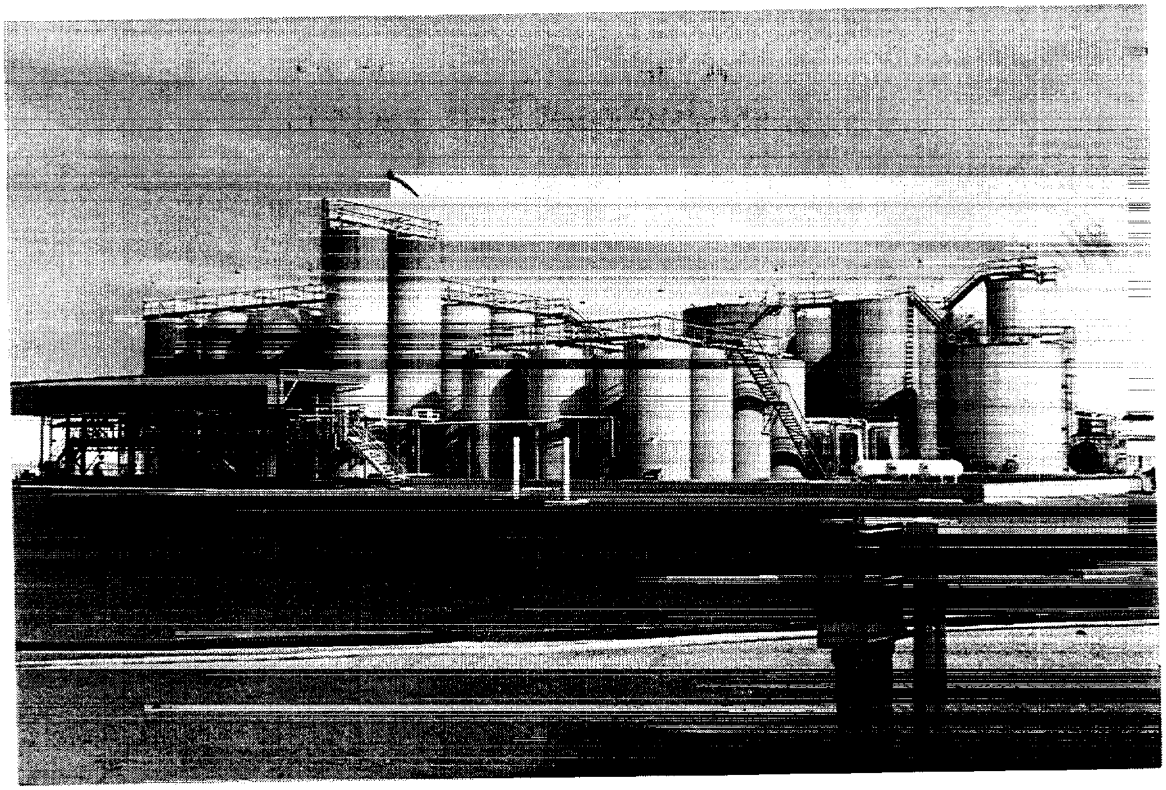

Figure 8.2 Tank block at a lube oil plant where severe damage occurred to larger tanks. Only one 9.2 m (30 ft) diameter by 12.3 m (40 ft) high nearly full tank had elephant foot in this tank block. The 3.7 m (12 ft) diameter by 14.8 m (48 ft) high tank - with the wind sock - had anchor bolt action shown in Figure 8.3. All tanks on pile and concrete mat foundation.

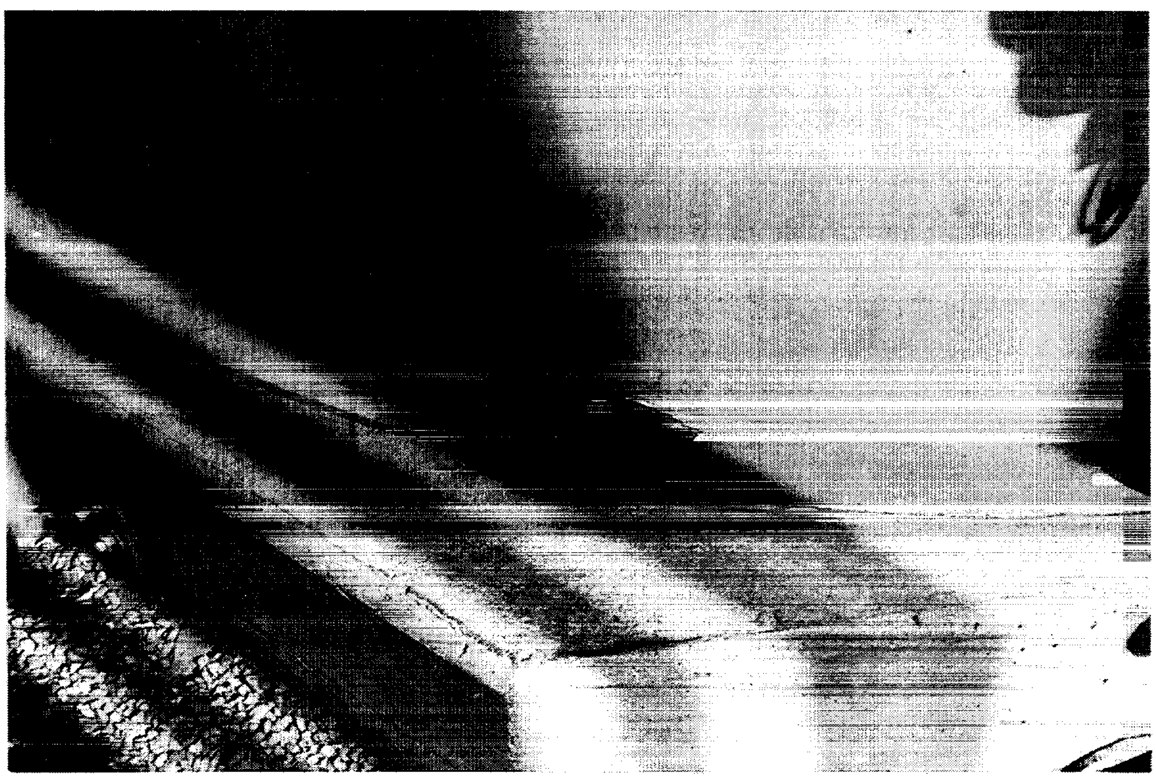

Figure 8.3 3.7 m (12 ft) diameter by 14.8 m (48 ft) high tank with 8ea. 31.7 mm (1¼in) anchor bolts and a ½in bottom plate. Tank was less than half-full.

Figure 8.4 View of cut-out of elephant foot shell of 9.2 m (30 ft) diameter by 12.3 m (40 ft) high tank which was nearly full at time of earthquake.

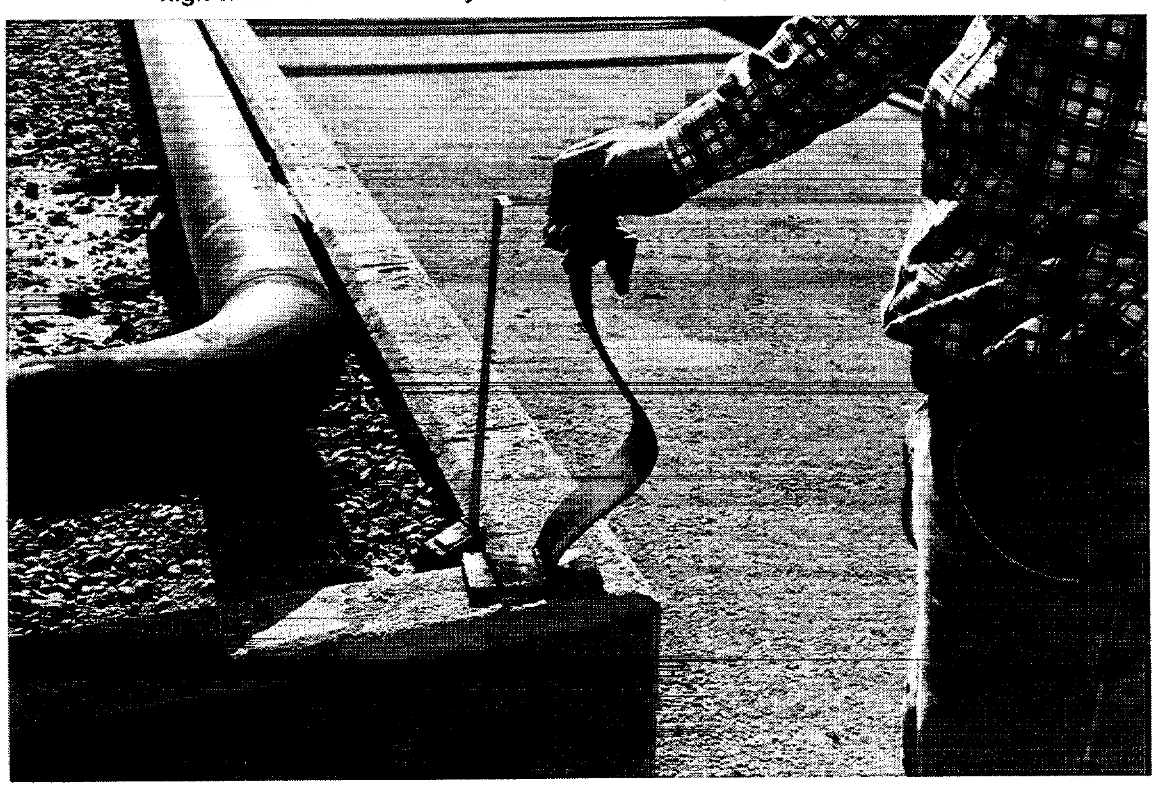

Figure 8.5 Additional view, same tank as Figure 8.4.

Figure 8.6 Elephant foot on 12.2 m (40 ft) diameter by 9.7 m (32 ft) high tank. Note absence of vertical crack lines in paint at weld.

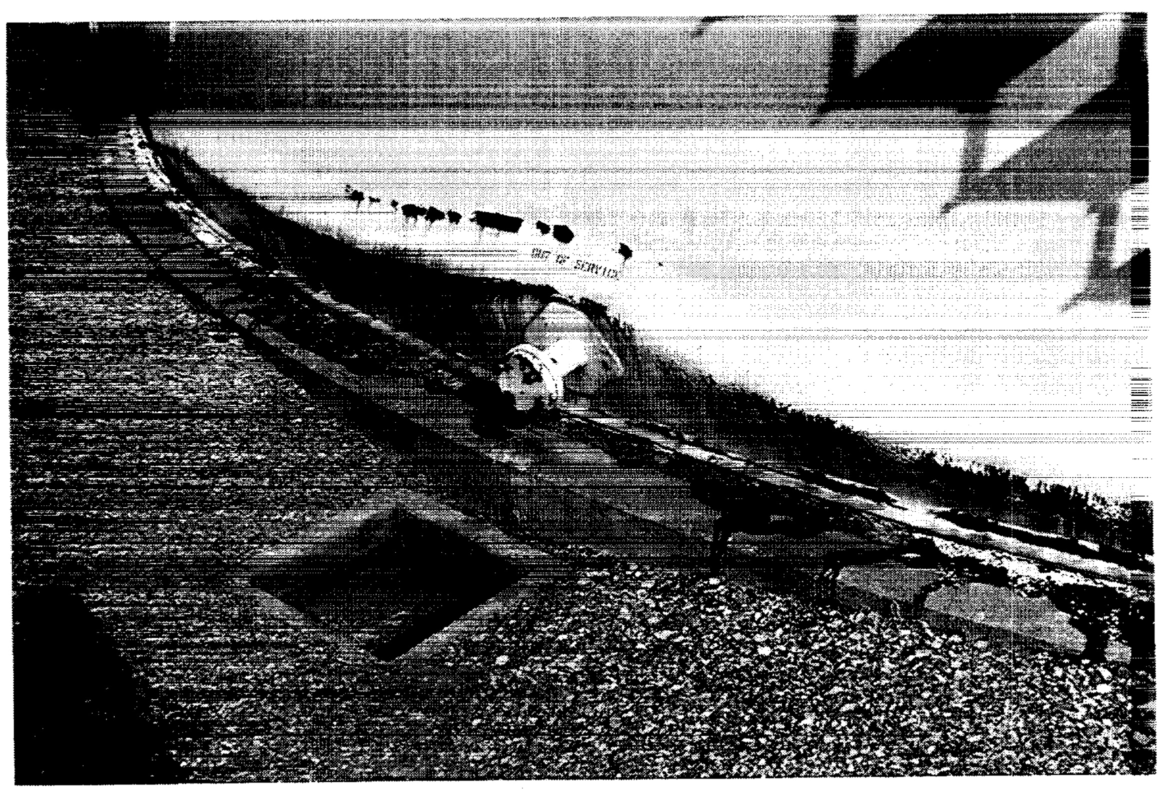

Figure 8.7 Same tank as Figure 8.6, elephant foot maneuver around reinforcing plate at nozzle.

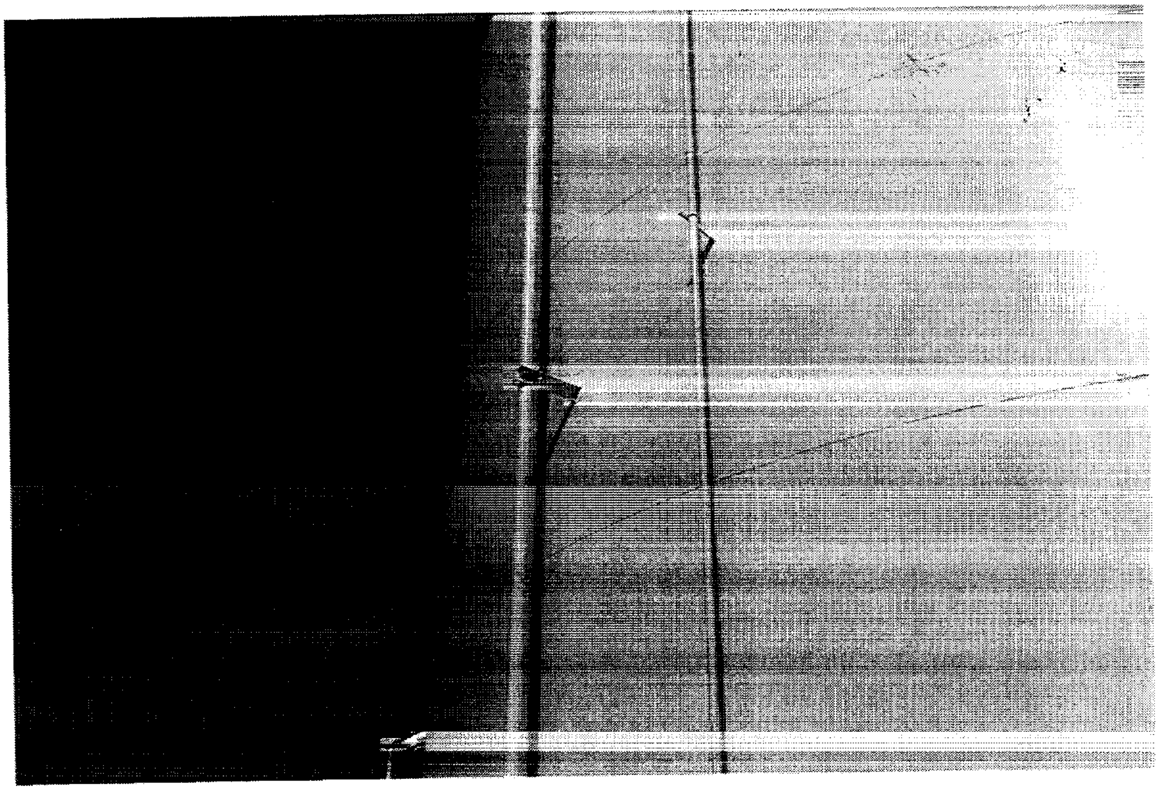

Figure 8.8 Bracket on pipe pulled out making a hole in the tank shell, through which product drained.

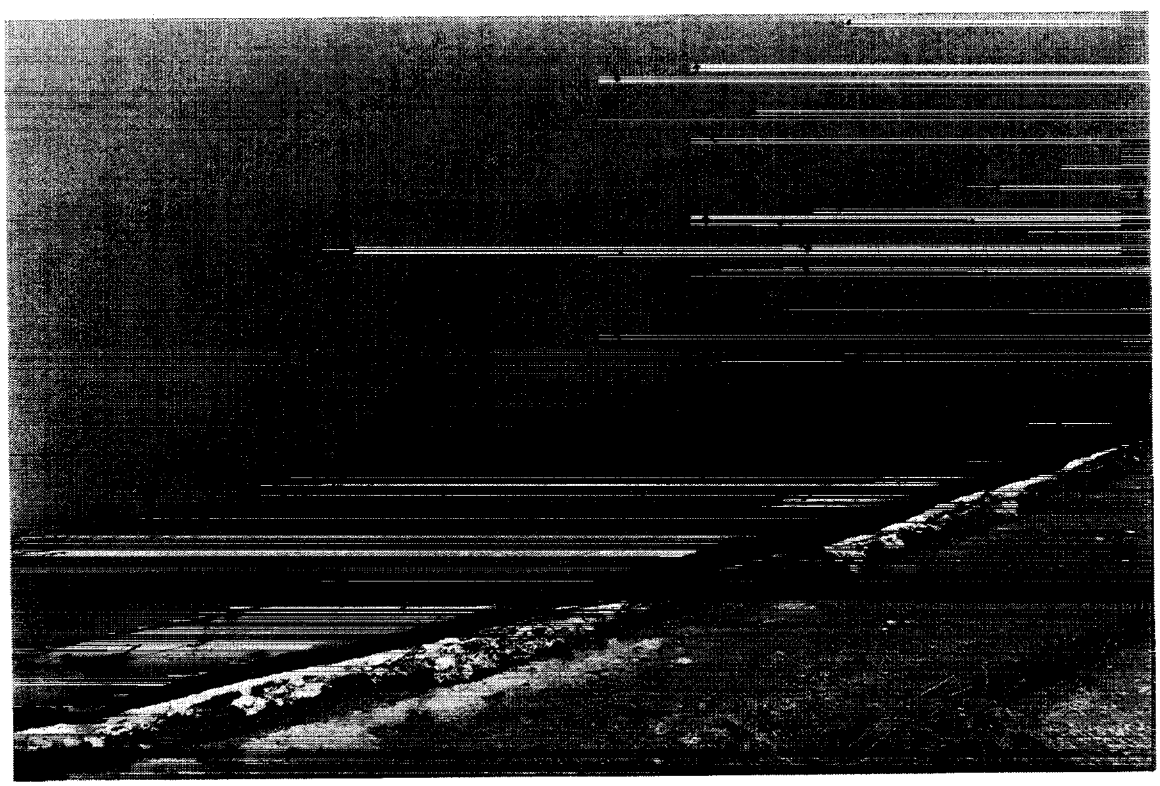

Figure 8.9 Start of an elephant foot buckle.

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9. THE 1992 LANDERS EARTHQUAKE

The magnitude 7.3 Landers earthquake occurred at 4:58 a.m. on June 28, 1992; this was shortly followed by the Big Bear magnitude 6.5 earthquake at 8:02 a.m. of the same day. Since all tank damage was in or near the Landers area, this report is directed solely to the Landers event. There were no petroleum storage tanks in the immediate area, hence this section almost totally discusses water tanks. Although a sparsely populated desert area, the area strongly affected by the Landers earthquake contained over 27 water tanks. Of these, only two failed. Figure 9.1 shows the location of the tanks. Figure 9.2 shows the surface faulting near the failed tanks. Figure 9.3 gives accelerometer values in the general area.

The High Desert Water District serves the Southern portion of the area effected by the earthquake. The District had sixteen tanks in service at the time of the earthquake. There was no significant damage to any of these tanks (all remained in operation) although there was ground settlement at some of the tanks. Most of the tanks were welded, however six were bolted construction. Virtually all are 7.3 m (24 ft) high, with diameters ranging from 8.0 m (26 ft) to 36.6 m (120 ft). All tanks are set on gravel bases. None were anchored at the time of the earthquake. Most tanks were set at higher elevations and appear to be setting on shallow alluvium or placed fill, which is underlain by firm soil or rock [36].

The Bighorn Desert View Water Agency (BDVWA) serves the northern portion of the area affected by the earthquake with CSA 70 serving a small area to the east of BDVWA. Of the ten tanks in service at the time of the earthquake, all remained in service with minor damage with the exception of Tank A which collapsed. This tank was a 17 m (56 ft) in diameter by 7.3 m (24 ft) high (welded) tank, constructed to AWWA Standard D100 in 1974 with a 6.35 mm (0.25 in) shell and 6.35 mm (0.25 in) bottom, and a 4.16 mm (0.1875 in) roof. It was set on a rock base without a concrete foundation or anchor bolts [37].

Tank A was located approximately 100 m west of the fault. It failed at the shell bottom plate joint at two locations. One was a 2.75 m (9 ft) rip on the north side of the tank, the other a similar failure at and below a manway on the west side. There was elephant foot buckling around the entire tank, with the most severe on the north side and the least severe on the southeast side. There was a 150 mm (6 in) riser pipe on the south side of the tank which lifted about 0.6 m (2 ft) out of the ground. This riser pipe was then bent and torn from the tank when the tank shell came back to grade. There appeared to be an 80 mm (3 in) horizontal movement of the tank to the north. Figures 9.4 and 9.5 show some of the damage to Tank A.

The second tank failure occurred at CSA 70, about 5 km east of Tank A. This tank was designed according to the API Standard 12B with a 11.8 m (38.6 ft) diameter and a 7.3 m (24 ft) height. It was erected in 1979 of bolted segments of 3.4 mm (10 ga.) shell and bottom plate thickness. Failure of this tank was by elephant foot buckling (all around) and the tearing of the shell at the clean-out door on the west side, and the pulling loose of Dresser Couplings on both the inlet and outlet piping. This tank was setting on a soil foundation and was not anchored. Figures 9.6 through 9.9 show the damage to the CSA 70 tank. It is interesting to note that all tank damage occurred slightly to the south of that area where surface faulting jumped from the Johnson Valley fault to the Homestead fault.

Approximately 90 km north-northwest of the epicenter is a petroleum storage/distribution terminal. Though there was no damage at this location, there was evidence of tank and structure movement. Most of the tanks at this location had heights equal to diameters or equal to two-thirds of the diameters. There was evidence of incipient buckling on a few of the tanks. East of this facility, about 2 km, are three large petroleum storage tanks (400,000 ± bbls). Two tanks had diameters of 83.2 m (273 ft) and heights of 15.2 m (50 ft); the remaining tank had a diameter of 67.2 m (222 ft) and a height of 14.5 m (48 ft). A free field accelerometer at the site had readings of 0.34 g north-south, 0.53 g east-west, and 0.21 g in the vertical direction. One tank was full, one was one-half full and one was nearly empty. All tanks conformed to API Standard 650, were floating roof tanks with concrete foundations, and sat on "good" alluvium. No damage was reported for any of these tanks [28].

Of interest in this earthquake was an accelerometer in close proximity (2 km) to the fault and about 38 km from the tanks that were lost because of extensive damage. Accelerations parallel to the fault were 0.70 g, and 0.75 g perpendicular to the fault, and .68 g vertical [38].

TABLE 9.1 BIGHORN DESERT VIEW WATER AGENCY

TANK	DIAMETER d m (ft)	HEIGHT H m (ft)	d/H
A	16.5 (54)	7.3 (24)	2.25
B	8.1 (26.5)	7.3 (24)	1.1
C	18.1 (59.5)	7.3 (24)	2.48
10	9.9 (32.6)	4.9 (16)	2.04
22-A	9.9 (32.6)	4.9 (16)	2.04
22-B	9.9 (32.6)	4.9 (16)	2.04
22-C	14.0 (46)	4.9 (16)	2.88
22-D	22.3 (73)	4.9 (16)	4.56
34	6.4 (21)	4.9 (16)	1.31

TABLE 9.2 HI-DESERT WATER DISTRICT

TANK	DIAMETER d (ft)	HEIGHT H m (ft)	d/H
2 M. G.	36.6 (120)	7.3 (24)	5.00
R-7	25.9 (85)	7.3 (24)	3.54
R-8	10.0 (33)	7.3 (24)	1.48
R-14	21.3 (70)	5.5 (18)	3.89
R-15	22.9 (75)	7.3 (24)	3.13
R-2	25.9 (85)	7.3 (24)	3.54
R-3	25.9 (85)	7.3 (24)	3.54
R-4	9.1 (30)	7.3 (24)	1.25
R-5	7.9 (26)	7.3 (24)	1.08
UPPER RIDGE	13.1 (43)	7.3 (24)	1.79
LOWER RIDGE	5.5 (18)	4.9(16)	1.13
UPPER FOX	24.4 (80)	12.2 (40)	2.00
LOWER FOX	10.9 (35.6)	4.9 (16)	2.24
GOLDEN BEE	14.4 (47.3)	9.8 (32)	1.45
HOMESTEAD	11.8 (38.6)	7.3 (24)	1.61
HOSPITAL DESERT GOLD	11.8 (38.6)	7.3 (24)	1.61
CSA-70-1*	11.8 (38.6)	7.3 (24)	1.61

* SAN BERNARDINO COUNTY SERVICE AREA 70

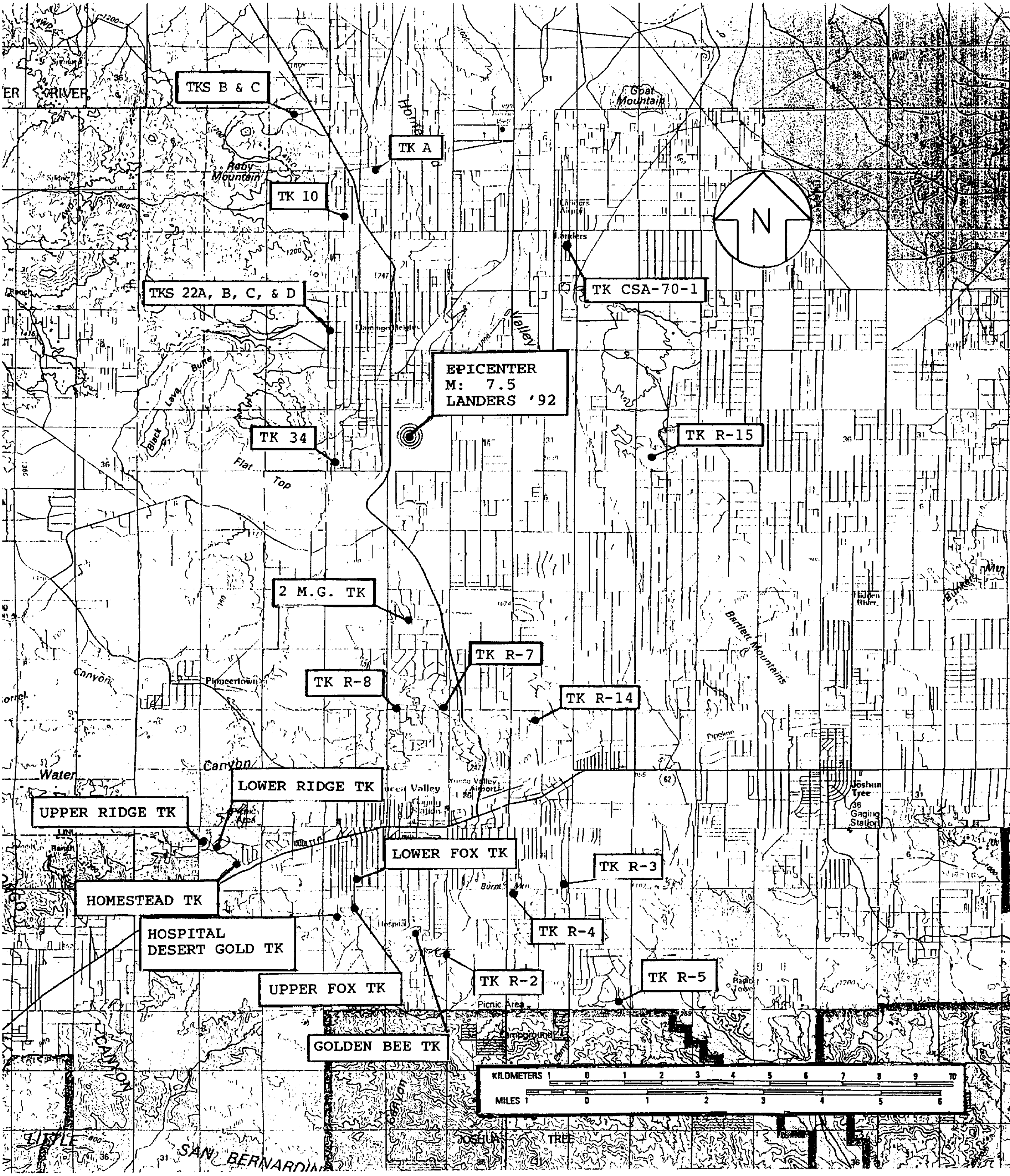

Figure 9.1 1992 Landers Earthquake Area Map

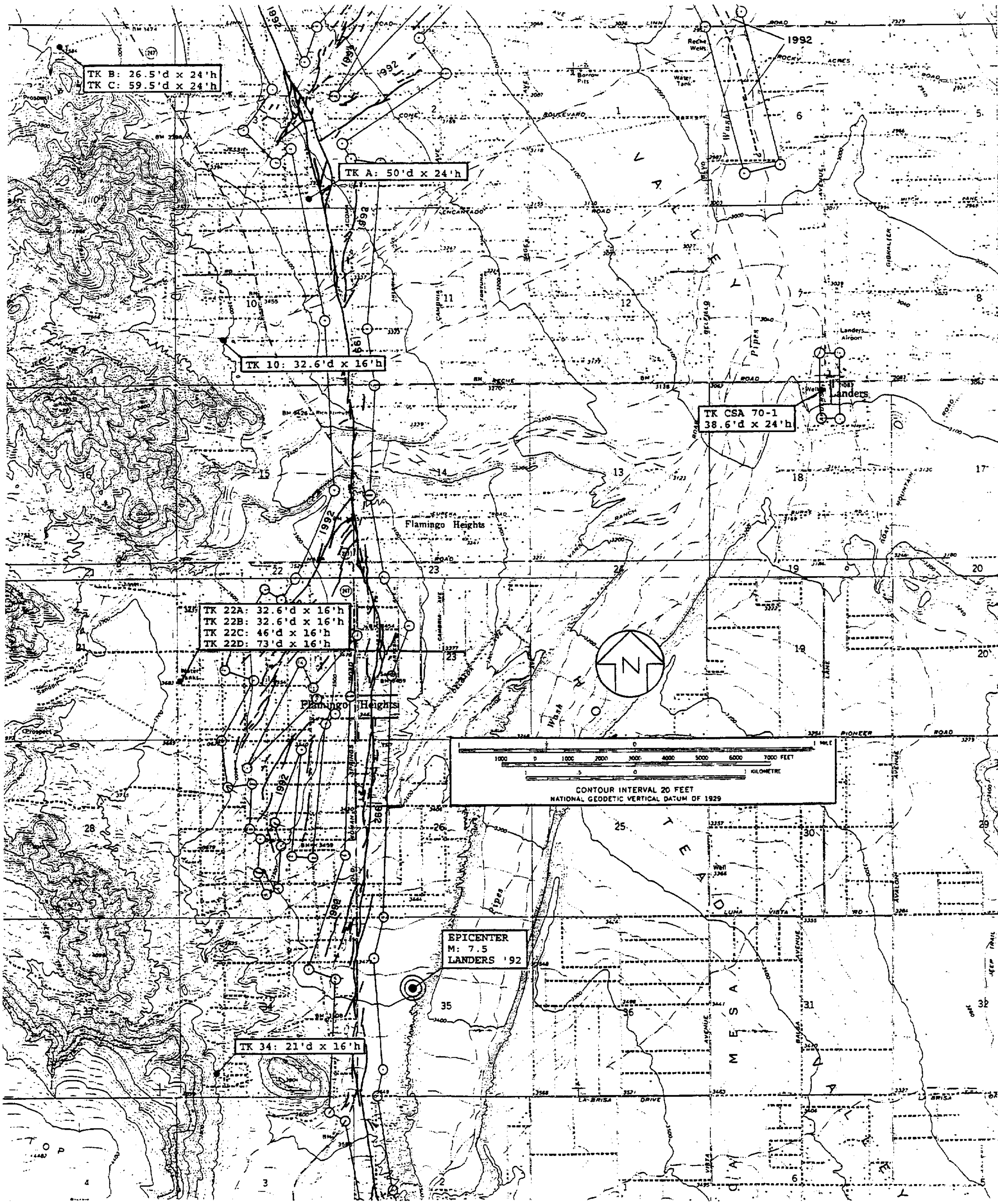

Figure 9.2 1992 Landers Earthquake Tank Locations Near Faulting [State of California Earthquake Fault Zones, Landers Quadrangle]

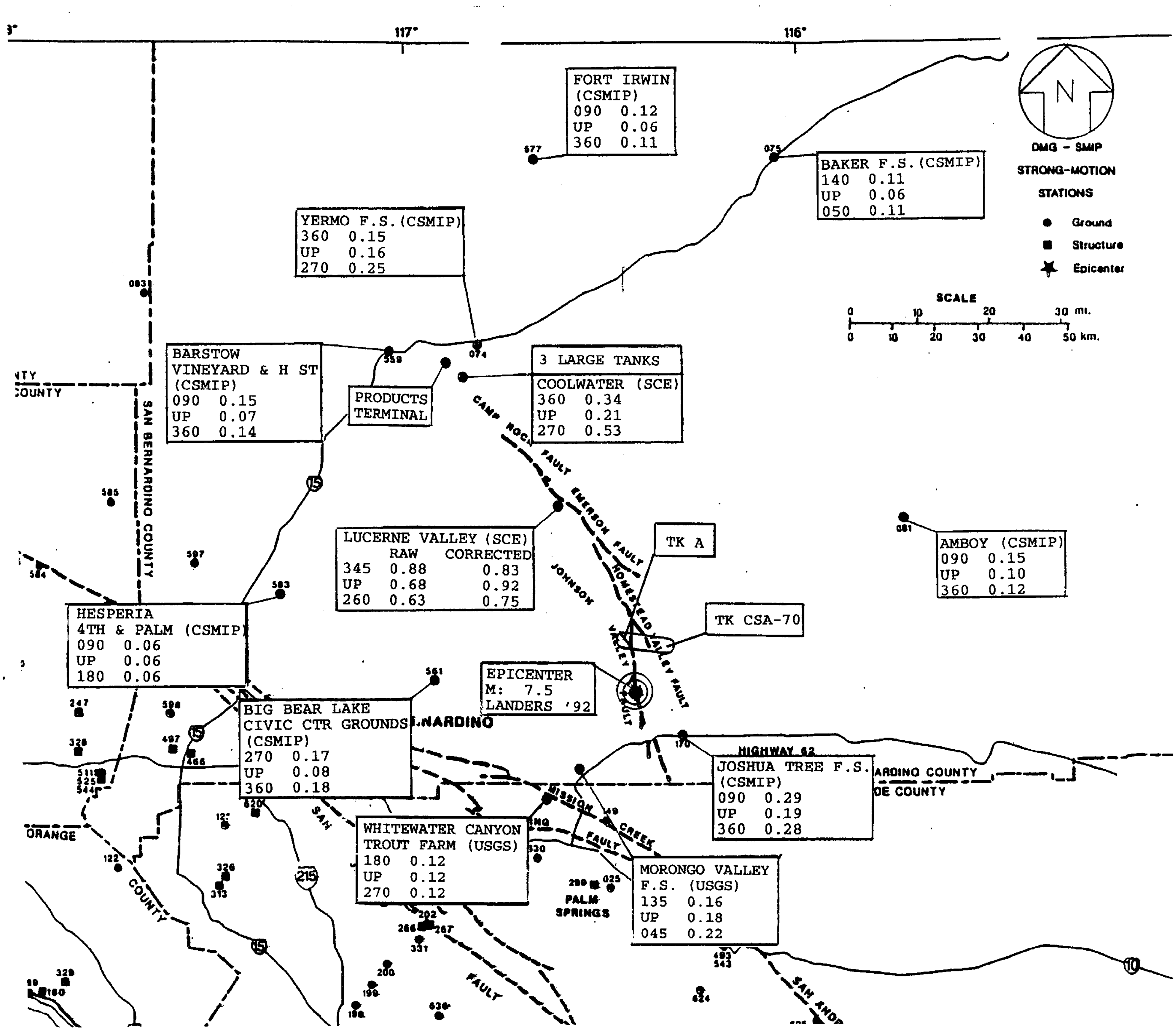

Figure 9.3 1992 Landers Earthquake Strong Motion Instrument Locations Near Landers and Failed Tanks [CDMG/CSMIP Strong-Motion Records from the Landers, California Earthquake of June 28, 1992.]

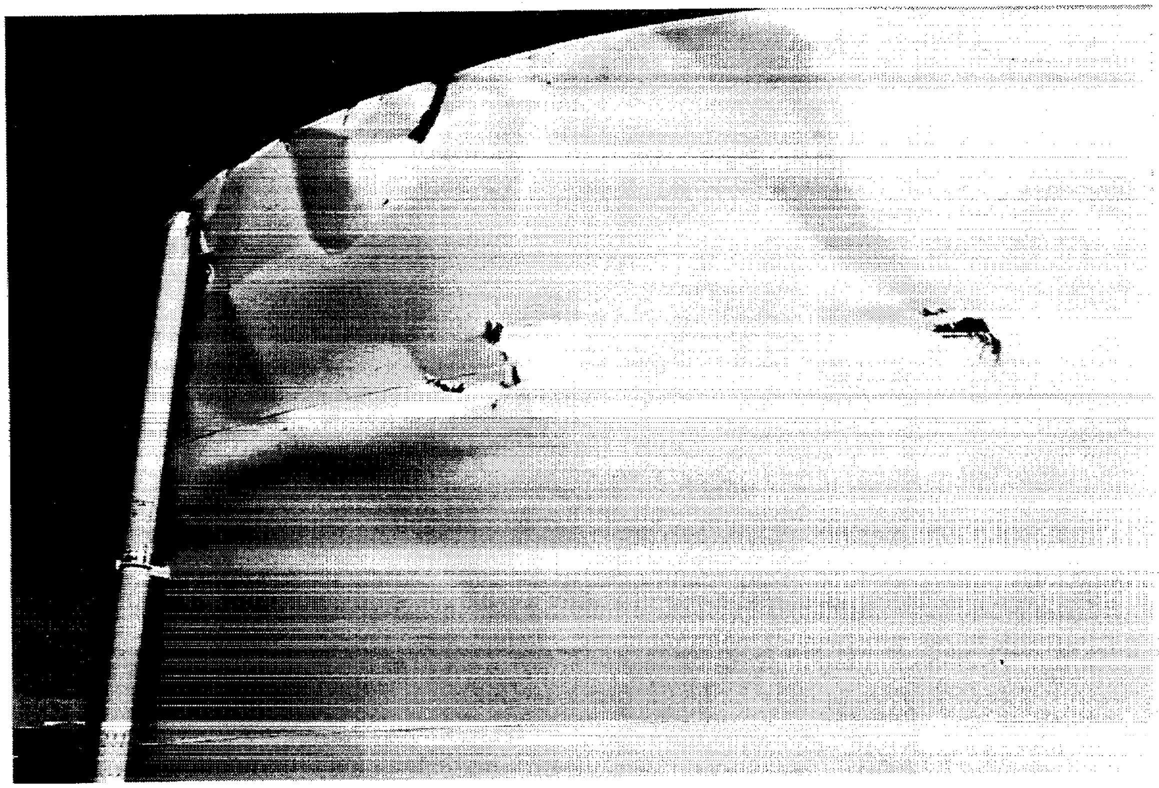

Figure 9.4 South side of Tank A. Pipe clamp slide was 0.6 m (22 in).

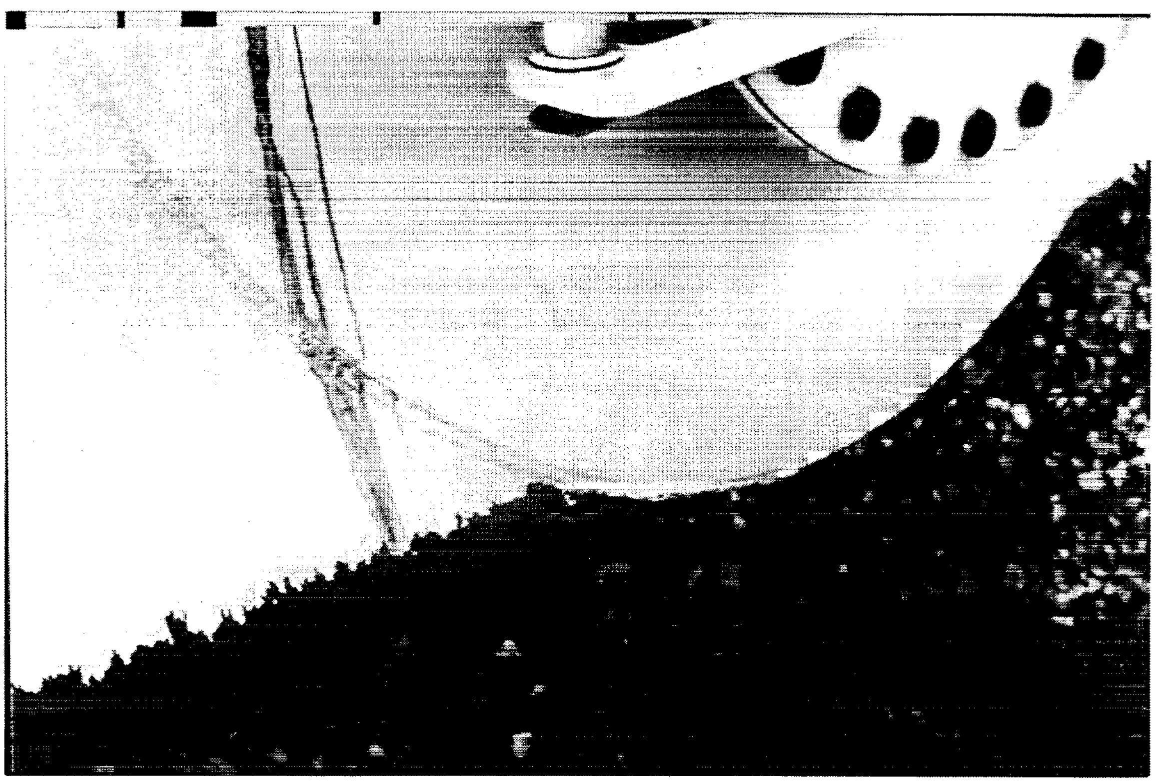

Figure 9.5 Tank A, tear on shell at the bottom of reinforcing plate.

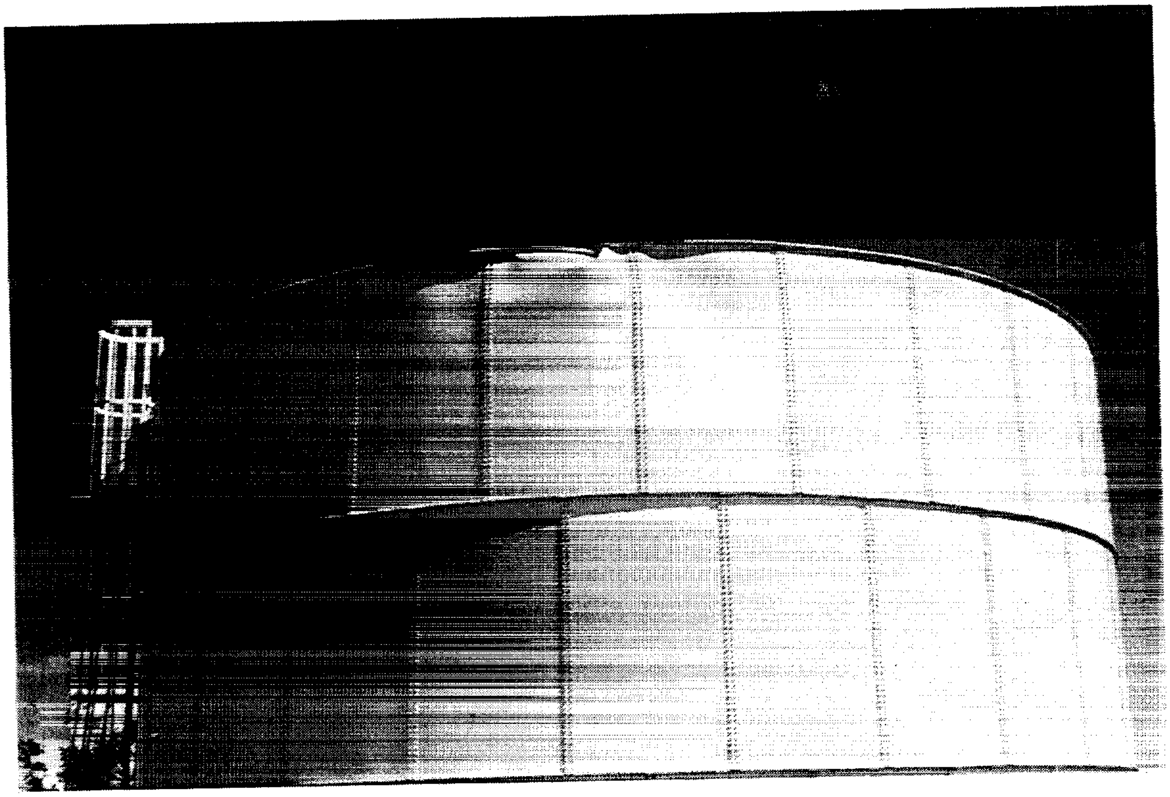

Figure 9.6 Roof/shell buckling on CSA-70.

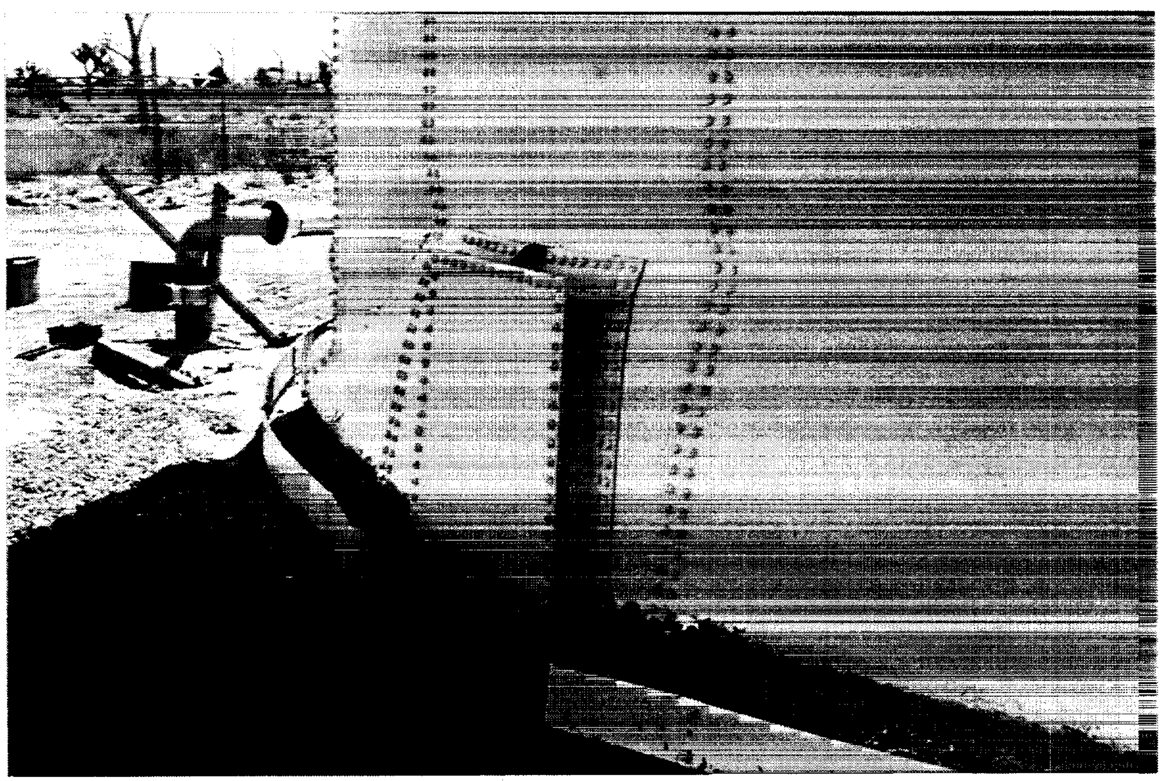

Figure 9.7 CSA-70 clean-out door, tank on rock foundation.

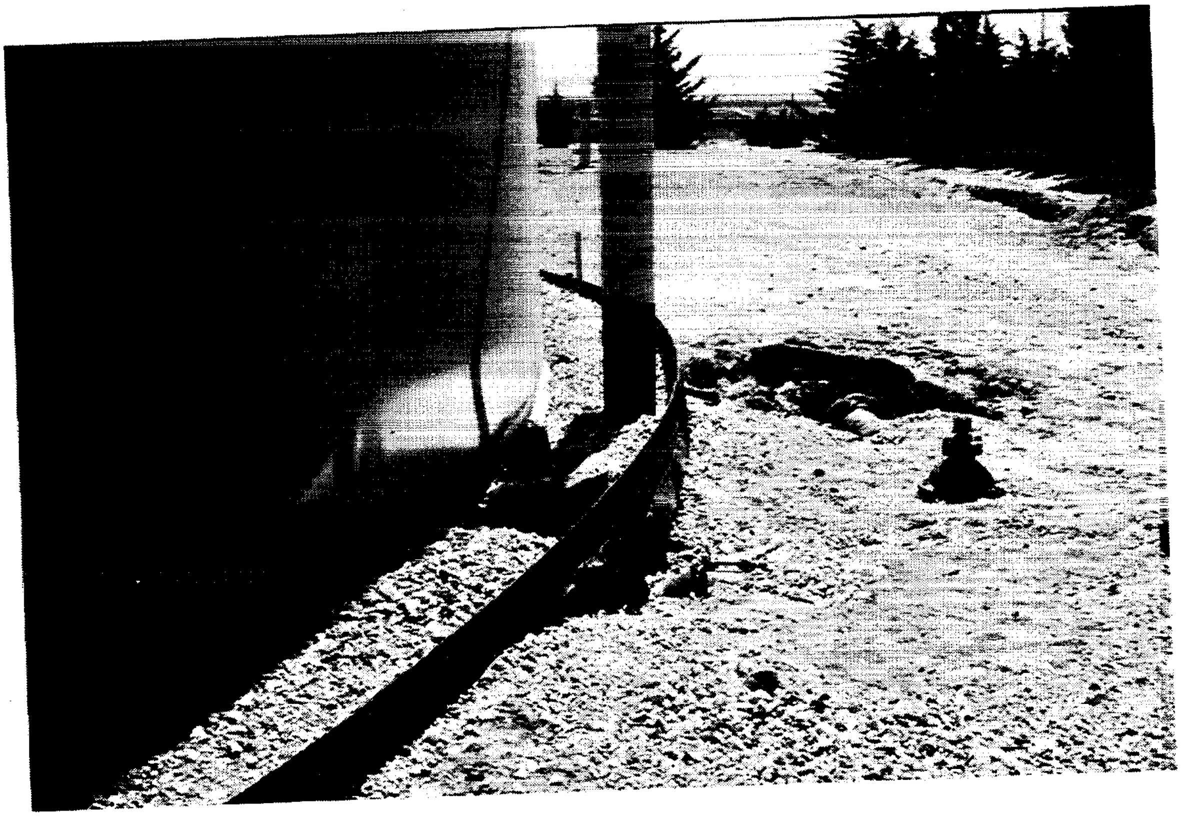

Figure 9.8 Tank A, riser pulled piping and rock retainer ring out of the ground.

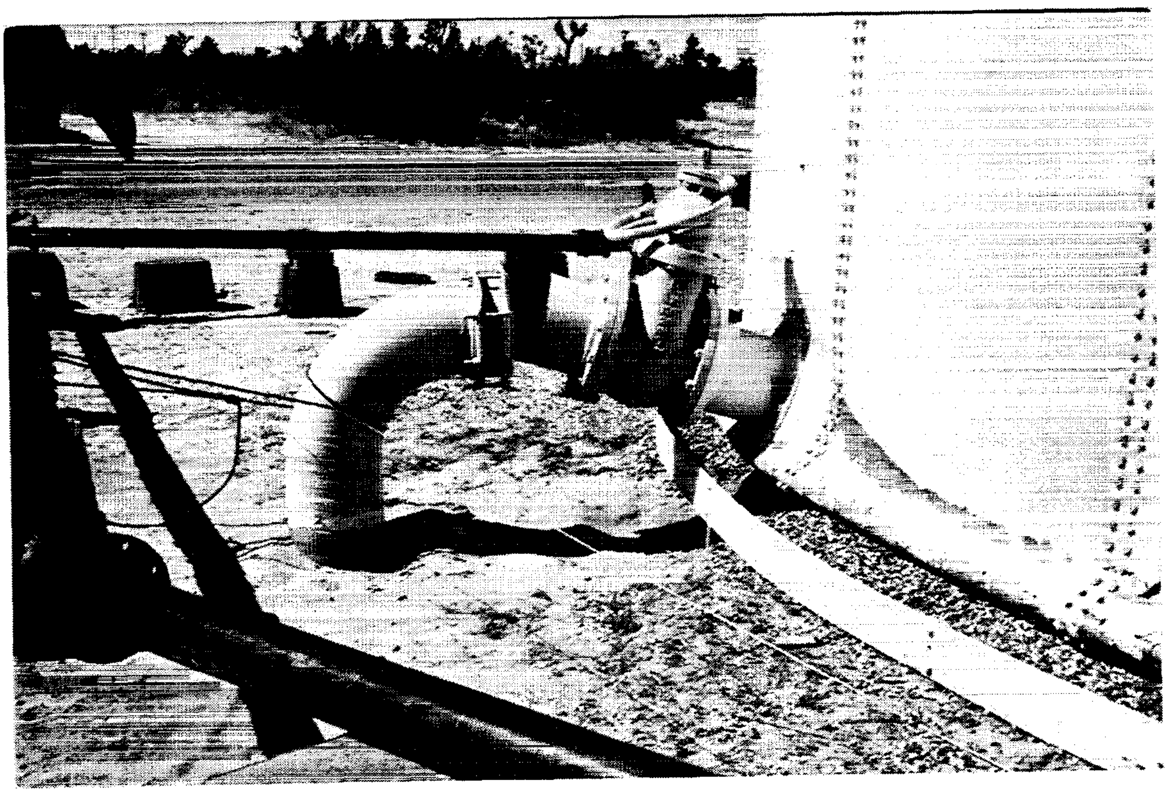

Figure 9.9 Piping at CSA-70.

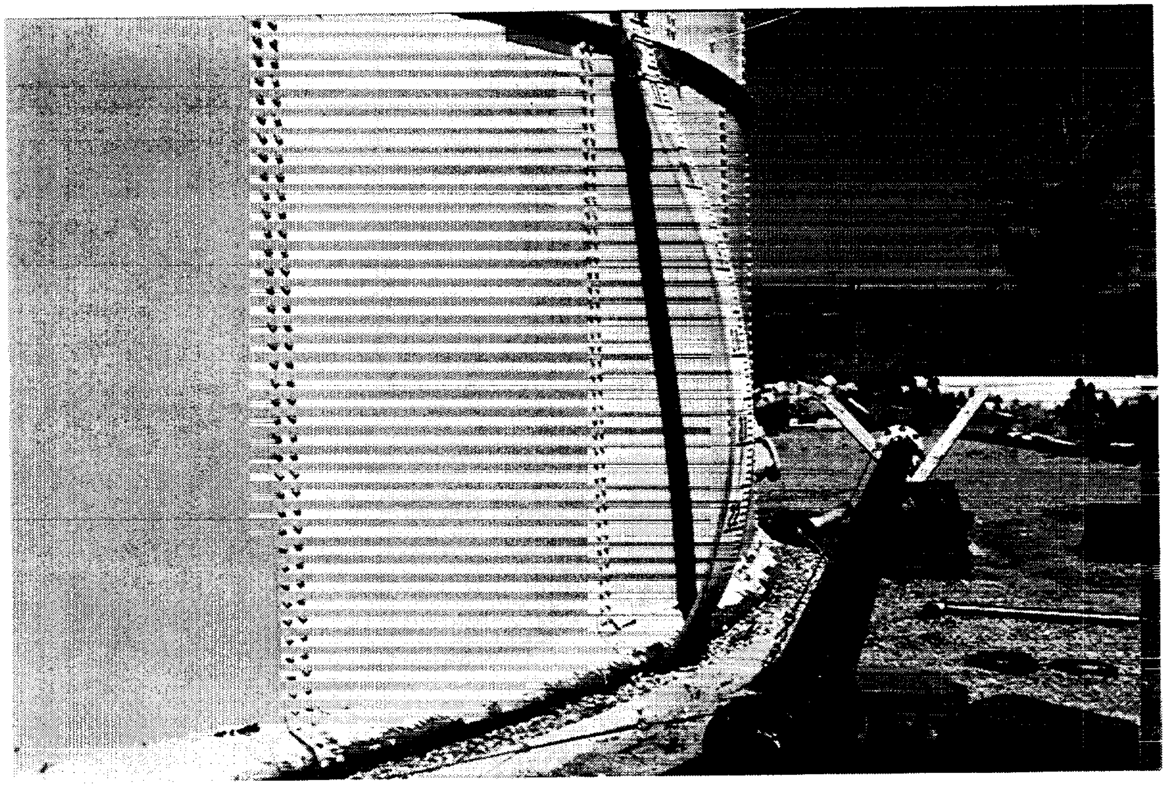

Figure 9.10 CSA-70 tank, elephant foot was fairly uniform around tank.

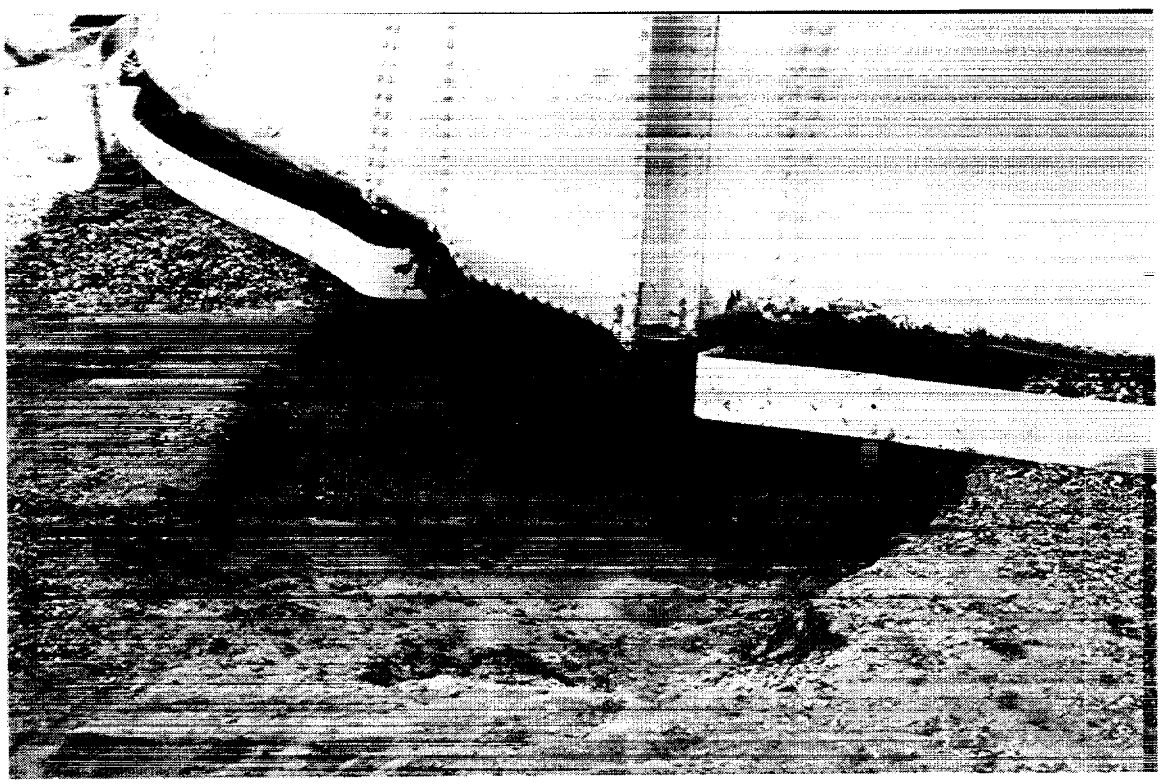

Figure 9.11 CSA-70 tank, damage of clean-out door, and washout of soil.

10. THE 1994 NORTHRIDGE EARTHQUAKE

This magnitude 6.7 earthquake occurred on January 17, 1994. It occurred on a blind thrust fault with the epicenter located in the San Fernando Valley near the community of Northridge. The area is shown on Figure 10.1. Tank damage was extensive and occurred over a wide area. Effects on petroleum tanks are covered first, followed by the effects on water tanks.

<u>Petroleum Tanks</u>

There are two product distribution terminals in the San Fernando Valley. Neither terminal sustained significant damage. The Van Nuys terminal is located 8 km east-southeast of the epicenter. The operating tanks at this terminal are shown in Table 10.1. The tanks at this location are cone roof with internal pans except for the wastewater tank, which has a cone roof only. All tanks were constructed in 1963 and conform to API Standard 650. The tanks are set on a rock base with no concrete foundations or anchorage. Damage consisted of bolts shearing on the walkway between two tanks. All product tanks were between one-third and two-thirds full at the time of the earthquake. This site also had five out of service tanks 3.2 m (10.5 ft) in diameter by 10 m (33 ft) high; two of these were nearly full of water at the time of the earthquake. Neither tank suffered significant damage although there was minor damage to a walkway at the top of the tanks [Table 10.1]. These tanks were not anchored but were on individual concrete pad foundations. See Figure 10.3.

TABLE 10.1 PETROLEUM TANKS, VAN NUYS

DESIGNATION	DIAMETER d m (ft)	HEIGHT H m (ft)	d/H	SERVICE	CAPACITY (bbls)
1	8.8 (29)	14.6 (36)	0.60	Fuel	5500
2	11.0 (36)	13.7 (45)	0.75	Fuel	8500
3	20.4 (67)	14.6 (48)	1.4	Fuel	30000
4	21.9 (72)	14.6 (48)	1.5	Fuel	34000
5	4.6 (15)	9.1 (30)	0.5	Wastewater	900

The Sepulveda terminal has three tanks for product storage and two tanks for wastewater storage. This terminal is located about 7 km east of the epicenter. Information on the tanks is given in Table 10.2.

TABLE 10.2 PETROLEUM TANKS, SEPULVEDA

DESIGNATION	DIAMETER d m (ft)	HEIGHT H m (ft)	d/H	SERVICE	CAPACITY (bbls)
A	19.8 (65)	11 (36)	1.8	Fuel	20000
B	21.9 (72)	11 (36)	2.0	Fuel	25000
C	18.3 (60)	11 (36)	1.67	Fuel	18000
AG1	3.7 (12)	7.3 (24)	0.5	Wastewater	450
AG2	3.7 (12)	7.3 (24)	0.5	Wastewater	450

All tanks were constructed according to the API Standard 650 in the mid 1960s. All fuel tanks have cone roofs with internal pans. The three fuel tanks are not on concrete ring foundations and have no anchorage. See Table 10.2 for the individual tank data.

At the time of the earthquake Tank A was about two-thirds and tanks B and C were about one-third full. No shell buckling was evident. There was sloshing with some product ending up on top of the pans, but without sinking them. The spillage was removed and the tanks remained in service.

One of the wastewater tanks was full at the time of the earthquake and one was empty. The tanks set on a common foundation and have sixteen one-inch anchor bolts equally spaced around the tank. The tanks were constructed to UL Standard 142. On the full tank it was evident that the paint between the nut and the chair plate had parted on all sixteen bolts. This paint crack is taken as an indication that the anchored bolts "worked". The empty tank did not have paint cracks. There were no signs of shell buckling on either tank. Figures 10.4 and 10.5 show the wastewater tanks. Figure 10.6 is a view of the Van Nuys products terminal.

There was a bolted construction crude oil tank in Aliso Canyon, about 10 km north of the epicenter which totally collapsed. This tank appears in photographs to be about 12.2 m (40 ft) in diameter by 7.3 m (24 ft) high. There were three other similar tanks in the block which did not collapse; the level in the collapsed tank is unknown but from the appearance of the mess created it contained considerable oil. See Figure 10.7.

Water Tanks

City of Simi (Water District 8)

The service area for this agency is approximately 21.5 km west of the epicenter. A portion of the service area surrounds the Southern California Water Company service area. Of the 34 tanks in the district about ten had problems; all of these were in the east end of the district. Principal problems were broken valves and fittings at the tanks with some tank movement (sliding). There was a particular problem at a buried tank drain (piping coming off the bottom of the tank), these underdrains are being replaced throughout the system as there was uplift and damage/breakage of the piping allowing the tank contents to drain [39].

Southern California Water Company (SCWC), Simi Valley

The Simi Service area of the SCWC lies west of Northridge, approximately 14.5 km from the epicenter, at the east end of the Simi Valley (see Figure 10.2).

The SCWC had five tank failures, all of which were bolted tanks. Failure was by elephant foot buckling, resulting in loss of contents. Three tanks were 12 m (39 ft) in diameter by 7.3 m (24 ft) high [d/H = 1.6], and two were 9.1 m (30 ft) in diameter by 7.3 m (24 ft) high [d/H =1.25]. All failed tanks were built in 1964. One 12 m (39 ft) in diameter by 7.3 m (24 ft) high and one 9.1 m (30 ft) in diameter by 7.3 m (24 ft) high survived the earthquake, but the water level in these two tanks was lowered 1.2 m (4 ft) the night before the earthquake. The water level in the tanks that failed is not known but it is believed they were nearly full. There were two 15.8 m (52 ft) in diameter by 9.8 m (32 ft) high, one 27.4 m (90 ft) in diameter by 9.8 m (32 ft) high and one 39.0 m (128 ft) in diameter by 9.8 m (32 ft) high welded tanks in the same general area which survived [40]. Table 10.3 lists the SCWC Simi Valley tanks [41].

TABLE 10.3 SOUTHERN CALIFORNIA WATER COMPANY - SIMI VALLEY

TANK	d m (ft)	H m (ft)	d/H	COMMENTS
LAUTENSCHLAGER 1	19 (64)	6.7 (22)	2.91	OK, Welded, 1965
LAUTENSCHLAGER 2	19 (64)	7.3 (24)	2.67	OK, Welded, 1988
TAPO	40 (130)	9.8 (32)	4.06	OK, Welded, 1963
CRATER EAST	18 (60)	7.3 (24)	2.5	OK, 1.3 m (4 ft) low, bolted
CRATER WEST	11.9 (39)	7.3 (24)	1.63	OK, 1.3 m (4 ft) low, bolted
ALAMO	30.5 (100)	6.3 (20.5)	4.88	OK, Welded, 1964
KATHERINE	11.9 (39)	7.3 (24)	1.63	Failed, bolted
REBECCA NORTH	11.9 (39)	7.3 (24)	1.63	Failed, bolted
REBECCA SOUTH	9.1 (30)	7.3 (24)	1.25	Failed, bolted
SYCAMORE NORTH	9.1 (30)	7.3 (24)	1.25	Failed, bolted
SYCAMORE SOUTH	9.1 (30)	7.3 (24)	1.25	Failed, bolted

City of Los Angeles, Department of Water and Power (CLADWP)

The CLADWP has approximately 10 - 12 tanks located in the mountains surrounding the San Fernando Valley to serve specific areas; CLADWP also had additional reservoirs storing the bulk of the water used in the city. Many of these tanks were old, built in the late 1920s or early 1930s. Many of the older tanks were riveted shells with wooden roofs. Inlet/outlet connections have Dresser Couplings and/or cast iron valves and fittings. Table 10.4 lists these tanks, and pertinent data on their size and performance. The first five listed tanks are located in the Santa Monica Mountains, south of Northridge. For these tanks, functional failure resulted in broken piping and spillage and not damage to the tank shell or bottom. Granada High Tank collapsed and was removed. This tank suffered damage in the San Fernando earthquake. Alta Vista 1 and 2 were neither damaged surviving both the San Fernando and Northridge earthquakes. Kittridge and Corbin tanks are believed to set south and west of the epicenter, and also have large d/H ratios. Sesnon Tank, which had damage in the 1971 San Fernando Earthquake, has been removed [42].

TABLE 10.4 CLADWP STEEL TANKS

DESCRIPTION *LOS ANGELES AREA*	DIAMETER d m (ft)	HEIGHT h m (ft)	VOLUME ml (MGAL)	d/H	AN-CHORED	TYPE	YEAR BUILT	AWWA	REMARKS
TOPANGA	11 (36)	9 (29.5)	0.8 (0.21)	1.22	NO	WELDED	1936	NO	Wood roof, no tank damage, replace broken inlet/outlet valve
ZELZAH	21.3 (70)	12.2 (40)	3.79 (1.0)	1.75	NO	WELDED	1948	--	Wood roof, roof collapsed, local buckling at top, replace broken valve
MULHOLLAND	15.8 (52)	10.2 (33.5)	1.89 (0.5)	1.55	NO	WELDED	1931	NO	Wood roof, overflow pulled away
BEVERLY GLEN	30.5 (100)	12.3 (40.5)	8.52 (2.25)	2.47	NO	RIVETED	1932	NO	wood roof, roof collapsed--replaced with hypalon roof, dresser coupling pulled out, local buckling
COLDWATER	30.5 (100)	12.3 (40.5)	8.52 (2.25)	2.47	NO	RIVETED	1925	NO	Wood roof, roof shifted and collapsed, inlet/outlet piping failure
GRANADA HI	16.8 (55)	10.7 (35)	2.27 (.60)	1.57	NO	RIVETED	1929	NO	Wood roof, tank collapsed, removed
ALTA VISTA 1	16.5 (54)	8.8 (29)	1.89 (.50)	1.86	NO	RIVETED	1929	--	Wood roof, no damage
ALTA VISTA 2	29.0 (95)	11.1 (36.5)	6.51 (1.8)	2.60	NO	WELDED	1954	--	Wood roof, no damage
KITTRIDGE 3 & 4	57.9 (190)	15.5 (51)	37.85 (10.0)	3.73	NO	WELDED	1973	--	Wood roof, no damage
CORBIN	47.5 (156)	9.1 (30)	15.1 (0.4)	5.20	NO	WELDED	1987	--	Wood roof, minor draw line damage, partially buried

Valencia Water Company

The service area for this company is north and slightly west of Northridge, about 20 km from the epicenter. The area is a foothill setting, similar to the adjacent Newhall County Water District , and sets generally on each side of Interstate Highway 5. Three tanks failed and another was damaged. The location of the Valencia Water Company tanks is shown on Figure 10.1. Table 10.5 lists each tank and its characteristics and performance. All welded tanks were constructed to the AWWA Standard D100 or similar criteria. All tanks were 90 - 95% full when the earthquake occurred.

TABLE 10.5 VALENCIA WATER COMPANY

TANK	d m (ft)	H m (ft)	d/H	DAMAGE
ROUND MOUNTAIN	40.3 (132)	9.8 (32)	4.1	No damage
HASLEY	36.6 (120)	12.2 (40)	3.0	No damage
MAGIC MOUNTAIN I	22.3 (73)	7.3 (24)	3.0	Failed, hit by Magic Mountain II, bolted
MAGIC MOUNTAIN II	18.3 (60)	7.3 (24)	2.5	Complete failure, tearing of bottom shell course at base, bolted
MAGIC MOUNTAIN III	24.4 (90)	9.8 (32)	2.8	No damage, this tank was partially buried
PRESLEY	21.3 (70)	9.8 (32)	2.2	No damage
4 MILLION	45.7 (150)	9.1 (30)	5.0	No problems or damage
SECO	22.3 (73)	7.3 (24)	3.0	No damage
LARWIN	18.3 (60)	12.2 (40)	1.5	Complete failure, elephant foot, pulled tie down straps, lifted foundation
POE	27.4 (90)	9.0 (32)	2.8	Roof rafter damage and roof sagging, some rafters fell, no elephant foot
PARAGON	22.3 (73)	9.8 (32)	2.3	No damage

One failure occurred at the Larwin tank. This tank was 18.3 m (60 ft) in diameter by 12.2 m (40 ft) high. It was set on a concrete ring foundation and was attached to the foundation with 3/8 x 3 flat bar embedded in the concrete foundation and welded to the tank at about 1.2 m (4 ft) spacing. The tank sustained roof damage, elephant foot buckling, nozzle tear-outs, and roof/shell joint failure; surprisingly it is reported that the tank did not have floor/shell weld joint failures. Figures 10.8 through 10.10 depict the tank damage. The tie-down straps were near vertical when installed, and their final position indicated that the tank slid or moved laterally. This tank was moved to this site and rebuilt in 1986, and was in compliance with the AWWA Standard D100 criteria [43].

The additional failures occurred at the Magic Mountain (MM) I and II tanks. Both tanks were bolted construction. MMI was 22.3 m (73 ft) in diameter by 7.3 m (24 ft) high. MMII was 18.3 m (60 ft) in diameter by 7.3 m (24 ft) high. The tanks are shown in Figures 10.11 and 10.12. MMII suffered the most catastrophic failure in that the shell bottom joint literally tore apart over half the circumference of the tank. MMI was damaged by MMII and it also was removed. A third tank, MMIII, a welded tank at the same setting was not damaged. This tank was partially buried (about .7 m (2.5 ft)) and had external roof rafters [44].

The Poe tank is 5 km north-northwest of the Larwin tank. At this tank some roof rafters fell and others were damaged, allowing sagging of the roof. There was no elephant foot buckling and no loss of contents. The 4 MIL tank between Poe and Larwin did not suffer damage. All other tanks in the system performed satisfactorily [43].

<u>Newhall County Water District (NCWD)</u>

The service area for this district is located approximately 19 km almost directly north of the epicenter of the Northridge earthquake. It is set in a foothill region north of the fork of the State Highway 14 and Interstate 5 freeway. The location of the districts tanks are shown on Figure 10.1. Table 10.6 identifies each tanks characteristics and the damage sustained. It is believed that all tanks were at least 90% full at the time of the earthquake. All tanks were welded and were constructed to the AWWA Standard D100, or to criteria near equivalent. None of the tanks were anchored [45]. Figure 10.13 shows a tank which had a thicker annular ring and did not elephant foot.

TABLE 10.6 NEWHALL TANKS

Tank No.	DIA m (ft) d	HT m (ft) H	d/H	FDN	BUILT	COMMENTS
2	12.2 (40)	9.8 (32)	1.25	gravel pad	1954	Broken/pullout piping, E.F. buckling, fdn settling
3	12.2 (40)	9.8 (32)	1.25	gravel pad	-	same as 2
4	12.2 (40)	9.8 (32)	1.25	gravel pad	1962	similar to 2, roof rafters pulled away and fell, AWWA tank
5	19.5 (64)	9.8 (32)	2.0	-	1962	Roof and rafter damage, E.F buckling, in/out piping sheared
6	6.1 (20)	6.1 (20)	1.0	-	1960's	Damage req'd this tank to be replaced
7	27.4 (90)	9.8 (32)	2.8	Concrete ring	1975	Roof-shell seam opened, rafters fell, 1/2" annular ring on this tank, no E.F. buckling
8	18.3 (60)	7.3 (24)	2.5	-	-	Rafters pulled from shell, roof damage
9						Future-not constructed
10	24.4 (80)	12.2 (40)	2.0	Concrete ring	1989	No apparent damage, AWWA tank

E.F.: Elephant Foot

A California Strong Motion Instrument Program (CSMIP) accelerometer was located at the Newhall Fire Station, near the center of the service area of the district. Its maximum readings were: 90°, 0.63 g; 360, 0.61 g and 0.62 g vertical.

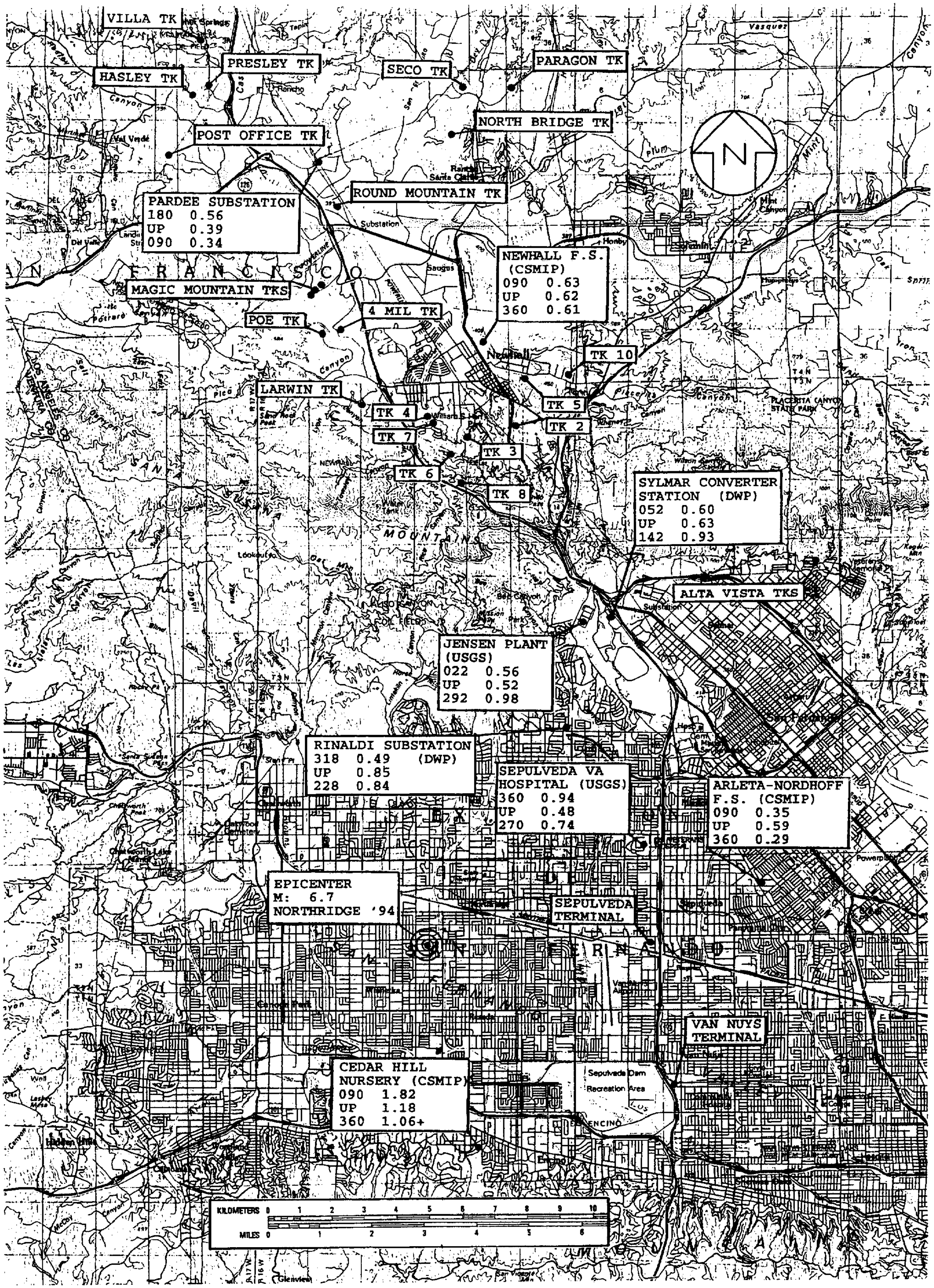

Figure 10.1 1994 Northridge Earthquake Area Map - San Fernando Valley and North

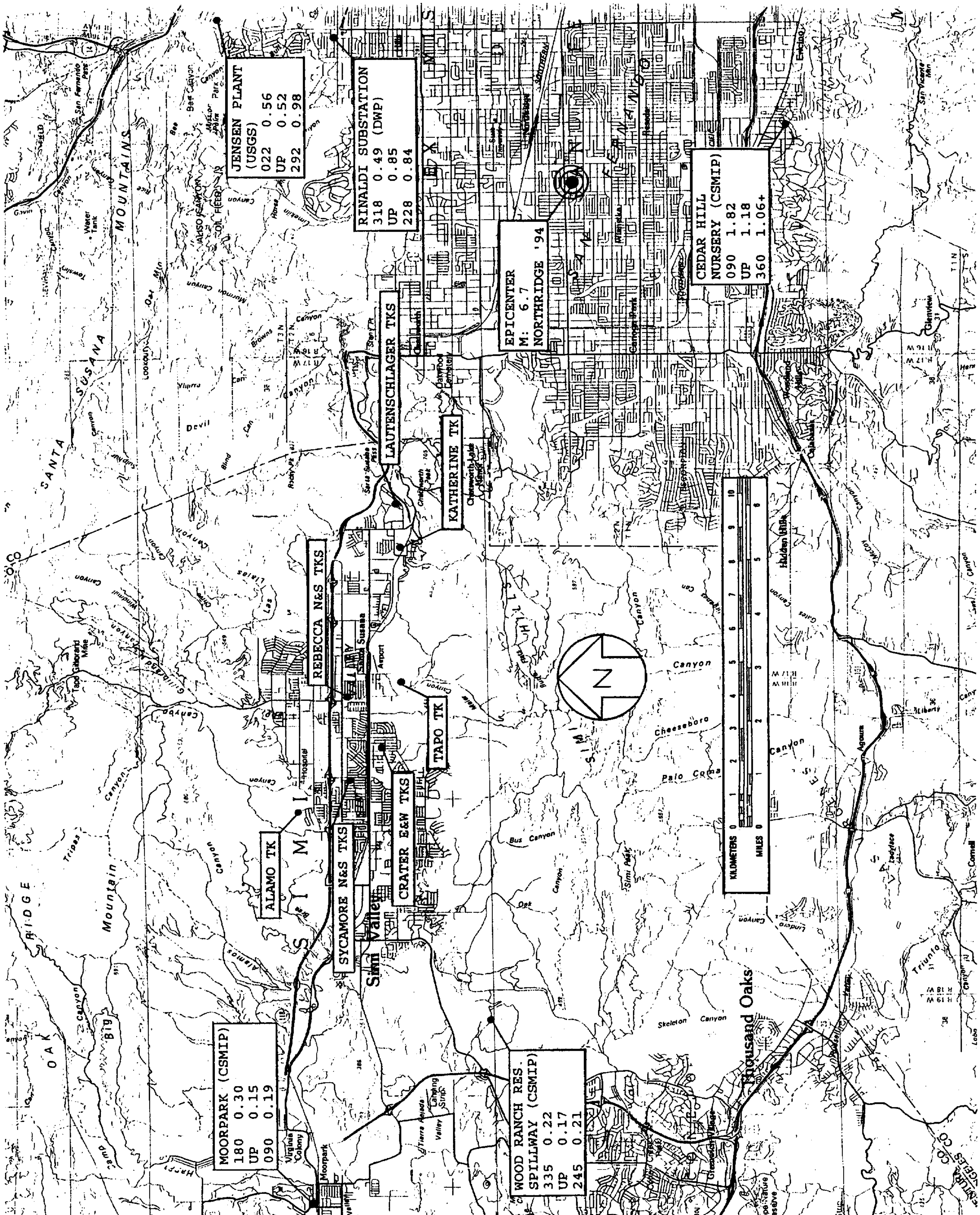

Figure 10.2 1994 Northridge Earthquake Area Map - Simi Valley

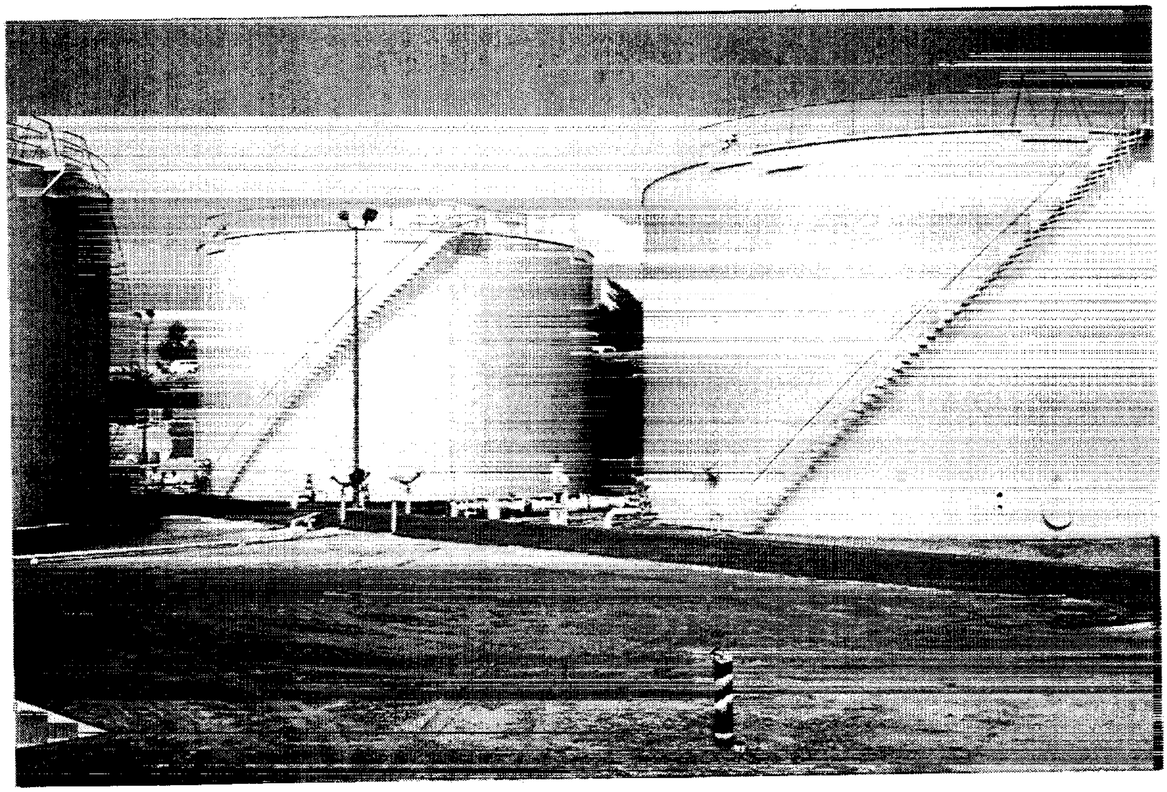

Figure 10.3 Sepulveda Products Terminal, internal pan tanks had no damage but product did slosh on the top of the pans.

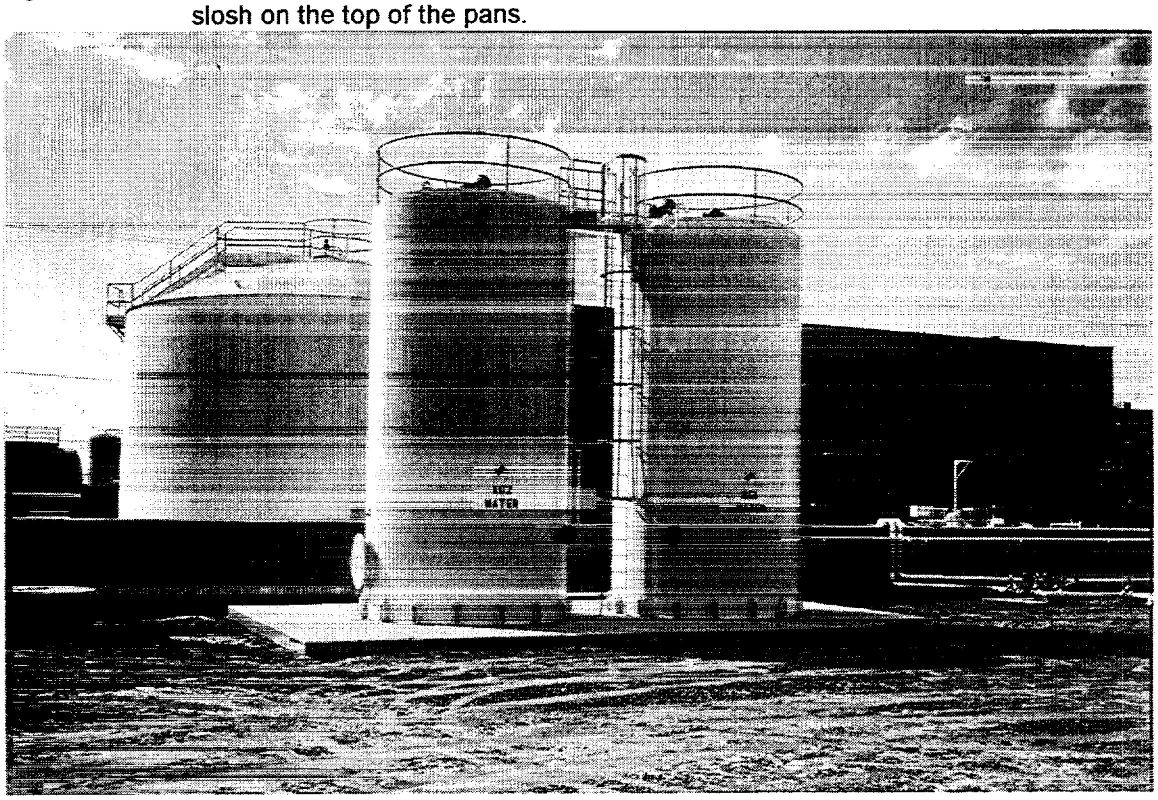

Figure 10.4 Wastewater tanks at Sepulveda Terminal, AG2 (on left) was full at time of earthquake, AG1 was empty. No damage to AG2.

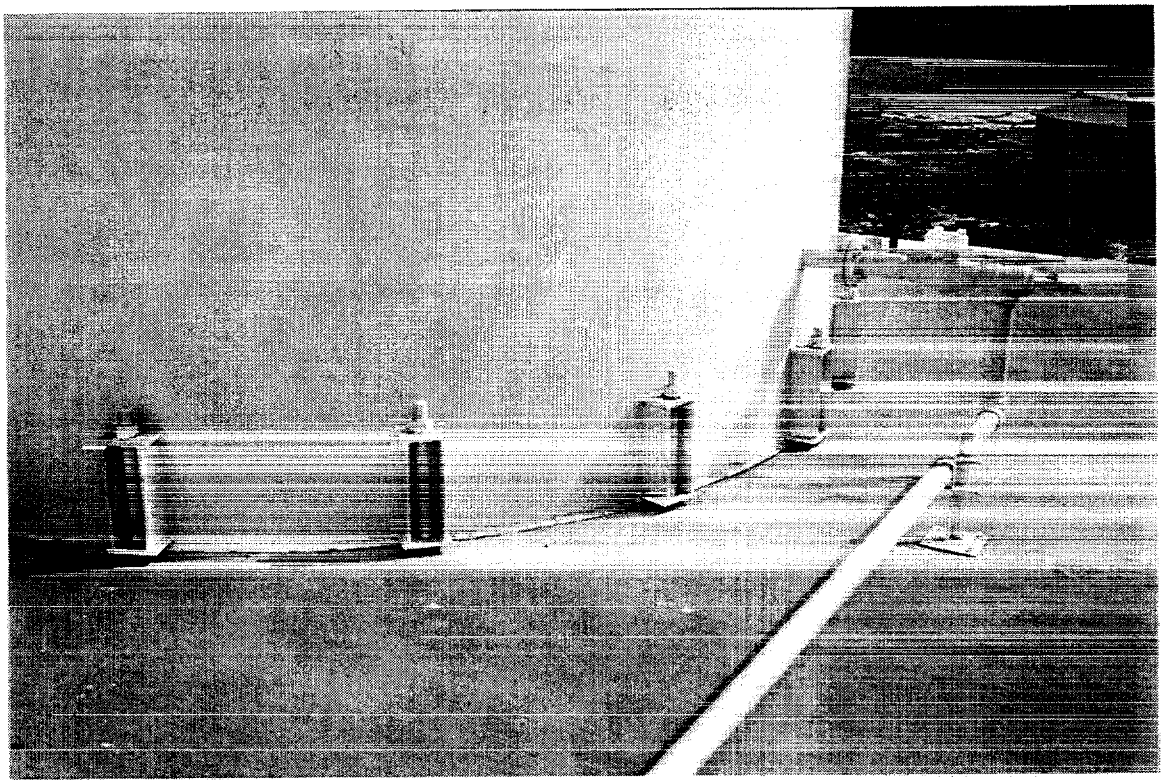

Figure 10.5 Anchor bolts and chairs on Tank AG2.

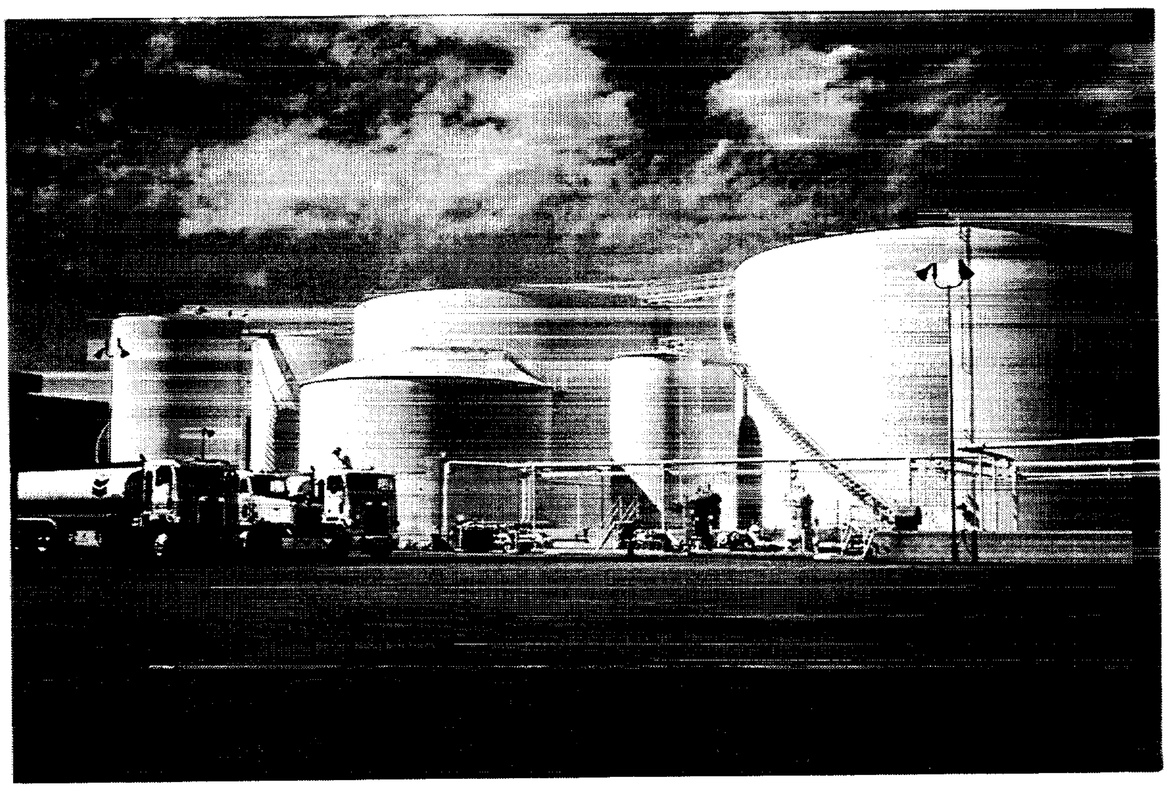

Figure 10.6 Van Nuys Terminal, no significant damage at this location.

Figure 10.7 Aliso Canyon bolted oil production tank, which collapsed [Courtesy of L.Lund].

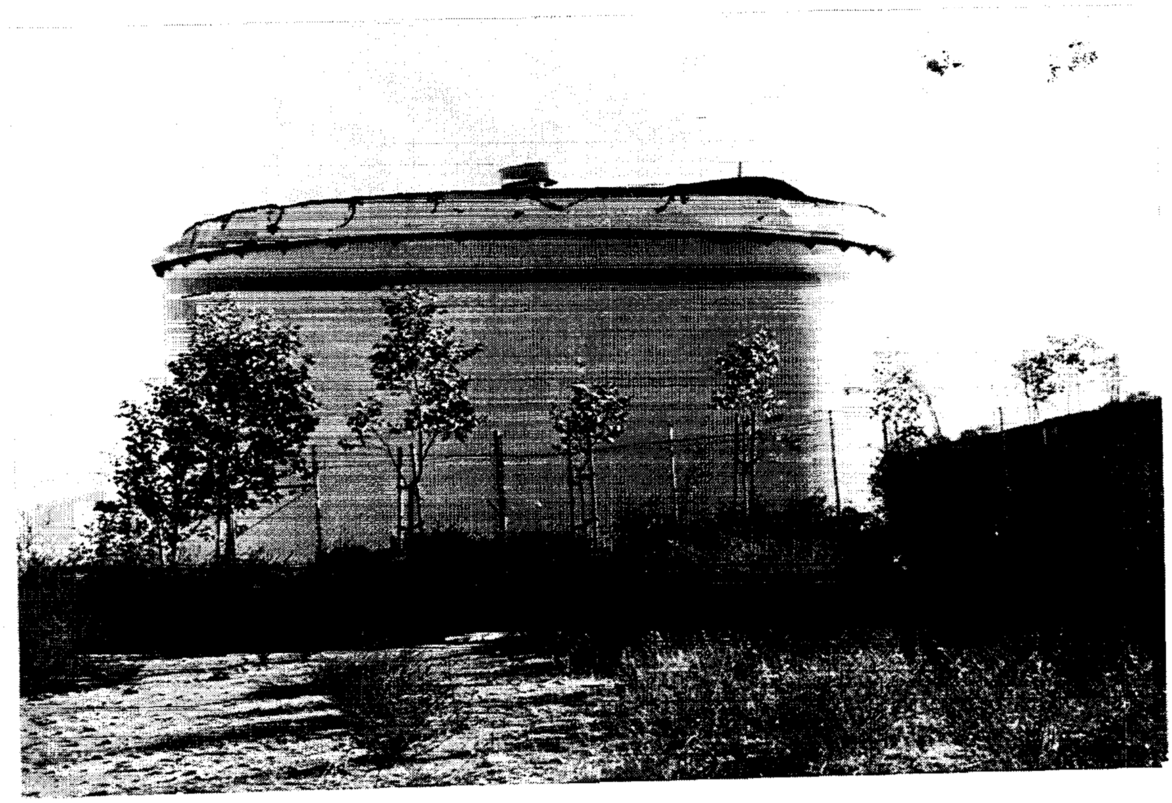

Figure 10.8 Larwin tank, 18.3 m (60 ft) in diameter by 12.2 (40 ft) high showing roof damage [Courtesy of L. Todd].

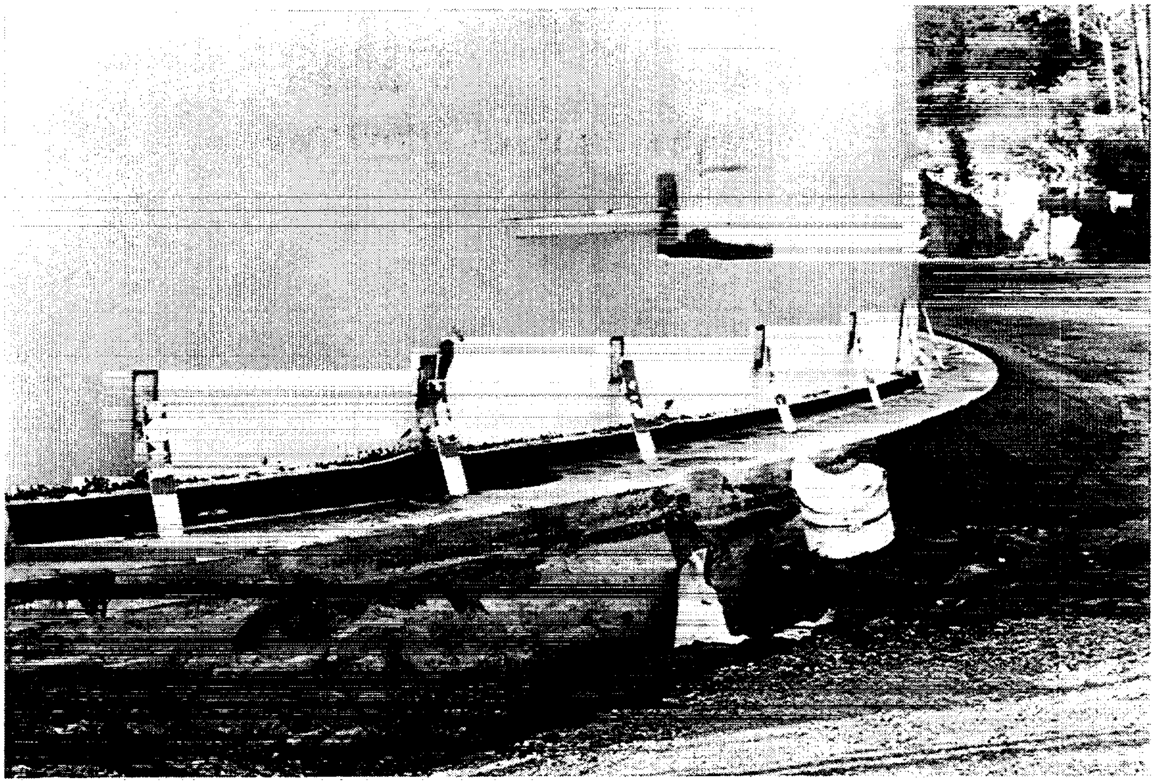

Figure 10.9 Larwin Tank, shows permanent bottom distortion and uplift and stripping of anchor straps [Courtesy of L. Todd].

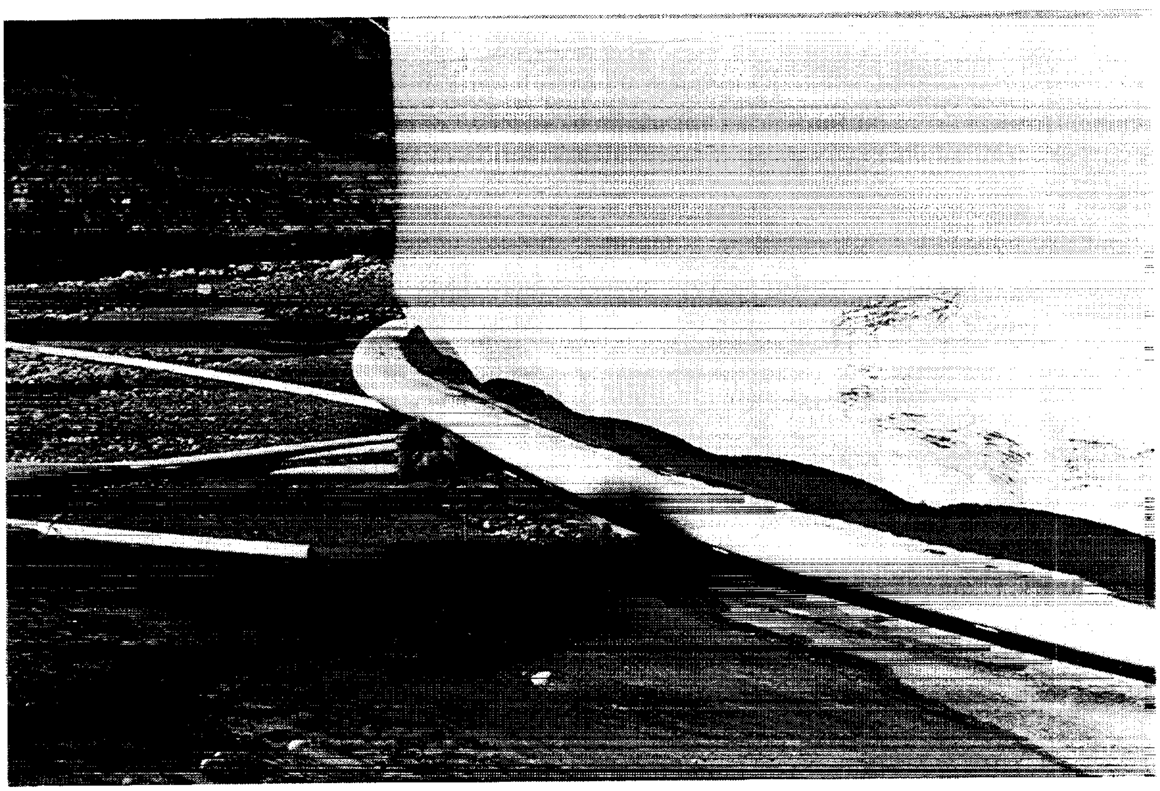

Figure 10.10 Elephant foot, and start of second bulge, straps on this side completely rolled over. (Courtesy of L. Todd)

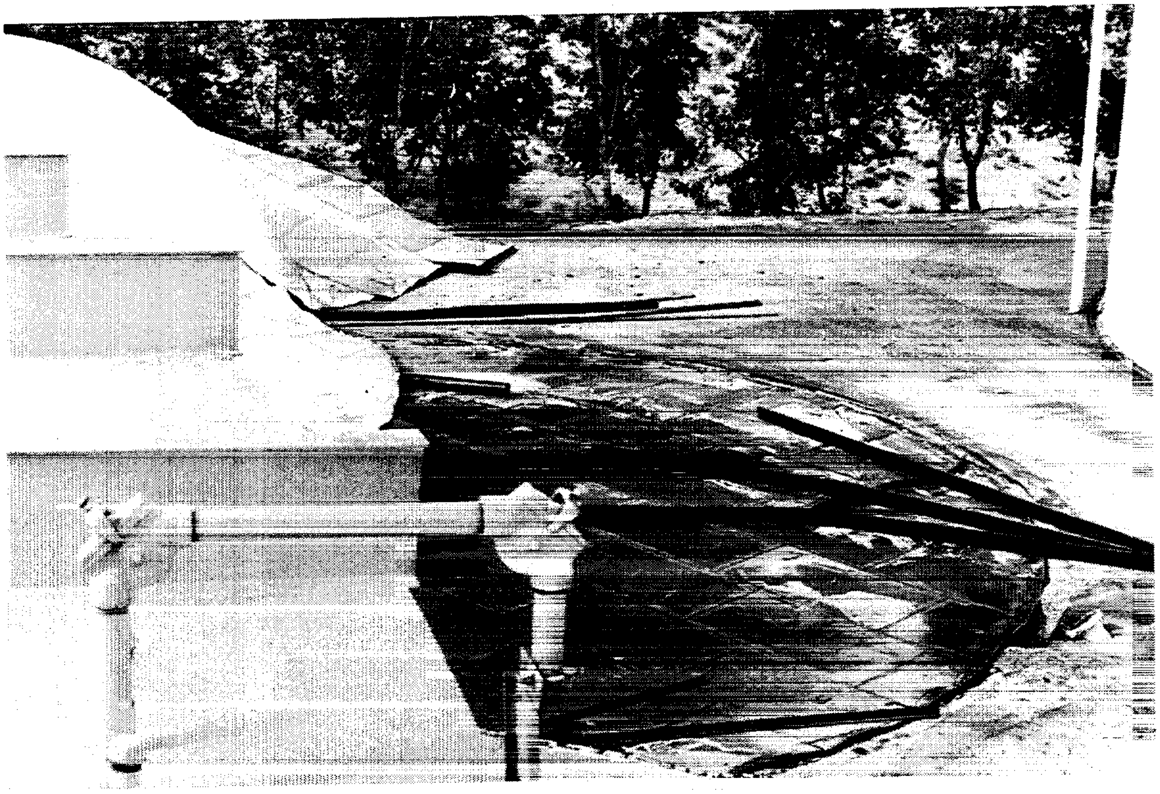

Figure 10.11 MMII, showing bottom and shell rip, note exterior rafters on MMIII [Courtesy of L. Todd].

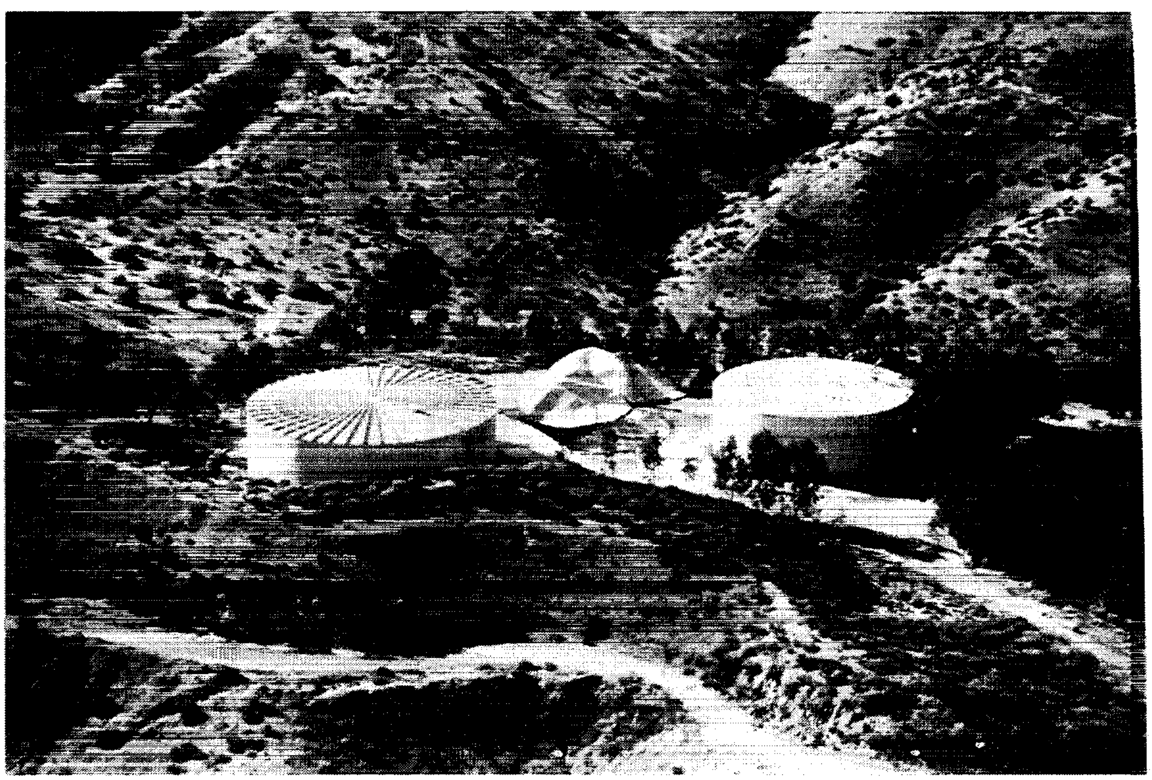

Figure 10.12 Setting for MM (Magic Mountain) tanks [Courtesy of E. Lindvall].

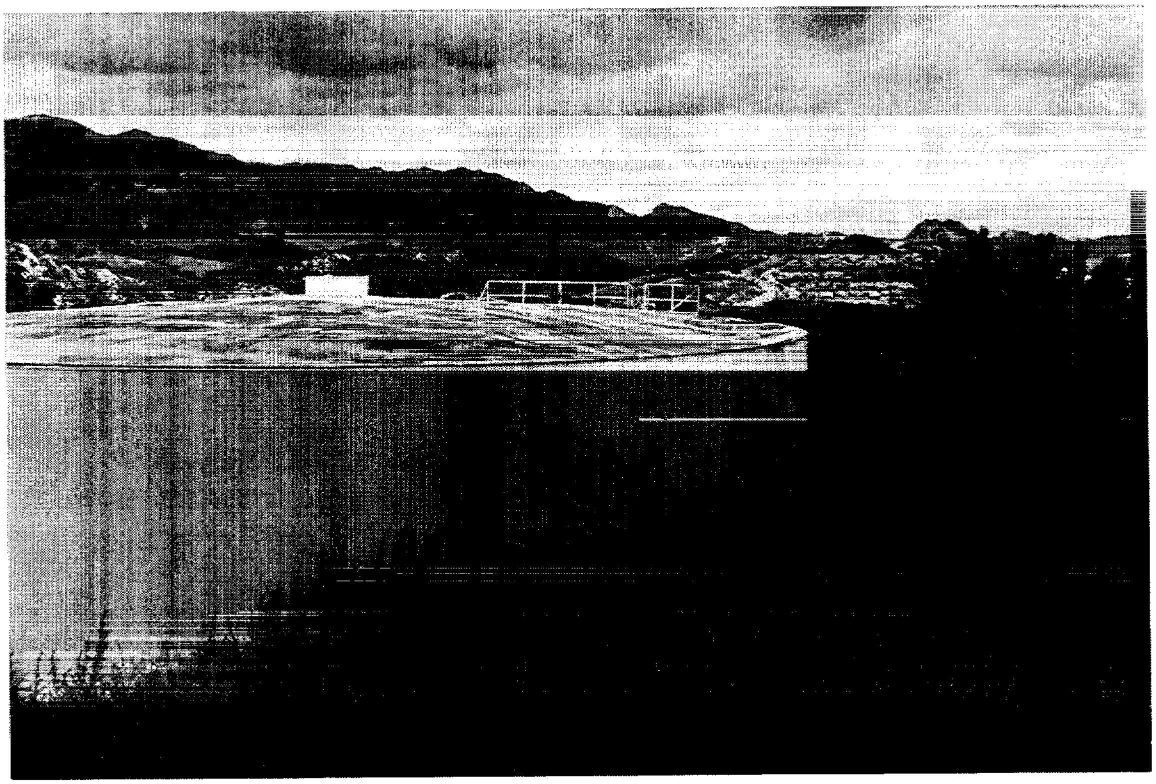

Figure 10.13 Roof, rafter, and shell damage on Tank 7, NCWD. This tank had a 12.7 mm (1/2 in) annular ring (or bottom plate) and did not elephant foot.

11. THE 1995 KOBE EARTHQUAKE

The magnitude 6.9 Kobe Earthquake on 17 January 1995 fortunately did not provide the tank problems which have resulted in prior Japanese earthquakes (Tokyo 1923, Nigata 1964 and Miyagi-Ken-Oki (Sendai) 1978). The closest major refineries which had tanks at risk were located about thirty-five kilometers from the epicenter at Osaka (1) and Sakai (2). Acceleration at these three refinery locations is estimated to be about 0.2g. Apparently there was no major damage at these refineries and details of the specific minor damage was not available [46]. Figure 11.1 is a map of the area.

A liquid storage tank terminal, about 10km east of the epicenter and on the waterfront, was damaged from site liquifaction. There was no loss of product from damaged tanks. This terminal is built on reclaimed ground and probably experienced peak accelerations of 0.6-0.8g. The terminal setting is 2-4km from active faulting. The damage is shown in Figures 11.2 thru 11.5, and consists principally of tank tilting, pipe support/piping loss of foundation supports, and walkway-platform loss of support. Figure 11.6 shows the seawall which is on two sides of the terminal, and some tilted tanks. Liquifaction was the principal cause of damage at this waterfront location.

There are numbers of sphere tanks (pressurized gas holders) on multiple cross-braced column legs located in the Kobe-Osaka area. No significant damage to these spheres was reported, although they were subjected to large accelerations [47].

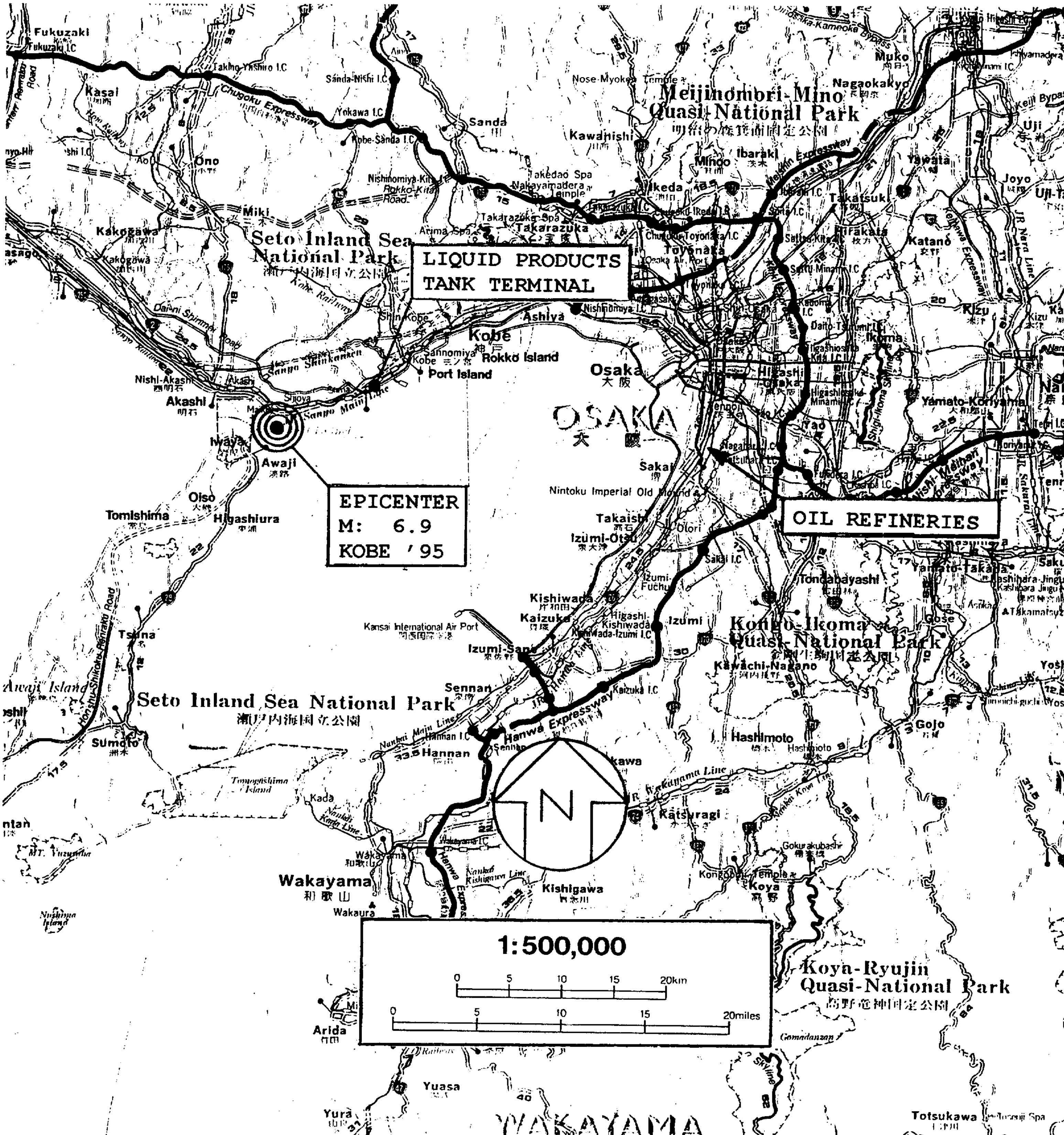

Figure 11.1 1995 Kobe Earthquake Area Map

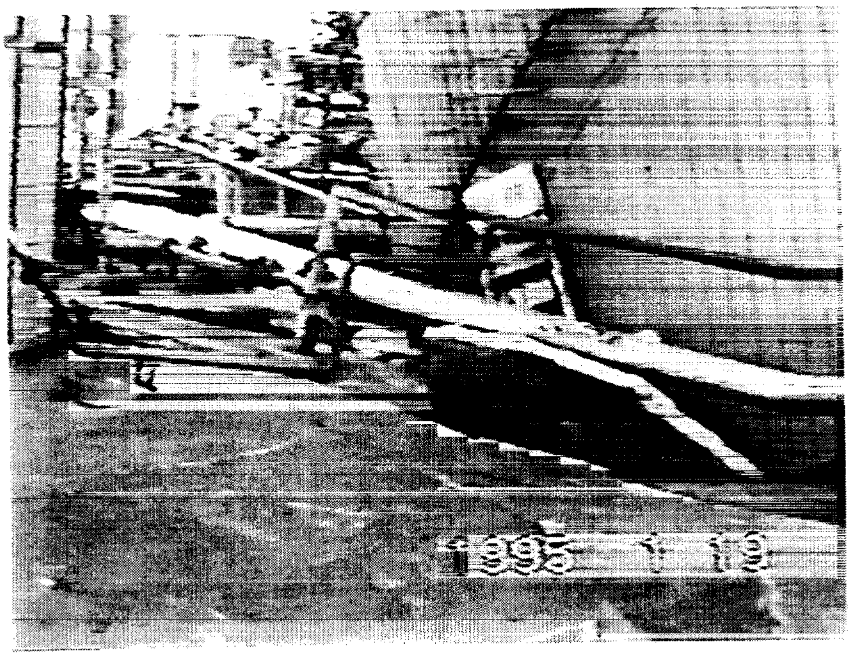

Figure 11.2 Settlement and tilting due to liquifaction (GATX video).

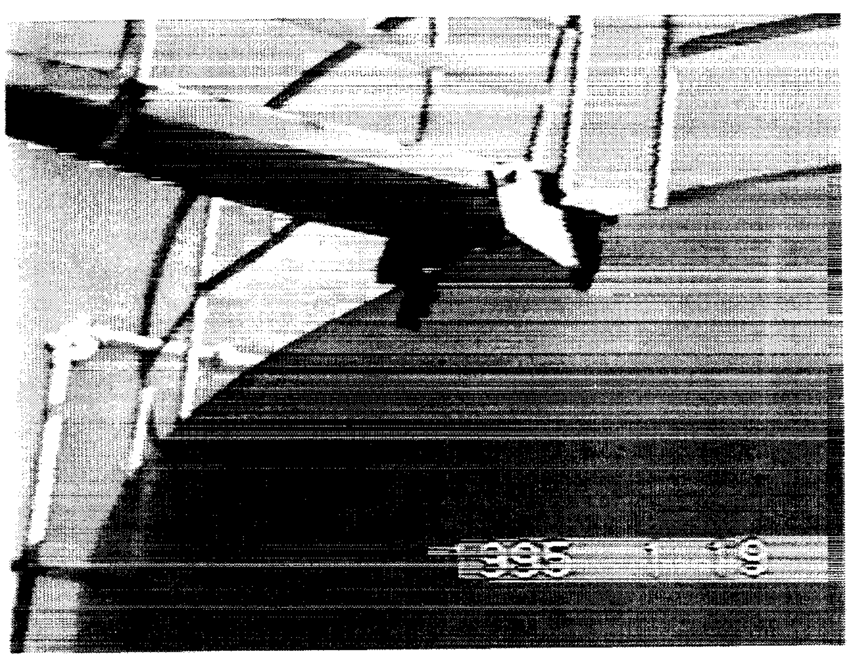

Figure 11.3 Inter-tank walkway joint failure (GATX video).

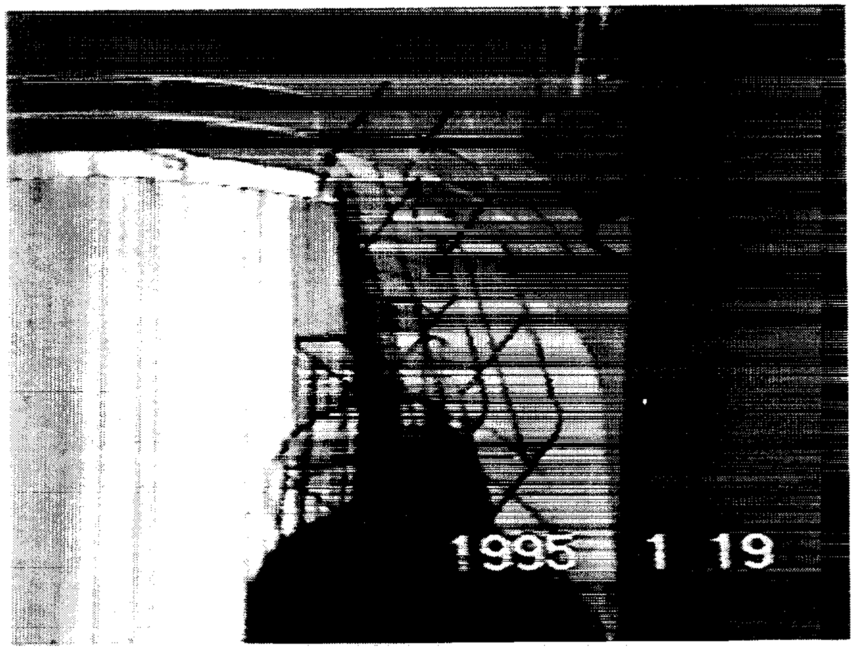

Figure 11.4 Walkway brackets pulled from tank shell (GATX video).

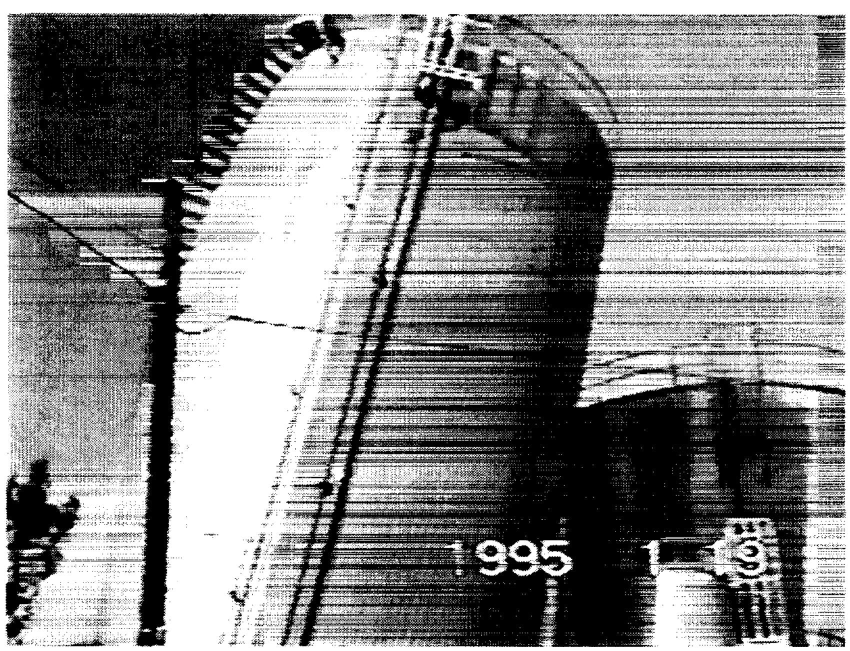

Figure 11.5 Tilted tank (GATX video).

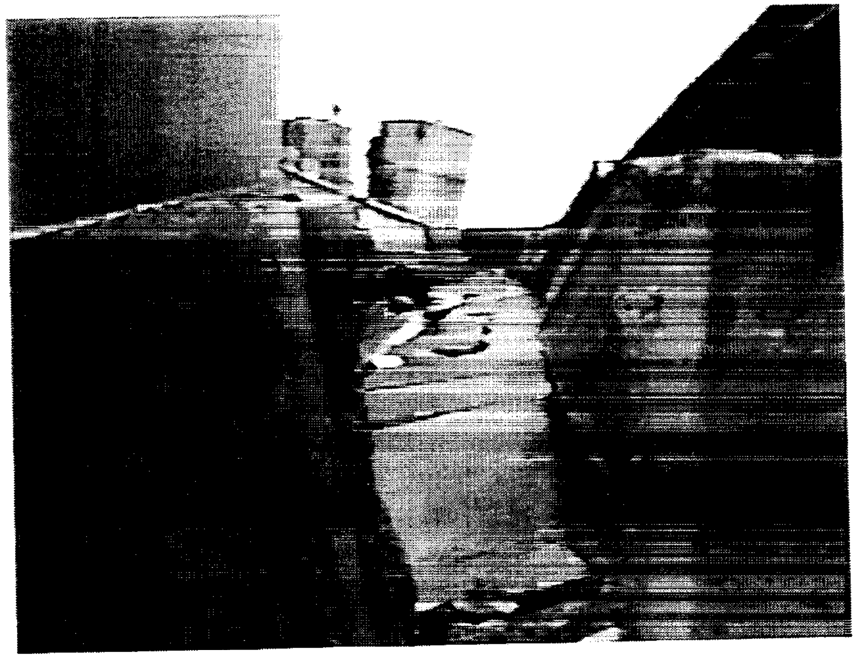

Figure 11.6 Seawall settlement and tilted tanks (GATX video).

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12. SUMMARY OF OBSERVATIONS

1933 Long Beach Earthquake. At the time of this earthquake there were probably more petroleum storage tanks in the Los Angeles - Long Beach area than at any other location in the world. The dearth of tank damage could be attributed to the relatively small magnitude of the earthquake, distance of tanks from the epicenter, "good" soil conditions at most tank locations, and most tanks not being full at the time of the earthquake. The destruction of the CLADWP Western Avenue riveted Water Tank (Tank "C") shows the possible effect of long period motion at a distance.

1952 Kern County Earthquake. Based on the size and location of the epicenter it would be expected that greater tank damage would have occurred. Those tanks in close proximity to the epicenter had low levels of oil in the tanks as a possible reason for the minimal damage. The catastrophic conflagration that occurred at the Paloma Gasoline Plant gives witness to what can happen. The sloshing of oil or product from the top of a tank at the roof/shell joint (as at the tanks at Weed Patch) or the damage to the roof/shell seals in floating roof tanks was first detected in this earthquake.

1964 Alaska Earthquake. This earthquake revealed the vulnerability of tanks at a great distance from the epicenter of a large earthquake. Tanks with diameters to height (d/H) ratios greater than two did not have elephant foot buckling. Those tanks with significantly lower d/H ratios did have elephant foot buckling when full or nearly full. Floating roof tanks did have seal damage, and it appears that some cone roof tanks had sloshing problems at the roof/shell joint.

1971 San Fernando Earthquake. This earthquake was characterized by a significant number of tank failures, and also by a number of tanks which did not fail. Virtually all of the tank failures were north of the surface faulting and on tanks which had d/H ratios of less than 1.5. The MWD Jensen Tank had no elephant foot buckling. The CLADWP Sesnon Tank had no lower elephant foot buckling but did have shell buckling at mid-height in the 7.9 mm (5/16 in) shell course. This tank had a 25.4 mm (1 in) bottom course and a 25.4 (1 in) by 0.9 m (3 ft) wide sketch plate annular ring. The CLADWP Alta Vista tanks with d/H ratios of about two or greater both survived the earthquake without damage.

1979 Imperial Valley Earthquake. The full tanks at the IID Steam Station had the same torn roof/shell damage that was displayed on the cone roof tanks at Weed Patch in the Kern County earthquake. The variety of tanks at the SFPPL Terminal (eighteen tanks) shows both the vulnerability and survivability of tanks subject to strong shaking. It is highly likely that anchorage would have prevented some of the failures. The availability of nearby strong motion data for this earthquake makes the complete tank data supplied by SFPPL very valuable.

1983 Coalinga Earthquake. This earthquake, which produced large accelerations, showed that large tanks do uplift, that sloshing in large floating roof tanks causes damage, that smaller bolted tanks with lower d/H ratios are vulnerable to damage and possible failure, and that large tanks are less vulnerable to elephant foot buckling than smaller tanks. Also evident from this earthquake is to not use bottom draw piping which is embedded in the earth below the tank.

1989 Loma Prieta Earthquake. This earthquake illustrated that tank damage can occur a considerable distance from the epicenter. Soil conditions obviously affect the performance of tanks, but no reason other than foundation design can explain why one set of tanks in close proximity to other tank settings should have significantly different seismic performance. Examination of the available information on water tanks near the area of strong shaking shows that the 100,000 gallon bolted tank which had elephant foot buckling probably had a d/H of one or slightly greater. The remaining water tanks were of a capacity that d/H would be expected to be larger than two. No shell buckling was indicated in damage reports on these larger tanks.

1992 Landers Earthquake. Though no petroleum storage tanks were damaged in this earthquake, the large number of water tanks in the affected area and the small amount of damage, other than two total failures, make this a significant earthquake for tanks. Considerations for Landers include: most water tanks operate near full, hillside settings may provide "improved" foundation conditions, the earthquake evidently propagated north, and the proximity of Tank "A" to the fault displacement and the location of Tank CSA-70 on the projection of fault displacement. Most tanks in the Landers area were low, with heights less than 7.4 m (24 ft). The sloshing and seal damage to large floating roof oil tanks which occurred in the Los Angeles area, 180 km from Landers, should be cause for concern.

1994 Northridge Earthquake. This earthquake significantly affected a number of tanks. Tanks well north (20 km) and west (15 km) of the epicenter suffered damage. We note here that distance to the epicenter is not necessarily a good indicator of probable damage, and that distance from faulting may be more indicative of damage potential. The total destruction of the Larwin Tanks (except for no floor/shell failure!) leaves questions to be answered. We see from pictures of this tank (Figures 10.9) that the shell appears to be raised from the floor in the manner that one would expect if floor/shell yielding at hinges were to take place (i.e., supporting the theory of the thicker annular ring.) Also, Newhall County Water District Tank 7 has a 12.7 mm (0.5 in) bottom, and this tank did not have elephant foot buckling. Damage to smaller bolted tanks was again experienced in this earthquake. Roof damage to water tanks seemed to be a feature of this earthquake.

The MWD Jensen Tank, which had upper shell damage and pulled anchor bolts in the 1971 San Fernando earthquake had its upper shell stiffened and the anchor bolts removed - this tank suffered no damage in the Northridge Earthquake. CLADWP Alta Vista 1 and 2 also had no damage in this earthquake. The City of Simi had problems with buried and backfilled underdrains pulling out from the bottom of the tank (a similar problem occurred on a large oil tank at Coalinga and a water tank at Loma Prieta).

1995 Kobe Earthquake. The lack of damage to storage tanks in the Kobe earthquake is hard to explain; perhaps it is because few tanks were located in the area of strong shaking. The survival of the sphere tanks could be indicative of improved seismic design since the failure of the Paloma spheres in the 1952 Kern County Earthquake.

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13. CONCLUSIONS/RECOMMENDATIONS

1. Unanchored tanks with d/H ratios of two (2) and above tend not to have elephant foot buckling. As this ratio decreases, the propensity to elephant foot buckling increases.

2. Cone roof petroleum storage tanks with frangible roof/shell joints and large d/H ratios have suffered failed roof/shell joints with the consequent spillage of oil or product. Floating roof tanks have experienced roof/shell seal damage. Internal pan tanks have had pan damage resulting in the pan sinking, or have had product splash on top of the pan.

3. It is important to have piping flexibility at tank connections, for both large and small pipe connections. (See Fig. 13-1).

4. All attachments to tanks should utilize reinforcing pads with no direct attachments to the shell.

5. Bolted tanks have not performed well in earthquakes. Whether this is due to the small d/H ratio generally present in this form of tank construction, or due to thinner shell plates because of limited heights and diameters is unclear. Bolted tanks which have failed have been unanchored. The latest AWWA D-103 Specification for bolted tanks has included provisions for seismic loadings.

6. Piping should not come through the bottom plate unless provided with flexibility.

7. Large tanks (d=40m+, d/H>2.5) do uplift, but appear to have no shell buckling (Coalinga, Imperial, Northridge). The necessity for anchorage for large tanks is questioned.

8. Annular rings with greater thickness than nominal bottom plate are apparently producing the intended effect.

9. Long period motion at a distance and soil/foundation conditions are two conditions which deserve additional attention and investigation.

10. Tanks have performed reasonably well in earthquakes; the effect of anchorage has not been significantly tested as of yet (especially for smaller tanks with d/H<1.5).

11. Roof/shell damage to cone roof tanks (both petroleum and water) has been evident in many earthquakes. It is believed that present industry practice is to not weld the roof rafters to the roof or the shell. There may

be thermal expansion reasons for not doing this. However, having continuity between these elements would most likely enhance the earthquake performance of the tanks. Sloshing may a problem that could be solved by modifying present construction methods.

12. Inlet-outlet piping should be made more flexible, and consideration should be given to making inlet-outlet piping from steel (including steel valves).

13. Additional studies should be made on tanks with d/H ratios of less than two to determine if elephant foot buckling can be eliminated, either by increasing shell thickness (Sesnon) or anchorage.

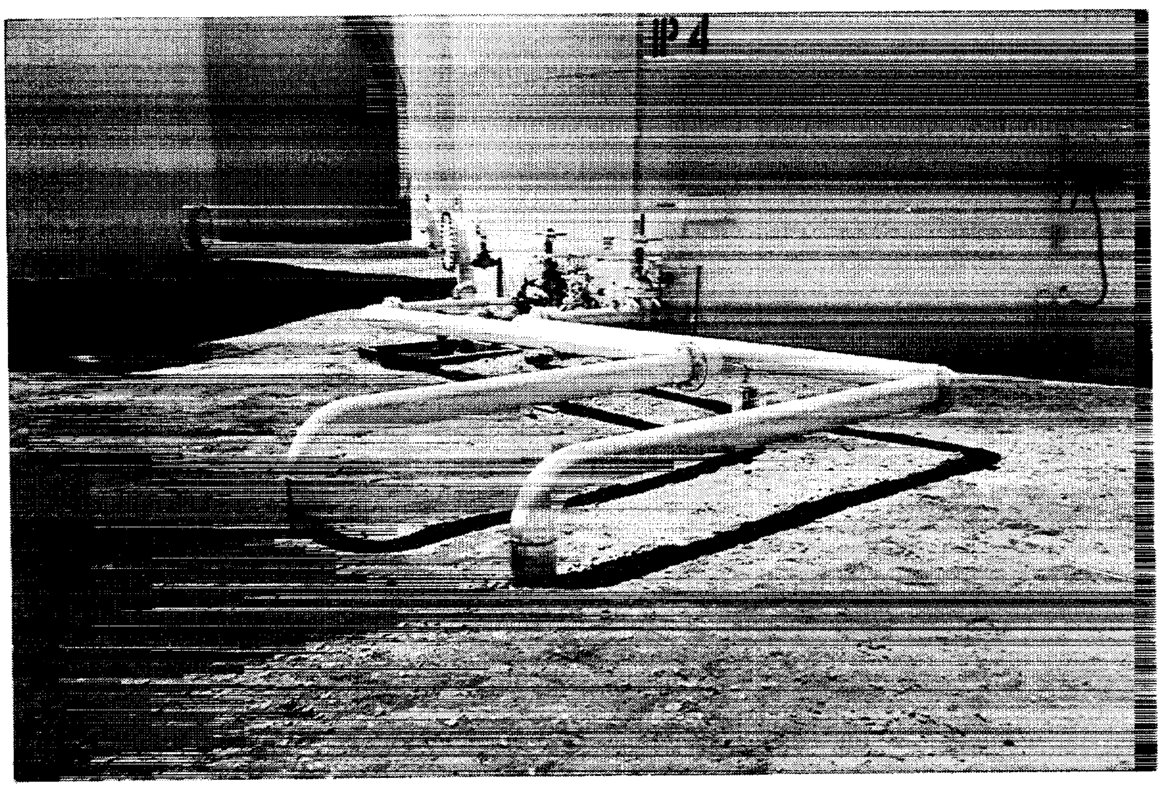

Figure 13-1 Inlet-Outlet piping which provides flexibility, note that the flanges in the horizontal runs are lap-joint stub end flanges. (Courtesy of J. Englehardt, SFPPL).

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APPENDIX A – POST EARTHQUAKE INVESTIGATION CHECKLIST FOR EVALUATING TANKS

A. Flat-Bottom Tanks

1. What type of tank (Cone Roof (CR), Cone Roof/Internal Pan (CR/IP), Floating Roof (FR))?

2. Height (shell height) and diameter of tank (H and d)?

3. Height of liquid in tank (at the time of the event)?

4. Name plate on tank, giving: MFG/ERCTR, CODE REF, H/d, Shell Thickness, ...

5. Commodity stored in tank (water, chemical, petroleum-crude or product)

6. Is piping "close coupled" to the tank?, or has flexibility been built into the system by having long (15 to 30 pipe diameter) angular piping runs connecting to the tank?, special joints or couplings used?

7. Are cast iron or steel valves and fittings used?

8. What are the soil conditions at the site?, groundwater depth?, alluvial or rock?, pile foundation?

9. Where are the tanks located relative to the epicenter and/or fault lines? Where do the tanks set relative to local topography?

10. Are there walkways between the tanks at the top of the tank? Did these fail or have damage?

11. What was the specific damage to the tank?
    a. Elephant foot? Approximate arc length; condition opposite the maximum elephant foot?
    b. Bolts or grounding straps pulled up?
    c. Small drain or relief piping?
    d. Inlet/outlet piping damage?
    e. Fitting/valve condition?
    f. Level gauges?
    g. Anti-rotation device damage (CR/IP, FR)?

12. Are there effects of piping being close coupled to the tank?

13. Does the tank have a concrete "ring" foundation under the shell?, or does it sit on a dirt or crushed rock base? Solid continuous foundation?

14. Is the tank anchored?, bolt size and spacing?, anchor detail?

15. Any details evidenced by paint cracks or patterns?

16. Are there "settlement" cracks in the soil adjacent to the tank?

17. What is the thickness of the bottom plate?, is it lap welded or butt welded?

18. Liquid sloshing and effects should be determined.

B. Horizontal Tanks/Spheres

1. Foundation damage?, concrete spalling?, diagonal bracing for spheres?, base plates?, and anchor bolts?

2. Piping damage?