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NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH
State University of New York at Buffalo

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ABSTRACT

On January 17, 1994 at 4:31 a.m., a magnitude 6.6 earthquake struck the Los Angeles metropolitan area. Epicentered in the San Fernando Valley town of Northridge, California, the earthquake caused serious damage to buildings and sections of elevated freeways; ignited at least one hundred fires as it ruptured gas pipelines; and disrupted water supply systems. As a consequence, 57 people died, another 1,500 were seriously injured, and 22,000 were left homeless. Over 3,000 buildings, most of which were residential structures, were declared unsafe for reentry due to earthquake damage. Los Angeles, a city which has extensively prepared itself for earthquakes, found that it had experienced the most destructive event since the 1906 San Francisco earthquake. Direct economic losses are estimated currently at over $20 billion.

This reconnaissance report provides a performance analysis of gas transmission lines, both during this earthquake and during previous earthquakes, in Southern California.

A detailed and systematic review of the seismic performance of gas transmission lines prior to the 1994 Northridge earthquake shows that all repairs in pipelines affected by traveling ground waves occurred in areas which experienced seismic intensities of MMI ≥ VIII. A review of gas transmission line performance during the 1994 Northridge earthquake discloses a similar pattern of seismic response. Approximately 91% of all pipeline damage caused by traveling ground waves in the 1994 event occurred in areas with MMI ≥ VIII. The earthquake-related damage has been predominantly in the form of ruptures at oxy-acetylene girth welds. The potential for damage in such welds appears to increase considerably for seismic intensities equal to and greater than MM VIII.

The type of pipeline most vulnerable to earthquake effects is the pre-WWII oxy-acetylene welded pipeline. Eighty-two percent of all earthquake-related repairs were caused by traveling ground wave effects in oxy-acetylene girth welded lines. The preponderant form of damage was rupture at the oxy-acetylene welds, which often are characterized by defects such as poor root penetration, lack of good

fusion, and overlapping and undercutting at the toe. The worst performers among the oxy-acetylene welded lines have been those constructed before 1930, some of which have experienced damage at a relatively high rate of over 1 repair/km (1.61 repairs/mi). Oxy-acetylene welding for major transmission lines appears to have been discontinued by SoCalGas after 1931.

In contrast to oxy-acetylene welded piping, pre-WWII pipelines with electric arc welds have fared much better when influenced by traveling ground waves. Damage under these conditions accounts for only 2.7% of the total repairs, which is 30 times less than the traveling ground wave damage in oxy-acetylene welded lines. Prior to WWII, welding practices often involved the use of unshielded electric arc techniques, which exposed the molten weld directly to the atmosphere.

Damage from permanent ground deformation associated with surface faulting, liquefaction-induced lateral spread, and landslides represents only 9.3% of the total repairs. This relatively low portion is associated with the relatively small percentage of surface area influenced by ground failure during an earthquake. Damage from permanent ground deformation can nonetheless be severe, resulting in some of the most conspicuous damage during a seismic event.

Post-WWII electric arc welded pipelines in good repair have never experienced a break or leak as a result of either traveling ground waves or permanent ground deformation during a southern California earthquake. The lack of damage to post-WWII electric arc welded pipelines does not mean they are immune to permanent ground deformation. On the contrary, there is substantial experience with modern pipeline failures in areas of severe landslides. The repair record shows that modern electric arc welded gas pipelines in good repair are the most resistant type of piping, vulnerable only to very large and abrupt ground displacement, and generally highly resistant to traveling ground wave effects and moderate amounts of permanent deformation.

This report is one of three NCEER reports resulting from reconnaissance activities following the Northridge, California earthquake. The other two reports are **The Northridge, California Earthquake of January 17, 1994: General Reconnaissance Report** and **The Northridge, California Earthquake January 17, 1994: Performance of Highway Bridges**.

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INTRODUCTION

The natural gas system in the Los Angeles metropolitan area is owned and operated by the Southern California Gas Company (SoCalGas). It is the largest U.S. gas system in terms of customers, with approximately 4.6 million metered services. According to company statistics for 1993, there are 6,123 km (3,803 mi.) of steel transmission pipelines and 43,162 km (26,809 mi.) and 24,045 km (14,935 mi.) of steel and plastic distribution mains, respectively. The transmission pipelines are predominantly 200 to 900 mm (8 to 36 in.) in diameter and are operated at pressures generally exceeding 1 MPa (150 psi). The distribution system is composed of pipelines predominantly 50 to 300 mm (2 to 12 in.) in diameter, limited to pressures of 0.42 MPa (60 psi) or less. The plastic piping is made of either medium or high density polyethylene. SoCalGas identifies an additional category of pipeline, referred to as distribution supply line, which is predominantly 50 to 300 mm (2 to 12 in.) in diameter and is operated typically in the range from 0.7 to 2.8 MPa (100 to 400 psi).

In this report, transmission and distribution pipelines are defined in accordance with the Federal Code of Regulations [Office of the Federal Register, 1990] and General Order No. 112-D pertaining to the State of California [Public Utilities Commission (PUC) of the State of California, 1988]. In essence, a transmission line transports gas from a gathering line or storage facility to a distribution center or storage facility, and operates at a hoop stress of 20% or more of the specified minimum yield stress (SMYS) of the pipe steel. A distribution line means a pipeline other than a transmission or gathering line. Distribution supply lines may be classified as transmission or distribution lines, depending on hoop stress level and function.

The pipeline system exists in an area of high seismic activity. Since 1933, there have been at least 11 major earthquakes of local magnitude (M_L) 5.8 or larger with epicenters inside the region of the gas transmission system. Serious earthquakes affecting areas of southern California serviced by natural gas pipelines include the 1933 Long Beach, 1952 and 1954 Kern County, 1971 San Fernando, 1979 Imperial Valley, 1986 North Palm Springs, 1987 Whittier Narrows, 1991 Sierra

Madre, 1992 Landers, 1992 Big Bear, and 1994 Northridge earthquakes.

Given the importance of natural gas as an energy source and the public safety concerns associated with the distribution of combustible substances, it is useful to review the actual performance of a gas delivery system under conditions of unusually severe load. A major earthquake often is accompanied by pipeline loadings which exceed those normally encountered in operation, thus providing information about the limits of component performance and the overall system response to multiple damages. This information is not only relevant to areas of high seismic activity, but to all areas in which infrastructure management requires an understanding of complex network performance and the outcomes of various damage scenarios.

Earthquake magnitudes are reported herein on the basis of published information in terms of local or surface wave magnitudes (M_L or M_s, respectively), with surface wave values given for magnitudes exceeding 6.5. It should be recognized that small adjustments in some originally reported magnitudes have been proposed on the basis of a recent evaluation of earthquake records for southern California [Hutton and Jones, 1993]. For the earthquakes covered in this work, the newly proposed adjustments result in magnitudes which are within 3% of those given in the conventional published sources.

The report is organized into four sections, of which the first provides background and introductory information. The second section summarizes the performance of high pressure gas pipelines in 10 southern California earthquakes. The statistics of pipeline damage are used to assess relative risk associated with pipelines of different age when subject to traveling ground waves or permanent ground deformation. The third section covers transmission pipeline performance as a result of the 1994 Northridge earthquake The statistics of pipeline repair are compared with those of previous earthquakes. In the fourth section, an overall evaluation of performance is given, and lessons learned from the earthquake response are discussed.

SECTION 2

PERFORMANCE DURING PREVIOUS EARTHQUAKES

This section provides a review of gas transmission and supply line performance during past earthquakes. Major earthquakes which have occurred in the SoCalGas operating area are summarized, and the earthquakes which affected transmission and/or supply line operation are identified. Case histories of pipeline performance during severe earthquakes are presented. Statistics pertaining to pipeline response and pipe characteristics are summarized and used to show important trends in pipeline behavior.

2.1 Summary of Major Earthquakes

Table 2-I summarizes information pertaining to ten of the most severe earthquakes which have occurred in southern California since 1933. The table provides data on the earthquake magnitude and maximum intensity, epicentral location, portion of pipeline network subjected to strongest shaking, and general observations about gas transmission and supply line response. The 1940 Imperial Valley earthquake is not included in the table because this area was not serviced with natural gas pipelines at the time of the earthquake.

No damage or disruption of transmission and supply lines were experienced in six of the earthquakes. In some of these cases, the earthquake epicenter and location of surface faulting were relatively close to transmission pipelines. For example, the epicenter of the 1986 North Palm Springs earthquake was approximately 5 km (3 mi.) from Lines 2000, 2001, and 5000, which are post-WWII lines of 750 to 900 mm (30 to 36 in.) diameter. In addition, surface faulting caused by the 1992 Landers earthquake has been traced to within tens of meters of a 150-mm- (6-in.)-diameter line conveying gas to Yucca Valley and Joshua Tree and a similar distance from Line 4000, a post-WWII 900-mm- (36-in.)-diameter pipeline.

Four earthquakes resulted in significant damage to the gas pipeline system. They are the 1933 Long Beach, 1952 and 1954 Kern County, and 1971 San Fernando earthquakes. Although the 1979 Imperial Valley earthquake did not damage any gas transmission lines, three lines were crossed by surface ruptures along the Imperial fault and excavated for observation and stress relief. Case histories

TABLE 2-I. Summary of Major Earthquakes in the Area of the Southern California Gas System

Earthquake	Magnitude[1]/ Intensity[2]	Location of Epicenter	Area Most Severely Affected	Gas Pipeline Performance	Selected References
1933 Long Beach	$M_L = 6.3$ MM VIII - IX	5.6 km (3.5 mi.) southwest of Newport Beach	Long Beach, Compton, and shore areas from Manhattan to Laguna Beach	Extensive damage to pipelines of Long Beach Municipal Gas Department, particularly areas of liquefaction	Wood [1933] Bryant [1934] Hoff [1934]
1952; 1954 Kern County	$M_s = 7.7$ MM VIII - X	40 km (25 mi.) south of Bakersfield near Wheeler Ridge	Area of approximately 10,000 km^2 (4000 mi.^{2}) south of Bakersfield	Damage to several transmission lines within 10 to 25 km (6 to 16 mi.) of Wheeler Ridge	Oakeshott [1955] Newby [1954] Steinbrugge and Moran [1954]
1971 San Fernando	$M_L = 6.4$ MM VIII - X	13 km (8 mi.) northeast of San Fernando	Area of approximately 520 km^2 (204 mi.^{2}) around San Fernando	Serious damage to transmission and supply lines and disruption of service in San Fernando and Sylmar	Southern California Gas Co. [1973] O'Rourke, et al. [1992]
1979 Imperial Valley	$M_s = 6.6$ MM VI - VII	3 km (1.9 mi.) south of U.S.-Mexico border and 10 km (6.2 mi.) from Mexicali	Imperial Valley from Brawley to Calexico and Holtville	No damage to transmission lines, although three transmission lines were crossed by surface ruptures along the Imperial fault. The lines were excavated for inspection and stress relief	Dobry, et al. [1992] McNorgan [1989]
1986 North Palm Springs	$M_L = 5.9$ MM VII	16 km (10 mi.) northwest of North Palm Springs	Area of approximately 250 km^2 (9.6 mi.^{2}) centered on epicenter	No damage or disruption reported. Epicenter was 8 km (5 mi.) from three 750- to 900-mm (30- to 36-in.) transmission lines	EERI [1986]
1987 Whittier Narrows	$M_L = 5.9$ MM VIII	5 km (3 mi.) east of Rosemead	Crescent-shape area of approximately 500 km^2 with MM VII - VIII centered on Monterey Park	No damage to transmission and supply lines	Schiff [1988] Leyendecker, et al. [1988] Jones and Hankson [1988]

TABLE 2-I. Summary of Major Earthquakes in the Area of the Southern California Gas System (completed)

Earthquake	Magnitude[1]/ Intensity[2]	Location of Epicenter	Area Most Severely Affected	Gas Pipeline Performance	Selected References
1991 Sierra Madre	$M_L = 5.8$ MM VII	20 km (12 mi.) northeast of Pasadena between Cogswell Reservoir and Mt. Wilson	Area including Pasadena, Sierra Madre, Monrovia, and Arcadia	No damage to transmission and supply lines	EERI [1991]
1992 Landers and 1992 Big Bear	$M_s = 7.5$ MM VIII - IX and $M_s = 6.5$ MM VII	Centered between Landers and Yucca Valley	Area including Landers, Joshua Tree, Yucca Valley, and Big Bear Lake	No damage to transmission lines; 900-mm (36-in.) and 150-mm (6-in.) transmission lines were located just north and south, respectively, of the main surface faulting	EERI [1992]

[1] Magnitude reported as M_L = local magnitude and M_s = surface wave magnitude
[2] Maximum Modified Mercalli Intensity or range in intensities as reported or inferred from descriptions of damage

of these earthquakes and associated pipeline response are provided in the next several sections.

2.2 1933 Long Beach Earthquake

2.2.1 General Earthquake Characteristics

The Long Beach earthquake occurred on March 10, 1933 at 5:54 p.m. PST. A local magnitude of 6.3 has been assigned to the earthquake [Barrows, 1973]. Strong ground shaking was reported to have lasted from 5 to 15 seconds [Wood, 1933], with considerable variation in duration experienced as a function of location. The earthquake was felt over an area of 260,000 km^2 (100,000 $mi.^2$). Maximum seismic intensities were reported as MM VII to VIII, with a few isolated areas of MM IX [Barrows, 1973]. Damage consistent with MM VII to VIII was produced in an area roughly bounded by an elliptical curve through Manhattan Beach, Inglewood, Norwalk, Fullerton, Santa Ana, and Laguna Beach, with the greatest concentration of damage being in and near Compton and Long Beach [Wood, 1933]. The earthquake originated on the Newport-Inglewood fault, which is a zone of folds and ruptures comprising a northwesterly trending belt of dome-shaped hills from Newport Mesa in Orange County to the Baldwin and Cheviot Hills north of Culver City in Los Angeles County [Barrows, 1973]. The epicenter was located about 5.6 km (3.5 mi.) southwest (offshore) of Newport Beach, California at geographical coordinates 33° 34.5'N latitude, 117° 59'W longitude. The focal depth of the earthquake was 9.7 km (6 mi.) [Barrows, 1973].

2.2.2 Liquefaction, Landslides, and Surface Faulting

Liquefaction was reported in areas of saturated artificial fill and loose alluvial deposits. Considerable damage occurred in parts of Long Beach, Compton, Willowbrook, Lynwood, Southgate, and Huntington Park, and was particularly severe at locations which were formerly marshy along Compton Creek and the previous courses of the Los Angeles River [Wood, 1933]. Numerous sand boils and mud volcanoes were observed in the area west of Santa Ana and north and northwest of Newport and Huntington Beach, as well as in the vicinity of Compton. Oakeshott [1973] noted that fracturing and dislocation of streets and curbs were extensive in the saturated lowland sediments of the Compton basin. Wood [1933] reported:

> "Along the shore between Long Beach and Newport Beach, and in a few localities nearby a short distance inland, road fills across marshy

> land, and similar earth construction resting on wet sand or mud, settled, shook apart, or moved laterally, causing considerable damage to the concrete highway surfaces, and to the approaches to highway bridges, which, being better founded, were less affected. Analogous phenomena were observed where piers and landings adjoin the shore. In a few places elsewhere the roadway was buckled."

Barrows [1974] pointed out that the greatest damage to any of the bridges affected by the earthquake was sustained by the Anaheim Bridge. The overall length of the bridge was reduced about 225 mm (9 in.), with the most prominent contribution to the shortening being the shifting of the south end of the bridge to the north.

A few small landslides and falls of earth and loose rock material were observed at artificial embankments, road cuttings, and steep cliffs. According to Wood [1933], effects of this kind were too few and small to be characteristic of the shock. No surface faulting was detected.

2.2.3 Locations of Liquefaction and Pipeline Damage

Figure 2-1 shows the locations of main line repairs of water, gas, and oil lines as plotted by Hoff [1934], and superimposed on a map of liquefaction susceptibility prepared by Tinsley, et al. [1985]. The liquefaction susceptibility map for the area west of the San Gabriel River was based on groundwater data from Mendenhall [1905a;b] and Conkling [1927]. These sources of groundwater data refer to water levels which existed in the years prior to the 1933 earthquake. Subsequent development in the Los Angeles area has resulted in the lowering of groundwater levels to elevations significantly below those reported by Mendenhall and Conkling. Accordingly, Tinsley, et al. also have prepared a liquefaction susceptibility map that represents the more recent groundwater data. The liquefaction susceptibility map for the area east of the San Gabriel River, also prepared by Tinsley, et al., was based on groundwater data from Sprotte, et al. [1980], and reflects more current groundwater elevations. The shaded areas in Figure 2-1 are areas Tinsley refers to as having "very high" and "high" susceptibility to liquefaction on the basis of geologic age, type of sedimentary deposits, and groundwater depth. Youngest Holocene deposits of fluvial origin are most susceptible.

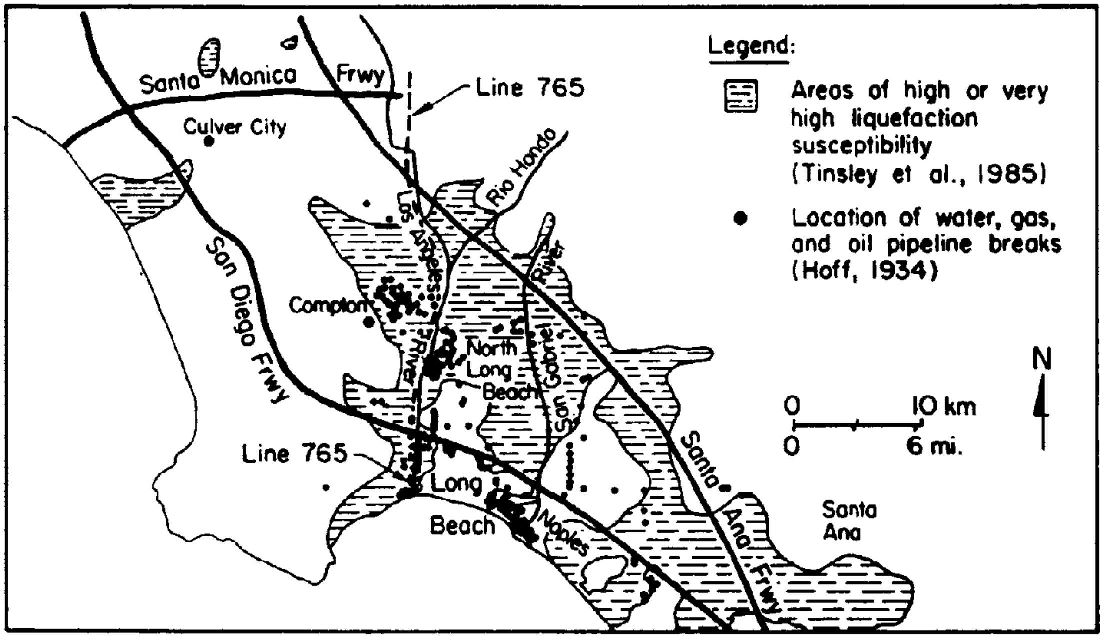


FIGURE 2-1. **Pipeline Damage Caused by the 1933 Long Beach Earthquake [adapted from Hoff, 1934]**

As shown in Figure 2-1, the areas with the greatest number of repairs were the mouth of the San Gabriel River (Naples and North Seal Beach) and the North Long Beach/Compton/Clearwater area. About 85% of all plotted repairs fall within these areas of high and very high liquefaction susceptibility.

The Naples area is located at the mouth of the San Gabriel River and, before being settled, was a swampy lowland. The development in this area was entirely on artificial fill or "made ground." At the time of the Long Beach earthquake, this area was characterized by high groundwater, depths less than 1.3 m (4 ft), and silt, loam, and sand deposits. It is in this area where more than one-third of the pipeline failures attributed to the earthquake occurred.

The North Long Beach/Compton/Clearwater area is located near a previous confluence of the Rio Hondo River, Compton Creek, and the Los Angeles River. The high concentration of breaks near North Long Beach (see Figure 2-1) was adjacent to the Los Angeles River and was located on part of the floodplain. This area is characterized by deep alluvial deposits and, at the time of the earthquake, also was characterized by shallow groundwater levels.

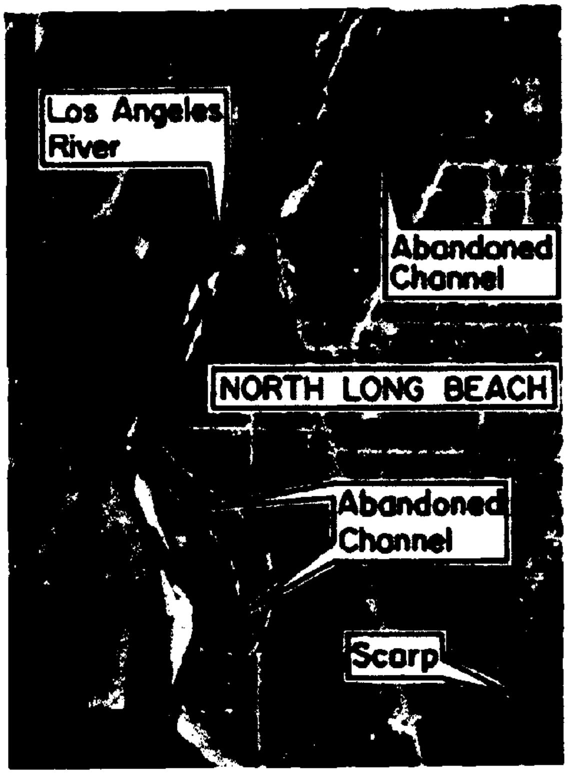
Figure 2-2 shows a portion of a 1928 aerial photo of North Long Beach. Several abandoned river channels are indicated by arrows. As discussed in the section of this work on improvements in pipeline replacement procedures, river channel deposits have been shown in previous earthquakes to be susceptible to liquefaction. In the photograph, river channels can be traced into partially developed portions of North Long Beach, thereby implying the presence of sediments which have the potential for liquefaction when saturated. A scarp also is indicated in the photograph, which was cut by the Los Angeles River. The entire area northwest of the scarp, at one time, has been either channel, bar, or overbank. The liquefaction and high concentration of pipeline damage reported in the North Long Beach area demonstrates the close correspondence between this type of depositional environment and the potential for buried piping problems during an earthquake.

2.2.4 Pipeline Performance

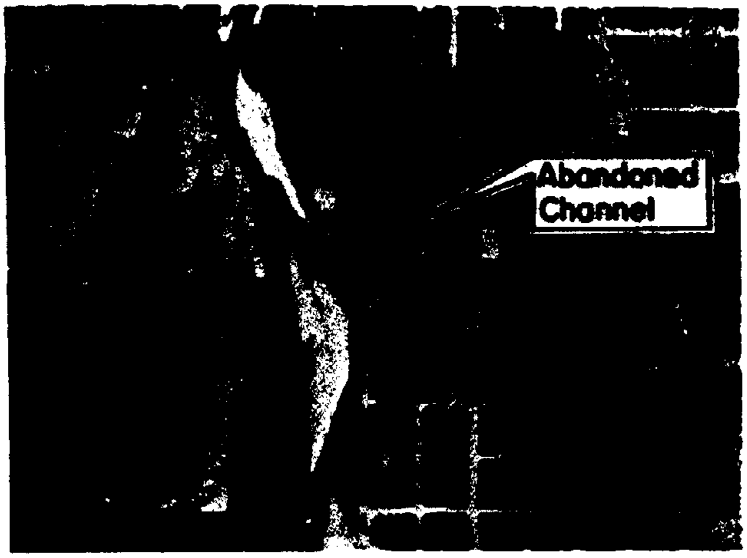
Pipeline damage caused by the 1933 Long Beach earthquake has been described by Bryant [1934] and Hoff [1934]. There were more than 500 main line breaks of water, gas, and oil lines in the areas of maximum seismic intensity [Hoff, 1934]. Within the City of Long Beach gas distribution system, there were a total of 119 main breaks, 91 of which were in the high pressure feeder mains [Bryant, 1934]. Approximately 40 km (25 mi.) of the pipeline network, referred to as the high pressure system, were composed of 200- to 500-mm- (8- to 20-in.)-diameter feeder mains operated at 0.21 MPa (30 psi). There were 620 km (385 mi.) of 50- to 300-mm- (2- to 12-in.)-diameter low pressure pipelines operated at between 0.02 and 0.03 MPa (3 and 5 psi).

The National Board of Fire Underwriters [1933] provided the following description of Southern California Gas Company pipeline response:

> "Five major and ten minor breaks were experienced in the company's welded steel transmission mains. The company's private telephone system connecting all parts of the gas system remained in service.



a) View of North Long Beach



b) Close-up

FIGURE 2-2. Aerial View of Channel Deposits in North Long Beach from 1928 Photograph (Fairchild Aerial Photography Collection at Whittier College, Flt. C-300, M:154)

> All mains south of Manchester Avenue in Los Angeles were shut off soon after the first shock. A large crew of men was kept busy about five days following the earthquake restoring gas service."

It is not known which SoCalGas transmission lines experienced difficulties, nor where the breaks referred to by the National Board of Fire Underwriters were located. A detailed investigation, however, was performed for Line 765, the approximate location of which is shown in the figure.

Line 765 was constructed in 1931. It was 650 mm (26 in.) in diameter, with 6.4 mm (0.25 in.) wall thickness. It was composed of Grade A and B steel with electric arc welded, belled end pipe according to the same procedures used for portions of Line 85, which are described in the forthcoming sections on the 1952 and 1954 Kern County and 1971 San Fernando earthquakes. It had been operated at an MAOP of 1.0 MPa (150 psi) just before it was removed from service in 1992. Although the pipeline was located in the region of maximum seismic intensity, including locations of known liquefaction adjacent to the Los Angeles River, there are no records of pipeline damage or repair to this line dating from the time of the 1933 earthquake. The work orders associated with this line were collected and reviewed by SoCalGas personnel. A detailed review of existing records indicate that no repairs were reported on Line 765 from 1931 to 1946.

A study of the main repairs in the distribution systems operated by the Long Beach Municipal Gas Department reveals that ground type and weld quality were the factors which contributed most to failure. Every failure discovered in the high pressure system occurred at a welded joint, and more than 50 of the 91 breaks were in artificially-filled areas. Forty-six breaks were discovered in the large diameter mains [460 to 510 mm (18 to 20 in.)] that supplied the Harbor District of Long Beach, which was an area where artificial fills were predominant [Bryant, 1934]. Repair crews reported that the original welds lacked proper penetration and proper bond with the pipe body [Bryant, 1934].

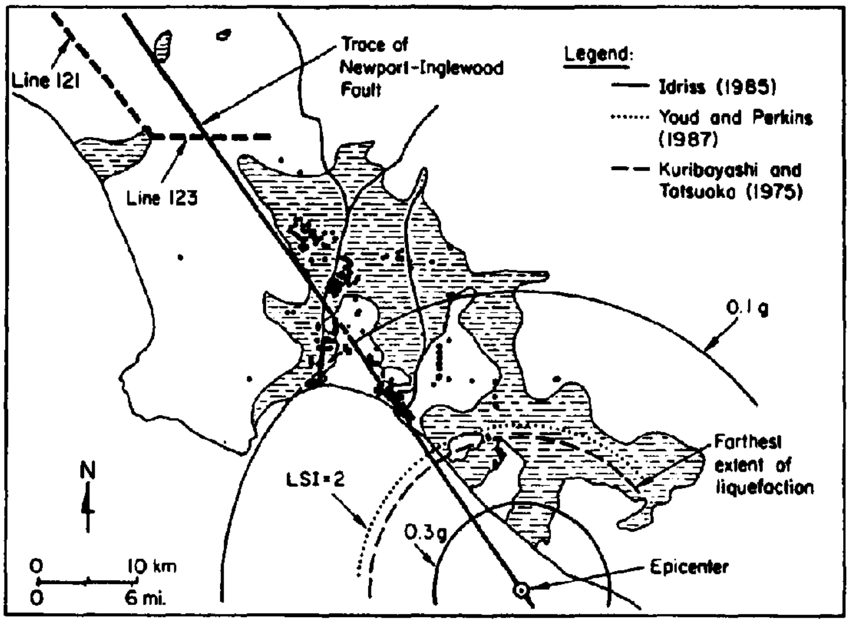
Other damage to the gas system included about 1,650 service risers broken off below ground at the elbow, and about 1,000 services sheared off at their connections to the mains. Over 90% of the main connection failures were located in the loose, artificially-filled ground in the Naples area [Bryant, 1934]. The majority of the services in this area had screw-type fittings and were laid in shallow ditches.

2.2.5 Estimated Peak Acceleration and Liquefaction Potential

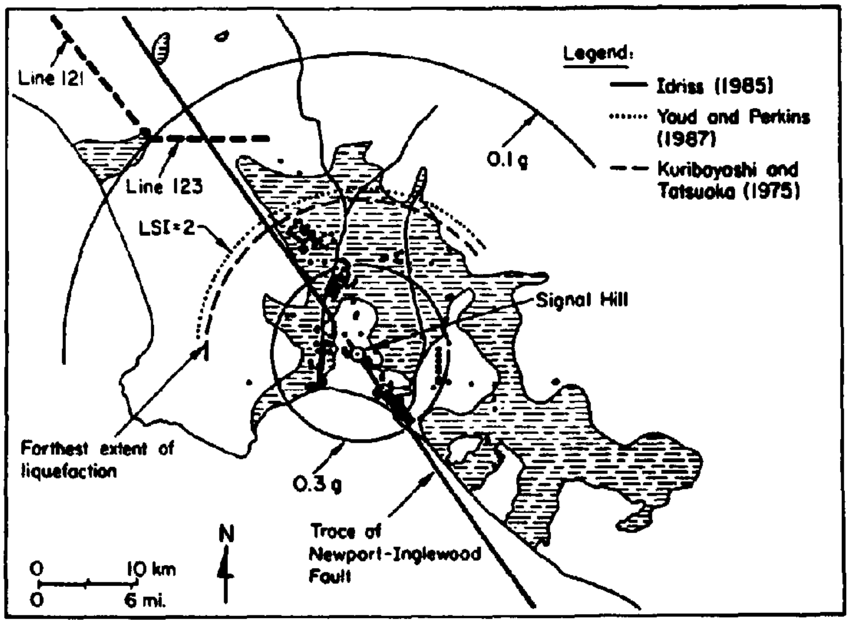
It is of interest to review the pipeline damage resulting from the 1933 earthquake in light of the estimated peak ground accelerations and the potential for soil liquefaction derived from empirical prediction procedures. Attenuation relationships developed by Idriss [1985] were used to estimate peak ground accelerations, and relationships proposed by Kuribayashi and Tatsuoka [1975] and Youd and Perkins [1987] were used to estimate the maximum areal extent of soil liquefaction.

Kuribayashi and Tatsuoka [1975] established for various Japanese earthquakes a linear relationship between earthquake magnitude and the logarithm of the maximum epicentral distance at which liquefaction was observed. Their relationship provides a remarkably good average trend for a much larger database developed by Ambraseys [1988] for worldwide earthquakes. The Youd and Perkins relationship links a parameter, known as Liquefaction Severity Index (LSI), with the moment magnitude of an earthquake and closest distance from the seismic source. The LSI is the general maximum horizontal displacement, expressed in inches, associated with liquefaction-induced lateral spreads on active floodplains, deltas, or other areas of gently-sloping late Holocene fluvial deposits. An advantage of using LSI is that it provides an estimate of the magnitude of potential lateral displacement, and thus can be used to judge liquefaction effects on buried gas pipelines. Both the moment magnitude, M_w, and surface wave magnitude, M_s, were taken as 6.2 in using the attenuation and liquefaction relationships. These values are consistent with the interrelationships among magnitude scales described by Hanks and Kanamori [1979].

Figure 2-3a shows circular contours of equal peak ground acceleration, LSI = 2, and maximum distances to liquefaction as determined from the empirical relationships described above, all with reference to the coordinates generally taken as the actual epicenter of the earthquake [Wood, 1933; Richter, 1958]. Benioff [1938] has pointed out that these coordinates, in fact, represent the location at which fault rupture originated and then propagated northward. Benioff



a) Centered on Epicenter



b) Centered on Northern Limit of Fault Rupture

FIGURE 2-3. Contours of Peak Ground Acceleration, LSI = 2, and Maximum Distance to Liquefaction concluded that faulting extended from the generally assigned epicenter a distance of 27 km (17 mi.) to the vicinity of Signal Hill. The zone surrounding the fault trace from the origin of rupture off Newport Beach to Signal Hill is the area within which most aftershocks occurred [Toppozada, et al., 1989].

The radial distances centered on the coordinates generally associated with the main shock result in circular contours of equal peak acceleration and farthest extent of liquefaction, which are inconsistent with the pattern of pipeline damage. The preponderance of liquefaction effects and pipeline damage fall well beyond the limits of LSI = 2 and maximum epicentral distance derived from the Kuribayashi and Tatsuoka relationship. Moreover, the locations of concentrated liquefaction and pipeline damage at North Long Beach and Compton are outside the radial distance for 0.1 g peak acceleration.

Figure 2-3b provides an alternative plot in which the seismic source is chosen as the northern limit of surface faulting near Signal Hill. The resulting contours of equal peak acceleration, LSI = 2, and farthest extent of liquefaction are consistent with the locations of pipeline damage and reported incidents of liquefaction. The pipeline damage apparently provides supplemental evidence regarding the direction and dispersion of seismic energy. Taking the seismic source as the northern limit of faulting results in a damage scenario which is conformable with the peak accelerations and liquefaction occurrences extrapolated from empirical data.

2.3 1952 and 1954 Kern County Earthquakes

2.3.1 General Earthquake Characteristics

The principal Kern County earthquake occurred on July 21, 1952 at 4:52 a.m. PDT. It has been assigned a surface wave magnitude of 7.7 [Hanks and Kanamori, 1979] and was felt over an area of 415,000 km^2 (160,000 mi.^{2}) [Steinbrugge and Moran, 1954], including most of southern and central California, southwestern Nevada, and western Arizona. Seismic intensities greater than or equal to MM VIII have been assigned to an area of approximately 10,000 km^2 (4,000 mi.^{2}) in the vicinity of Bakersfield, CA [Neumann and Cloud, 1955]. Richter [1958] reported that MM IX "was manifested over much of the area near the fault, and effects due to shaking assignable to X (such as large fissures and damage to underground pipes) were developed at many localities." The epicenter was located about 44 km (27 mi.) south-southeast of Bakersfield near Wheeler Ridge [Degenkolb, 1955] at geographical coordinates 35° 00'N latitude, 119° 02'W longitude. The focal depth of the earthquake was about 16 km (10 mi.) [Oakeshott, 1955].

The causative fault of the 1952 Kern County earthquake is the White Wolf fault. This fault is at least 52 km (32 mi.) in length [Buwalda and St. Amand, 1955], trends N 43° E, dips 20 degrees [Stein and Thatcher, 1981], and extends from west of Wheeler Ridge to the vicinity of Harper's Peak [Buwalda and St. Amand, 1955]. According to Oakeshott [1955], the fault rupture was a left lateral reverse movement. The primary movement was reverse, with lesser lateral displacement.

2.3.2 Liquefaction, Landslides, and Surface Faulting

There is little evidence of liquefaction associated with the earthquake. Steinbrugge and Moran [1954] reported that minor ground slumps, subsidence, and horizontal offsets in cotton rows were observed. These deformations were referred to as "earth lurching," and involved horizontal displacements of several centimeters to a half meter. Warne [1955] observed that the ground fracture patterns occurred in looped and hooked patterns, and often were associated with sloughs, which are undrained marshy depressions. Although the occurrence of these deformations in irrigated fields and saturated depressions implies some relationship with liquefaction, there were no specific investigations undertaken to substantiate that liquefaction contributed to the movements.

Large numbers of landslides occurred as a result of the main 1952 Kern County earthquake and its aftershocks. Hundreds of large and small landslides occurred on the day of the main shock. The slides were most numerous near the White Wolf fault, but many occurred as far away as 80 to 100 km (50 to 60 mi.) [Buwalda and St. Amand, 1955]. Several types of slides resulted, including rock falls, rock slides, loose and shallow soil flows, and massive landslides. The hummocky topography in the area along the northwest face of Bear Mountain is typical of landslide areas. The White Wolf fault zone, an active reverse fault that has created a high scarp, was described by Buwalda and St. Amand as a "very favorable zone for landsliding on a large scale."

The White Wolf fault is known to extend for 27 km (17 mi.) along the northwest slope of Bear Mountain to Comanche Point, and has been projected across the San Joaquin Valley to Wheeler Ridge for a total length of about 50 km (32 mi.) [Dibblee, 1955]. Surface ruptures were mapped over a distance of approximately 35 to 39 km (22 to 24 mi.) along the northeastern sector of the fault [Buwalda and St. Amand, 1955]. Richter [1958] reported that the principal expression of surface faulting was in the form of a 1.2-m- (4-ft)-high surface scarp on the west flank of Bear Mountain, which was downthrown to the west. The faulting did not occur as a clean rupture along the trace, but developed as a series of ruptures with different trends and diverse displacements. The fault zone crossed the Southern Pacific railroad tracks in three places, and three tunnels at two of these crossings were severely damaged.

2.3.3 Pipeline Performance

Gas pipeline damage caused by the 1952 and 1954 Kern County earthquakes has been described by Newby [1954] and Lind [1954]. As a result of this earthquake and a subsequent smaller Kern County earthquake in January, 1954, there were ten incidents of damage at welded transmission line joints and two incidents of leaks at locations of external pipeline corrosion. Nine of the damaged welds were oxy-acetylene, and one was at an electric-welded band positioned at the location of an original oxy-acetylene weld. Figure 2-4 shows the locations of the damage relative to the epicenters of the main shock and the January 12, 1954 earthquake, which had a Richter magnitude of 5.9. Newby [1954] described the damage with reference to the figure as follows:

> "It developed that the 12-inch acetylene welded line installed in 1921 had broken welds at the three locations marked 1 on Figure No. 1 (Figure 2-4). The ends of the pipe were from 1/2 to 2 inches apart at the different breaks. The 12-inch line that had been reconditioned in 1932, and electric-welded using chill rings, failed at location marked 2. This weld evidently failed from compression and then from tension....
>
> Pit hole leaks popped out on a 22-inch line near Taft and on an 18-inch line at Wheeler Ridge, locations 3 (Figure 2-4). These leaks were from external corrosion. Location 4 shows where 275 feet of 18-inch line was uncovered to relieve strain from the 1952 quake.
>
> We experienced another of our many quakes on January 12, 1954 that was not considered serious. However, it evidently centered near our two 12-inch lines in the Maricopa Flat area.
>
> As shown on Figure 2-4, this quake parted the acetylene-welded line

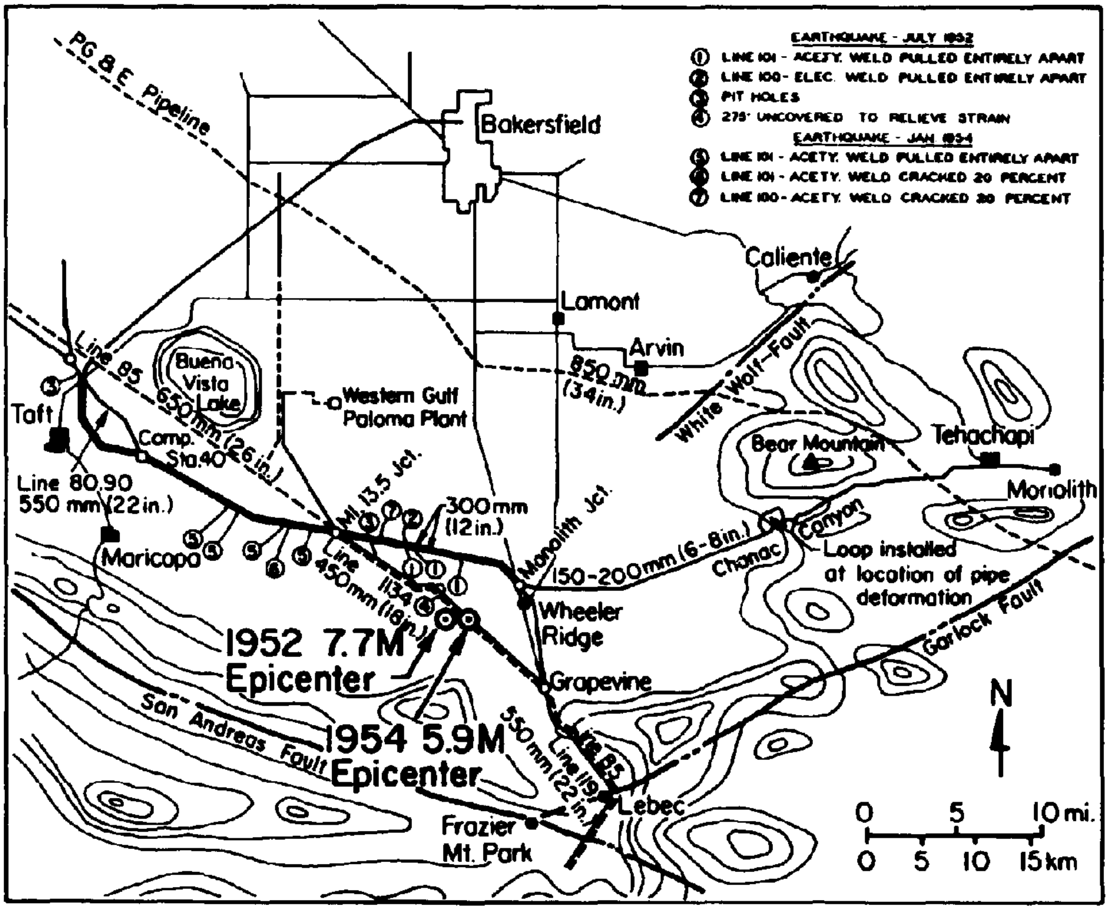


FIGURE 2-4. Gas Pipeline Damage Caused by the 1952 and 1954 Kern County Earthquakes [adapted from Newby, 1954]

> at four welds at locations marked 5, and cracked an acetylene weld 20% at location marked 6, and on the electric-welded line, a lone acetylene weld cracked 20% at location 7."

Newby also reported that the 150-mm- (6-in.)-diameter line providing gas to Tehachapi was deformed upward from the ground at two locations along a steep hillside where ground ruptures were observed. The line was intact. The line had been installed in 1926 with oxy-acetylene welds. A supplemental pipeline (referred to as a loop in Figure 2-4) was installed to provide a parallel emergency path. The original was kept in service without any repairs.

Company records indicate that Lines 100 and 101 were installed in 1913 and 1921, respectively. The wall thickness of each pipe is 6.4 mm (0.25 in.), and the grade of steel is unknown. Maximum and minimum operating pressures for these lines are 2.69 and 1.31 MPa (390 and 190 psi), respectively, with a maximum allowable operating pressure (MAOP) of 2.76 MPa (400 psi). Both pipelines were constructed with oxy-acetylene welds. Line 100 had been partially reconditioned in 1932 with electric-welded steel bands positioned at the locations of many original oxy-acetylene welds. Line 85 in the vicinity of the earthquake was installed in 1931 with a diameter of 650 mm (26 in.) and wall thickness of 6.4 mm (0.25 in.). The tensile strength of the steel is rated as 228 MPa (33 ksi) with an MAOP equal to 2.19 MPa (317 psi).

The section of Line 85 south of Grapevine was constructed originally with oxy-acetylene welds. In 1932, this section was partially reconditioned by reinforcing selected oxy-acetylene welds, especially those at angles and bends. The oxy-acetylene welds were reinforced with steel bands, plates, or by overlaying the original weld with an electric arc weld. A detailed review of appropriate pipeline strip maps indicates that approximately 30% of all initial welds were reinforced in this manner.

The section of Line 85 north of Grapevine was constructed originally with electric arc welds. The welding process differed from modern procedures for butt welded transmission pipelines, such as those specified in API Standard 1104 [American Petroleum Institute, 1987]. Archer [1931] has described the electric arc welding procedure as follows:

> "The ends of the joints were all of double bell type, using a heavy liner, or chill ring, which, after being tack-welded, fits inside the ends as they are brought together. The principal function of this liner is to provide for proper penetration of the electric weld, and to eliminate the danger of 'burning through' of the arc, thus avoiding the formation of slag or icicles protruding on the inside of the pipe."

Line 80.90 was constructed in 1930 with Grade B steel. It is 550 mm (22 in.)

in diameter, with wall thickness of 6.4 mm (0.25 in.). Company records do not indicate the type of welds. The line had an MAOP of 2.76 MPa (400 psi).

Line 119 runs parallel to Line 85 in the area affected by the earthquake. It was constructed in 1930 of pipe with 7.92-mm-(0.312-in.)-thick, Grade A steel wall, and 550 mm (22 in.) nominal diameter. Records of the type of girth welds could not be found.

Line 1134 was constructed in 1941. Its diameter varies from 450 to 500 mm (18 to 20 in.), and its MAOP is 25 MPa (360 psi). It was composed at the time of the earthquake of Grade B steel, with 6.4-mm- (0.25-in.)-thick wall and electric arc welds. Leaks from external corrosion were observed at Location 3 in Figure 2-4. Landslides along Wheeler Ridge caused an elbow to deform. Approximately 84 m (275 ft) of the line were uncovered to relieve strain along the northwest flank of Wheeler Ridge.

Lind [1954] described the earthquake performance of a 864-mm- (34-in.)-diameter transmission line owned by the Pacific Gas and Electric Company. The pipeline was of post-WWII vintage with 11-mm (0.43-in.) wall thickness, minimum transverse yield strength of 330 MPa (48 ksi), and minimum transverse ultimate strength of 448 MPa (65 ksi). The MAOP at the time of the earthquake was 5.5 MPa (790 psi).

As shown in the figure, this line crossed the White Wolf fault about 9.7 km (6 mi.) southeast of Arvin [Lind, 1954], about 30 km (19 mi.) from the epicenter. Estimations by Stein and Thatcher [1981] indicate that strike-slip movement near the point of crossing was 1.0 m (3.3 ft) and reverse slip was 0.40 m (1.3 ft). The pipeline crossed the fault at an angle with respect to the strike of approximately 100° and was covered by about 0.75 m (2.5 ft) of medium to dense material [Lind, 1954]. The pipe did not buckle, nor was it compressed sufficiently to cause shell wrinkling. Removal of cover during stress relief operations caused the pipe to lift as a beam a total of 720 mm (28 in.) over an uncovered length of 170 m (558 ft) [Lind, 1954].

Using the epicentral coordinates and the attenuation relationship proposed by Idriss [1985] for California earthquakes, it is possible to estimate the peak ground acceleration at locations of pipeline damage from both the 1952 main shock and 1954 aftershock. As shown in Figure 2-4, all locations of weld damage in 1952 were within 10 km (16 mi.) of the epicenter, and would have been subjected to between 0.5 and 0.6 g peak ground acceleration on the basis of the above attenuation relationship. All locations of weld damage in 1954 were between 10 and 24 km (16 and 39 mi.) of the epicenter, and are associated with peak ground accelerations of 0.11 to 0.23 g, as estimated by the same attenuation relationship. The damage in 1954, which was comparable to that in 1952, was triggered by an earthquake of much lower magnitude than the 1952 main shock, and apparently is associated with considerably lower levels of peak acceleration. It is not clear why comparable levels of pipeline damage resulted from such significantly different earthquakes. There were ten aftershocks within one month of the main 1952 earthquake, with magnitudes ranging from 5.5 to 6.4 [Richter, 1958]. There were no additional aftershocks exceeding a magnitude of 5.0 until the January, 1954 event. The seismic activity following the main shock may have contributed to the weakening of certain joints on Lines 100 and 101, thereby increasing their vulnerability to the 1954 earthquake.

2.4 1971 San Fernando Earthquake

2.4.1 General Earthquake Characteristics

The 1971 San Fernando earthquake occurred on February 9, 1971 at 6:01 a.m. PST. It has been assigned a local magnitude 6.4, and affected an area of 220,000 km^2 (85,000 $mi.^2$) including southern California, western Arizona, and southwestern Nevada [Coffman, et al., 1982]. Seismic intensities of MM VIII to XI were assigned to an area of approximately 530 km^2 (204 $mi.^2$) in the vicinity of San Fernando. An MMX was assigned to zones of large permanent ground deformation associated with surface faulting within the Sylmar section of the San Fernando fault and liquefaction-induced landslides and lateral spreads in the Lower and Upper San Fernando Dams. The epicenter was located about 13 km (8 mi.) north-northeast of San Fernando in the western San Gabriel mountains at geographical coordinates 34° 24'N latitude, 118° 23.7'W longitude. The focal depth of the earthquake was 8.4 ± 4 km (5.2 ± 2.5 mi.) [Bolt and Gopalakrishnan, 1975].

The strong motion record closest to the epicenter was acquired at Pacoima Dam, 8 km (5 mi.) south of the epicenter and 4 km (2.5 mi.) north of the surface faulting. The record from the main shock showed vertical accelerations of 0.72 g and horizontal accelerations of 1.25 g, the highest recorded at that time for an earthquake [Cloud and Hudson, 1975]. Another important source of strong motion data was the seismoscope, located about 17 km (10.5 mi.) south of the epicenter on the east abutment of the Lower San Fernando Dam. The seismoscope recording, its interpretation, and conversion to acceleration history are described by Scott [1973] and Seed, et al. [1975]. Allowing for the uncertainties involved in the seismoscope record interpretation, Scott suggested that peak accelerations of 0.55 to 0.6 g could be inferred from the record.

2.4.2 Liquefaction, Landslides, and Surface Faulting

Large ground deformations caused by the earthquake have received considerable attention in the technical literature, and have been described in detail in a case history study of the earthquake and its effects on buried lifeline facilities [O'Rourke, et al., 1992]. Only a brief summary of the large ground deformations triggered by the earthquake is given here, with the understanding that additional information may be obtained by reference to the above-mentioned case history.

Considerable ground deformation caused by liquefaction was observed near the Upper Van Norman Reservoir. On the west side of the reservoir, cracks extended from the Van Gough School to the west edge of the reservoir. Severe ground deformation occurred at the Joseph Jensen Filtration Plant, triggered by liquefaction of a layer of underlying loose alluvium [Dixon and Burke, 1973; Youd, 1973]. Aerial photo analyses have disclosed as much as 2 to 3 m (6 to 9 ft) of lateral soil movement along the western edge of the reservoir [O'Rourke, et al., 1992]. The area east of the Upper Van Norman Reservoir was subjected to large ground deformations as a result of the earthquake. Lateral spreading caused by soil liquefaction has been identified as the primary source of ground movement. The large ground deformations and associated soil conditions have been described in various published papers [e.g., Youd, 1971 and 1973; Fallgren and Smith, 1973 and 1975; Weber, 1975; O'Rourke and Tawfik, 1983].

Ground cracks caused by soil liquefaction also were seen around the tail race pond and near the San Fernando Powerhouse. Permanent ground movements resulting from soil liquefaction also were noted northeast and east of the Lower Van Norman Reservoir at Blucher Avenue [Lew, et al., 1971].

There were thousands of landslides in the hilly and mountainous terrain above San Fernando Valley [Morton, 1975], but for the most part, they occurred in relatively remote areas where there was little impact on lifeline facilities. A few landslides were significant and deserve some comment. Soil slumps occurred near the First Los Angeles Aqueduct, and a large landslide caused extensive damage to a 1,900-mm- (76-in.)-diameter welded steel pipeline conveying water as part of the Second Los Angeles Aqueduct [Subcommittee on Water and Sewerage Systems, 1973].

Five principal zones, or segments, of surface displacement have been identified along the San Fernando fault [Weber, 1975], extending from the Lower Van Norman Reservoir to Big Tujunga Wash. Offset measurements and descriptions of surface displacements have been reported by numerous investigators [e.g., U.S. Geological Survey Staff, 1971; Barrows, et al., 1973; Sharp, 1975; Weber, 1975]. The actual rupture surface was relatively complex. There was a marked thrust, or compressive, component of movement along the Tujunga segment, whereas the Mission Wells and Sylmar segments were characterized by smaller thrusts with larger vertical components of movement [Sharp, 1975]. All segments displayed prominent left lateral components of slip.

The 1-km- (0.62-mi.)-long Mission Wells segment of the fault dipped 60° north, with the northern block uplifted 250 mm (10 in.), thrusted 200 mm (8 in.) to the south, and left laterally displaced 30 mm (1.2 in.) [U.S. Geological Survey Staff, 1971; Weber, 1975]. In the central part of the 3-km- (1.9-mi.)-long Sylmar segment of the fault, displacements across the entire fault zone were composed of 1.9 m (6.2 ft) of left lateral slip, 1.4 m (4.6 ft) of vertical offset, and 0.6 m (2 ft) of thrust [U.S. Geological Survey Staff, 1971]. The largest individual ground ruptures showed displacements approximately one-half of the maximum displacements across the entire width of the zone. Most of the left lateral slip and thrust was concentrated along the southern 25- to 80-m- (82- to 262-ft)-wide section of the fault zone. North of this section, vertical offsets and extension fractures were the predominant forms of ground rupture [U.S. Geological Survey Staff, 1971].

2.4.3 Pipeline Performance

Gas transmission and supply line damage as a result of the San Fernando earthquake has been described by the Southern California Gas Company [1973], O'Rourke and Tawfik [1983], O'Rourke and McCaffrey [1984], and O'Rourke, et al. [1992]. Figure 2-5 shows a map adapted from the Southern California Gas Company [1973] on which are plotted the gas transmission and supply lines most significantly affected by the earthquake, locations of damage between San Fernando and just north of Clampitt Junction, and the approximate zones of permanent ground deformation associated with liquefaction adjacent to the Upper Van Norman Reservoir, as well as surface faulting along the Sylmar and Mission Wells segments of the San Fernando fault.

Substantial damage was sustained by Lines 1001 and 115. Line 1001 was a 300-mm- (12-in.)-diameter steel pipeline, constructed in 1925 with oxy-acetylene welds and operated at MAOP of 2.4 MPa (345 psi). The pipe wall thickness was 5.6 mm (0.22 in.) of unknown grade steel. Because of numerous breaks, predominantly at welds, over 8 km (5 mi.) of the line were abandoned. Line 115 was a 400-mm- (16-in.)-diameter steel pipeline of unknown grade, constructed in 1926 with oxy-acetylene welds. It had an MAOP of 1.4 MPa (205 psi) with a pipe wall thickness of 7.9 mm (0.312 in.). In the approximate 9.7-km- (6-mi.)-length of pipeline between Clampitt Junction and San Fernando, there were 52 breaks. Shell buckling of the pipeline occurred in the vicinity of its crossing of the Sylmar segment of the San Fernando fault [Southern California Gas Company, 1973].

Line 85 was a 650-mm- (26-in.)-diameter pipeline with the pipe wall 6.4 mm (0.25 in.) thick, SMYS of 228 MPa (33,000 psi), and was operated at MAOP of 1.7 MPa (250 psi). It was damaged at seven locations within the zone of lateral spreading along the east side of the Upper Van Norman Reservoir. The portion of the line within the lateral spread was constructed with electric arc welds applied at belled pipe ends, as described by Archer [1931] in Subsection 2.3.3 dealing with the 1952 and 1954 Kern County earthquakes. In Figure 2-5, the location marking the division between the electric arc and oxy-acetylene parts of Line 85 is shown.

North of the division, the pipeline was partially reconditioned, as explained

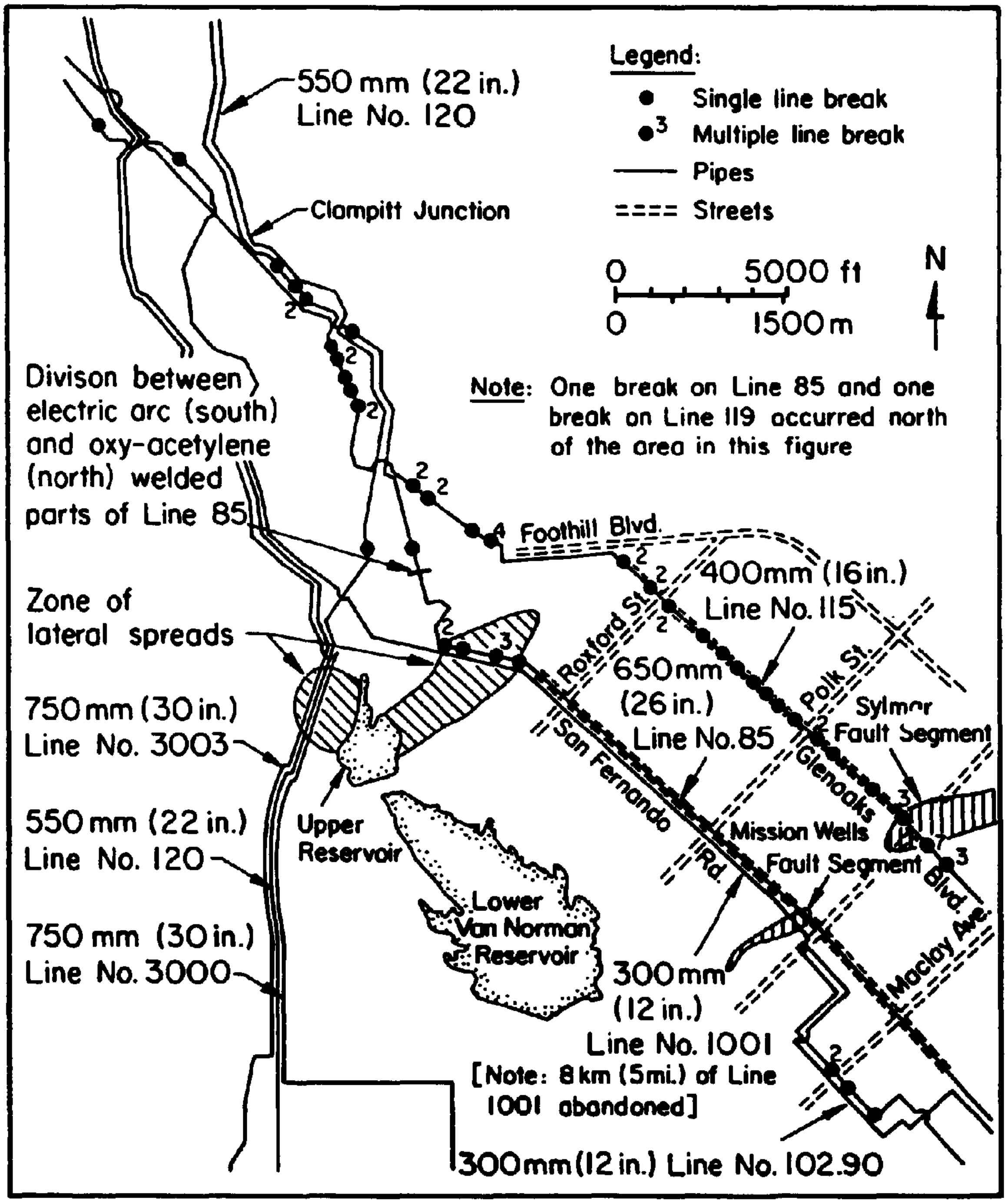


FIGURE 2-5. **Locations of Gas Pipeline Damage, Lateral Spreads, and Fault Segments Associated with the 1971 San Fernando Earthquake [adapted from Southern California Gas Company, 1973]**

in Subsection 2.3.3. The pipeline was damaged at three other locations north of the division, of which only two are shown in the figure. All damage north of the division was at original oxy-acetylene welds, and no repairs were made at joints in this area which were reinforced in 1932 with electric arc welding procedures. No difficulties were experienced where the line crossed the Mission Wells segment of the fault.

The utility corridor on the western side of the Upper Van Norman Reservoir was subjected to as much as 3 m (9 ft) of lateral deformation caused by liquefaction; soil movements were distributed primarily across a 400- to 500-m- (1,300- to 1,640-ft)-length of the corridor. Pipelines at this location were of modern construction. One 560-mm- (22-in.)-diameter (Line 120) and two 760-mm- (30-in.)-diameter (Lines 3000 and 3003) gas pipelines, each constructed in 1966 of X-52 steel, were not damaged. A more detailed description of the pipelines and soil displacement pattern is given by O'Rourke and Tawfik [1983] and O'Rourke, et al. [1992].

The locations of soil liquefaction and lateral spreads on both sides of the reservoir were in the toe areas of alluvial fans, deposited at the base of Grapevine, Weldon, and Bee Canyons. Small streams and conspicuous deposits of alluvium and debris can be seen at the base areas of these canyons in the 1929 aerial photographs of the region. The relatively high water table adjacent to the reservoir caused loose deposits of sand to be saturated, thereby creating an environment conducive to liquefaction. Ground surface gradients and base inclinations of soil deposits downslope toward the toes of the alluvial fans promoted a pattern of lateral ground deformation which was similarly directed. The extent of lateral spreading was confined to the width of the alluvial fan deposits, and thus can be bracketed by tracing the shapes of these landforms from aerial photographs.

Breaks at oxy-acetylene welds occurred in Line 102.90 just south of the Mission Wells segment of the San Fernando fault. This pipeline was constructed in 1920-21, with 300-mm- (12-in.)-diameter and 6.4-mm- (0.25-in.)-wall thickness of unknown grade, and had an MAOP of 1.4 MPa (205 psi).

Lines 119 and 120 each sustained one break. The portion of Line 119 in which the break occurred was constructed in 1937. It was a 550-mm- (22-in.)-diameter, Grade B steel pipe, with 7.9-mm- (0.312-in.)-thick wall. The line was composed of bell end seamless pipe, with electric arc welding at the joints. A part of the 550-mm- (22-in.)-diameter Line 120 was replaced with X-52 grade steel pipe adjacent to the Jensen Plant in 1966. The remaining portion, in which the break occurred, was constructed in 1930 with 7.9-mm- (0.312-in.)-thick wall pipe of Grade B steel. The pipe was fabricated with bells and was electric arc welded. The line failed at a 19° elbow.

2.5 1979 Imperial Valley Earthquake

2.5.1 General Earthquake Characteristics

The 1979 Imperial Valley earthquake occurred on October 15, 1979 at 4:16 p.m. PDT. It has been assigned a local magnitude of 6.6, and was felt over an area of 128,000 km^2 (49,000 $mi.^2$) [Dobry, et al., 1992], including southern California, southwestern Nevada, western Arizona, and northern Mexico. Seismic intensities of MM VI to VII have been assigned to the area in the vicinity of El Centro, CA. The epicenter was located about 10 km (6 mi.) east of Mexicali, Mexico, south of the United States-Mexico border, at geographical coordinates 32° 38.61'N latitude, 115° 18.53'W longitude. The focal depth of the earthquake was approximately 9.7 km (6 mi.) [Chavez, et al, 1982].

2.5.2 Liquefaction, Landslides, and Surface Faulting

As a result of the 1979 Imperial Valley earthquake, there were numerous instances of liquefaction-induced ground behavior, including sand boils, cracked ground, settlement, slumps, and lateral spreads. Youd and Bennett [1983] and Youd and Wieczorek [1982] described the lateral spreading that occurred at the Heber Road site, south of Holtville, CA. This site is located about 1.6 km (1 mi.) northeast of the Imperial fault rupture. A significant lateral spread at this site, 160 m (525 ft) wide and 100 m (328 ft) long, shifted the road and a parallel unlined canal as far as 2.1 m (7 ft) southward toward a 2-m-deep depression [Youd and Bennett, 1983], which was part of a remnant stream channel. Youd and Bartlett [1988] surveyed the site and determined that the maximum movement of the lateral spread was 4.24 m (13.9 ft).

Earth falls were reported along the bluffs of the New and Alamo Rivers. The majority of these were located within 12 km (7.5 mi.) of the Imperial fault surface rupture, but several were as far away as San Felipe Creek, 35 km (22 mi.) from the rupture [Youd and Wieczorek, 1982]. Several small rock slides and falls in both natural and cut slopes occurred in the Cargo Muchacho and Coyote areas and along Interstate 8 at Devils Canyon in the Jacumba Mountains [Dobry, et al., 1992].

Sharp, et al. [1982] reported surface rupture of the Imperial fault along a 30.5-km- (19-mi.)-long segment. The maximum right lateral cumulative horizontal movement, including 160 days of post-event creep, was about 0.78 m (2.5 ft). The point of maximum slip was located about 5.6 km (3.5 mi.) from the south end of the Imperial fault rupture. Surface ruptures also occurred along the Brawley fault zone and Rico fault.

2.5.3 Pipeline Performance

Three transmission lines operated by SoCalGas were affected by ground deformation along the Imperial fault as a result of the 1979 Imperial Valley earthquake. Information about pipelines, including installation date, composition, coating, joint type, depth of soil cover, and operating pressure has been compiled by Dobry, et al. [1992], and is presented in Table 2-II. Pipeline breaks did not occur, and excavations were performed to inspect the pipe and relieve stress generated by the ground movement.

To evaluate the full magnitude of fault displacement imposed on the pipelines since their installation, it was necessary to calculate the total movement as the sum of three components: preseismic creep, coseismic slip, and afterslip. Dobry, et al. [1992] developed a procedure for evaluating these components, which then were summed to yield the maximum fault offset each pipeline had been subjected to, from installation to the time of its excavation for inspection after the earthquake. Along Highway S-80, about 60 m (197 ft) north of the westbound lane, a 100-mm- (4-in.)-diameter gas pipeline was intersected by the Imperial fault. Between the time of installation and inspection, approximately 600 mm (24 in.) of cumulative fault displacement had occurred at the pipeline by preseismic creep, coseismic slip, and afterslip. A detailed description of the pipeline inspection along Highway S-80 is provided by McNorgan [1989]. Due

TABLE 2-II. Characteristics of Pipelines Influenced by Fault Movements During the 1979 Imperial Valley Earthquake [after Dobry, et al., 1992]

	Pipeline Location		
Characteristics	North Side State Rt. S-80 Line No. 41-85	East Side Dogwood Road Line No. 6000	West Side Dogwood Road Line No. 6001
Installation Date	1948	1948	1966
Nominal Diameter	100 mm (4 in.)	200 mm (8 in.)	250 mm (10 in.)
Wall Thickness	4.8 mm (0.188 in.)	7.1 mm (0.281 in.)	4.8 mm (0.188 in.)
Composition	A-25 Steel	API Grade B Steel	Grade X-42 Steel
Weld Type	Oxy-acetylene	Electric Arc	Electric Arc
Coating	No. 56[a]	Somastic[b]	No. 56[a]
Depth of Cover	900 mm (36 in.) sandy backfill dumped and rolled	900 mm (36 in.) sandy backfill dumped and rolled	900 mm (36 in.) sandy backfill dumped and rolled
Operating Pressure	2.8 MPa (400 psi)	2.8 MPa (400 psi)	5.0 MPa (725 psi)
SMYS	170 MPa (25 ksi)	240 MPa (35 ksi)	290 MPa (42 ksi)

[a] No. 56 coating consists of successive layers of: 1) red oxide primer, 2) filled asphalt, 3) two spiral wraps of cellulose acetate, 4) filled asphalt, and 5) paper wrapping

[b] Somastic coating composed of asphalt, aggregate, and fiber mixture

to the orientation of the pipeline with respect to the fault movement, net tensile stresses within the pipeline were induced by the right lateral fault displacement. Stresses in the pipeline were relieved by excavating the backfill. Since no pipeline damage was observed, the excavation was backfilled without further remediation.

Lines 6000 and 6001, 200 and 250 mm (8 and 10 in.) in diameter, respectively, crossed the Imperial fault at two places along Dogwood Road, approximately 9.5 km (5.9 mi.) north of the city of El Centro. The locations of fault-pipeline intersection are shown in Figure 2-6. Between the time of installation and excavation after the earthquake, approximately 400 mm (16 in.) and 315 mm (12.6 in.)

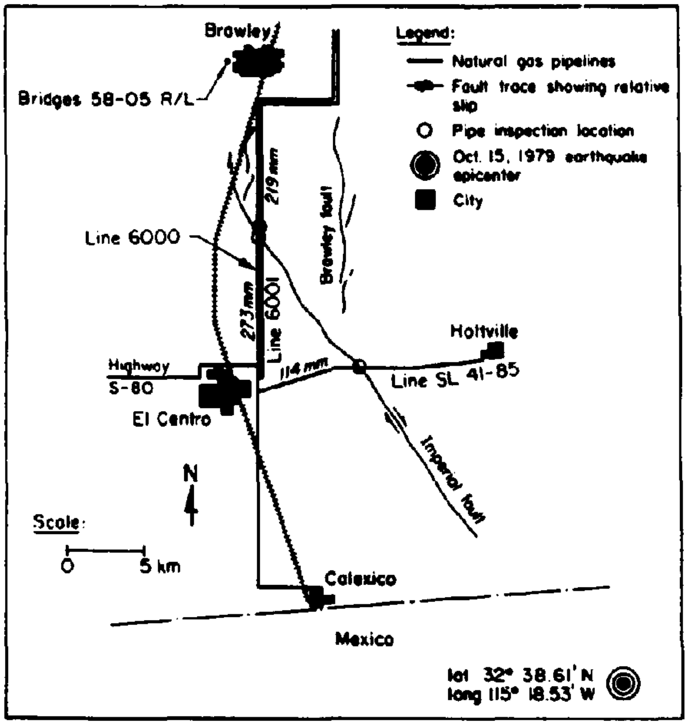


FIGURE 2-6. **Locations of Gas Pipelines Crossing the Imperial Fault [adapted from Dobry, et al., 1992]**

of cumulative fault displacement had been imposed on Lines 6000 and 6001, respectively. Vertical displacements also were imposed on the lines. Hart [1981] measured 50 mm (2 in.) of vertical displacement twelve days after the earthquake. Neither pipeline was damaged. Due to the compressive deformation of Line 6001 generated by fault movement, SoCalGas personnel elected to relieve stresses in the pipeline using a carefully planned procedure. Details of the stress removal operation carried out in February, 1981 are presented in McNorgan [1989]. To relieve the compressive stresses, a 3-m- (10-ft)-long section of pipe was removed. After removing the pipe section and excavating 61 m (200 ft) of the line, approximately 120 mm (4.7 in.) of expansion were observed.

2.6 General Characteristics of Pipeline Performance

Table 2-III provides a summary of pre-WWII transmission and supply line response

TABLE 2-III. Summary of Pre-WWII Transmission and Supply Line Response to Traveling Ground Waves

Installation Date	Line No.	Nominal Diameter mm (in.)	Wall Thickness mm (in.)	SMYS[h] MPa (ksi)	Welds	Earthquake	Distance Affected[a] km (mi.)	No. of Repairs	Repairs/km (Repairs/mi.)
1913	100	300 (12)	6.4 (0.25)	unknown	partially reconditioned[b]	1952 and 1954 Kern County	50.4 (31.3)	2[c]	0.04 (0.06)
1920-21	102.90	300 (12)	6.4 (0.25)	unknown	oxy-acetylene	1971 San Fernando	2.9 (1.8)	3	1.03 (1.65)
1921	101	300 (12)	6.4 (0.25)	unknown	oxy-acetylene	1952 and 1954 Kern County	48.3 (30)	8[c]	0.17 (0.27)
1925	1001	300 (12)	5.6 (0.22)	unknown	oxy-acetylene	1971 San Fernando	19.3 (12)	28	1.45 (2.33)[d]
1926	115	400 (16)	7.9 (0.312)	unknown	oxy-acetylene	1971 San Fernando	24.5 (15.2)	53	2.16 (3.48)[e]
1930	80.90	550 (22)	6.4 (0.25)	240 (35)	not recorded	1952 and 1954 Kern County	10.8 (6.7)	0	0
1930	120	550 (22)	7.9 (0.312)	240 (35)	electric arc	1971 San Fernando	11.3 (7.0)	1	0.09 (0.14)
1930	119	550 (22)	7.9 (0.312)	206 (30)	not recorded	1952 and 1954 Kern County	47.6 (29.5)	0	0
1931	85	650 (26)	6.4 to 7.9 (0.25 to 0.312)	228 (33)	electric arc[g]	1952 and 1954 Kern County	58 (36)	0	0
1931	85	650 (26)	6.4 to 7.9 (0.25 to 0.312)	228 (33)	partially reconditioned[b]	1952 and 1954 Kern County	36.7 (22.8)	0	0
1931	85	650 (26)	6.4 (0.25)	228 (33)	electric arc[g]	1971 San Fernando	8.7 (5.4)	0[f]	0
1931	85	650 (26)	6.4 (0.25)	228 (33)	partially reconditioned[b]	1971 San Fernando	14.5 (9.0)	3	0.21 (0.33)
1931	765	650 (26)	6.4 to 7.9 (0.25 to 0.312)	207 and 228 (30 and 33)	electric arc[g]	1933 Long Beach	16 (10)	0	0
1937	119	550 (22)	7.9 (0.312)	240 (35)	electric arc[g]	1971 San Fernando	6.5 (4.0)	1	0.15 (0.25)
1941	1134	450 to 500 (18 to 20)	6.4 (0.25)	240 (35)	electric arc	1952 and 1954 Kern County	24.3 (15.1)	0	0

[a] Based on area of greatest seismic intensity, MM VIII or greater
[b] Originally oxy-acetylene; many welds reinforced in 1932 with electric arc welds and electric arc welded bands and plates
[c] Cumulative breaks at welds for 1952 and 1954 earthquakes
[d] Pipe failure at fault crossing not included in break rate
[e] Break rate was locally as high as 6.04 breaks/km (9.72 breaks/mi.) on Glenoaks Blvd. between McClay and Foothill Blvd.
[f] Pipe failures at location of lateral spread on San Fernando Rd. not included in break rate
[g] Using belled end pipe with underlying steel ring
[h] Specified Minimum Yield Stress

to traveling ground waves during the 1933 Long Beach, 1952 and 1954 Kern County, and 1971 San Fernando earthquakes. Failures in Lines 1001 and 85 at the Mission Wells segment of the San Fernando Fault and the Juvenile Hall lateral spread, respectively, are not included in the data set. Some breaks in Line 1001 and 115 were caused by permanent ground movement, but could not be identified relative to the large majority of breaks generated by shaking effects. Consequently, the data for these lines do include some damage associated with ground failure. It should be recognized, however, that inclusion of a relatively small, but indeterminate, number of breaks caused by ground failure does not affect significantly the statistics and trends derived from the record of pipeline performance.

The information is organized according to pipeline installation date, starting with the oldest lines. Damage rates, expressed as repairs per km and mi., were evaluated by dividing the line repairs by the total distance of a given line within the area of highest seismic intensity. The review of gas transmission and supply pipeline performance for 10 southern California earthquakes presented in this section shows that pipelines have ruptured only in areas affected by MM VIII or larger. Hence, MM VIII or larger was used to establish the approximate limits of most intense shaking. The preponderance of damage to pre-WWII pipelines occurred as ruptures at oxy-acetylene welds. Damage not associated with pipeline rupture, in the form of leaks at corrosion pits, was not included in the data set.

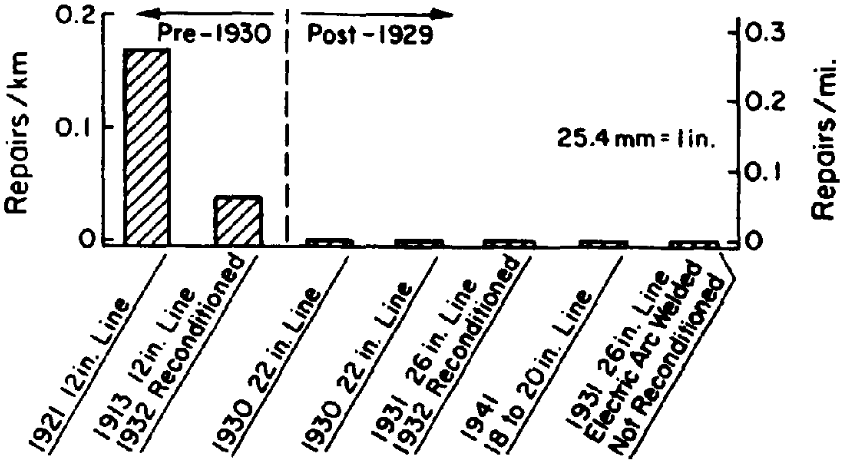
In developing Table 2-III, the 1952 and 1954 Kern County earthquakes were lumped as a single cause of damage. There are several reasons for this distinction. The 1952 main shock may have weakened various welds, thereby contributing directly to damage resulting from the 1954 event. Following the 1952 main shock, there were many aftershocks affecting the gas transmission lines, of which the 1954 event was the last substantial aftershock. To avoid the arbitrary nature of assigning specific levels of damage as consequences of one or more selected aftershocks, the 1952 main shock and 1954 aftershock were combined in an attempt to bracket the contributions to pipeline system damage of the Kern County earthquake sequence.

The potential influence of the 1954 event was assessed independently by using peak acceleration attenuation relationships proposed by Idriss [1985] to estimate the area potentially affected by MM VIII or greater through correlations between MMI and peak acceleration proposed by Richter [1958]. When the damage statistics for the 1954 event calculated with this estimate of affected area were added to the data set, there was little alteration in the overall statistics, with a maximum change of only 12% in the pre-1930 break rate to a lower, less conservative number.

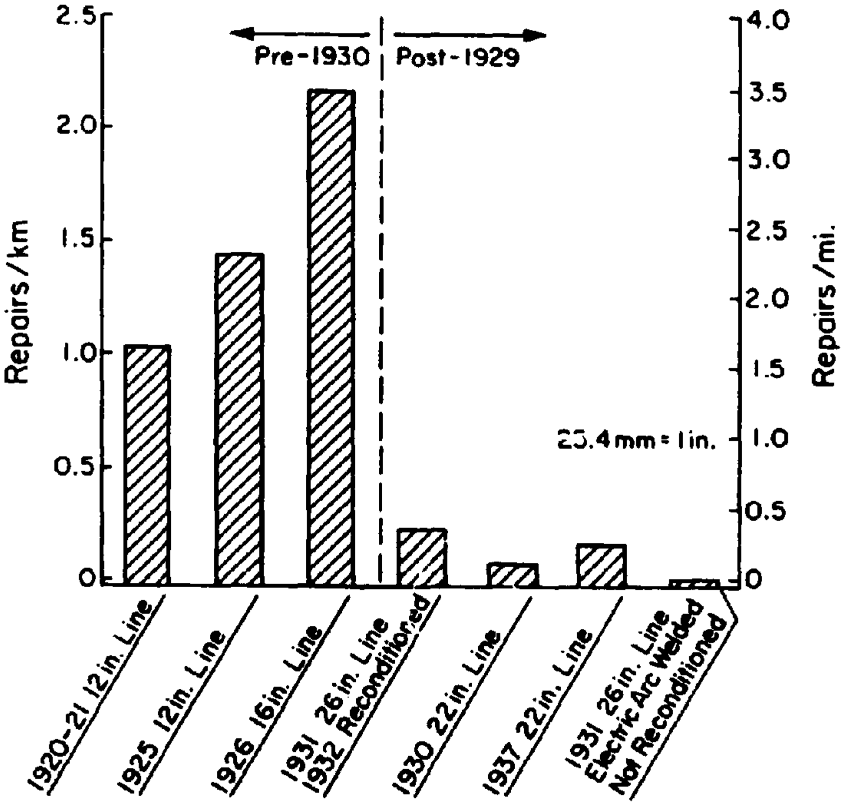
The information in the table can be used to point out some interesting trends, as illustrated in Figure 2-7. In this figure, the repair rates are plotted according to age of installation. Both earthquakes show similar trends, in that the damage rate for pipelines constructed before 1930 are approximately an order of magnitude higher than those constructed during or after 1930. In the Kern County earthquakes, Line 100, reconditioned by electric arc welded bands at the locations of original oxy-acetylene welds, experienced damage at a rate substantially reduced from the rates of pre-1930 pipeline damage. In fact, one of the two breaks associated with the 1913 pipeline, which was reconditioned in 1932 (see Figure 2-7a), was at an original oxy-acetylene weld that had not been reconditioned. If this incident of damage was reassigned or deleted, the repair rate for the pipeline would be reduced by half.

Figure 2-8 shows the data for both earthquakes expressed as a pie chart in which pre-1930, post-1929, and 1932 reconditioned pipelines are distinguished. It should be recognized that virtually all pipelines in the post-1929 category are known to have been electric arc welded, with the exception of Line 80.90 and a portion of Line 119, for which no records could be found about the types of welds. Pre-1930 pipelines account for approximately 93% of all damage associated with traveling ground waves. Only 2% of the damage was in unreconditioned post-1929 lines. Moreover, there is a substantial difference in the overall average repair rate associated with a given age category. The pre-1930 damage rate is nearly 20 times larger than the 1932 partially reconditioned pipeline rate, and nearly 100 times that of the post-1929 damage frequency.

A review of the repair records, and discussions with welders who repaired lines after the 1971 San Fernando earthquake, indicate that the damage listed in Table 2-III was predominantly at oxy-acetylene welds. This observation does not mean



a) 1952 and 1954 Kern County



b) 1971 San Fernando

FIGURE 2-7. Damage Rates for Gas Transmission and Supply Lines Affected Predominantly by Traveling Ground Waves

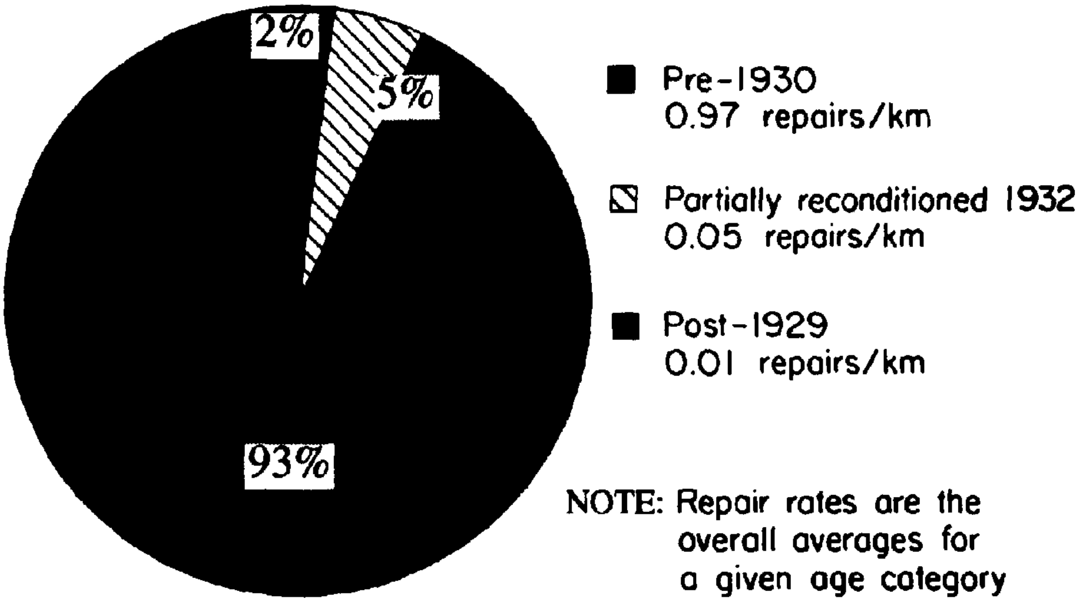


FIGURE 2-8. Pie Chart Showing Relative Proportions of Damage by Pipeline Age Category

that oxy-acetylene welds are intrinsically weak. On the contrary, the metallurgical quality of an oxy-acetylene weld is not significantly different from that of an electric arc weld, provided the work is performed by qualified welders according to proven procedures. Well-made oxy-acetylene and electric arc welds are about equal in strength, although the heat-affected zone adjacent to an oxy-acetylene weld is somewhat larger and the joint ductility somewhat less than those associated with an electric arc weld. The reason for the higher incidence of weld damage is associated with poor weld quality. As described by O'Rourke and McCaffrey [1984], repair personnel reported that many of the welds on Line 115 had characteristics such as poor root penetration, undercutting and overlapping at the toe, and lack of good fusion between the pipe and the weld. These types of features result in a flawed weld, and are not representative of the welds achieved under the quality control standards currently in effect.

Electric arc welded pipelines have shown substantially better performance under traveling ground waves than oxy-acetylene welded lines. Such performance is corroborated by the response of Line 85 to the 1971 San Fernando earthquake. Although the electric arc welded portion of this line was damaged by permanent ground deformation associated with lateral spread, no damage was experienced as a consequence of traveling ground wave effects. In the partially reconditioned portion of this line, all repairs were made at original oxy-acetylene welds. No repairs were made at welds reinforced with electric arc welding procedures.

In contrast to electric arc welded pipelines, the earthquake performance statistics show that oxy-acetylene welded lines have been damaged at a relatively high rate when subjected to seismic intensities exceeding MM VIII. Although most damage was sustained in pre-1930 oxy-acetylene welded pipelines, it would be prudent to regard all pre-WWII oxy-acetylene welded pipelines with caution. As previously mentioned, approximately 30% of all oxy-acetylene welds on Line 85, which was constructed in 1931, were reinforced in 1932 with electric arc welding procedures. Nevertheless, breaks were sustained at three original oxy-acetylene welds as a consequence of the 1971 San Fernando earthquake.

Electric arc welding first was introduced during 1929 for SoCalGas transmission lines. Between 1929 and 1931, both electric arc and oxy-acetylene welding were used. Since 1931, electric arc welding has been used on 400-mm- (16-in.)- and larger diameter pipelines. Furthermore, it appears as if such welding has been used for lines equal to or larger than 250 mm (10 in.) in diameter now incorporated in the transmission and supply lines of the system.

Table 2-IV provides a summary of transmission and supply line response to permanent ground deformation generated by surface faulting and liquefaction. Only pipelines with nominal diameters equal to or larger than 300 mm (12 in.) are listed in the table. All damage occurred in pre-1930 oxy-acetylene welded and 1931 electric arc welded pipelines. No breaks nor disruption of supply has been experienced in gas pipelines constructed with quality welds administered by modern electric arc techniques, such as those consistent with API Standard 1104 [American Petroleum Institute, 1987]. The table indicates that breaks were not sustained in modern, electric arc welded pipelines at locations of surface faulting and lateral spreads, even though the severity of ground deformation in these

TABLE 2-IV. Summary of Transmission and Supply Line Response to Permanent Ground Deformation Triggered by Earthquakes

Installation Date	Line No.	Nominal Diameter mm (in.)	Wall Thickness mm (in.)	SMYS[b] MPa (ksi)	Welds	Earthquake	Pipeline Response and Ground Deformation
1925	1001	300 (12)	5.6 (0.22)	unknown	oxy-acetylene	1971 San Fernando	1 break at fault crossing; approx. 200 mm (8 in.) thrust and 30 mm (1.2 in.) lateral offset. Multiple breaks at lateral spread on San Fernando Rd.; approx. 2 m (6.5 ft) lateral displacement perpendicular to the line
1926	115	400 (16)	6.4 (0.25)	unknown	oxy-acetylene	1971 San Fernando	Approx. 3 compression and multiple tension failures at fault crossing; 600 mm (24 in.) thrust and 1.9 m (6.2 ft) lateral offset
1931	85	650 (26)	6.4 (0.25)	228 (33)	electric arc[a]	1971 San Fernando	7 breaks at lateral spread on San Fernando Rd.; displacement same as above
1948	6000	200 (8)	7.1 (0.281)	240 (35)	electric arc	1979 Imperial Valley	No damage; approx. 400 mm (16 in.) of cumulative lateral movement at fault crossing
1966	120	550 (22)	7.1 (0.281)	360 (52)	electric arc	1971 San Fernando	No damage; approx. 2 to 3 m (6 to 10 ft) of ground movement at lateral spread along utility corridor on west side of Upper Van Norman Reservoir
1966	3000	750 (30)	9.5 (0.375)	360 (52)	electric arc	1971 San Fernando	Same
1966	3003	750 (30)	9.5 (0.375)	360 (52)	electric arc	1971 San Fernando	Same
1966	6001	250 (10)	4.8 (0.188)	290 (42)	electric arc	1979 Imperial Valley	No damage; approx. 315 mm (12.4 in.) of cumulative lateral movement at fault crossing

[a] Using belled end pipe with underlying steel ring; [b] Specified Minimum Yield Stress

instances generally was consistent with that causing rupture in pre-1930 and 1931 electric arc welded pipelines.

2.7 Summary

A detailed review of gas pipeline performance during past earthquakes indicates that, in general, transmission and supply lines have performed well. Six serious earthquakes with local magnitudes equal to or greater than 5.8 and epicenters within the region of the transmission system have not caused any damage or disruption of service in transmission and supply pipelines. Only the 1933 Long Beach, 1952 and 1954 Kern County, and 1971 San Fernando earthquakes resulted in high pressure pipeline damage. In each of these earthquakes, some pipelines have been affected adversely by both traveling ground waves and permanent ground deformation. In none of the earthquakes has there been damage by traveling ground waves to steel pipelines in good repair, constructed with modern welding techniques and quality control measures. Pipeline difficulties were most severe following the 1971 San Fernando earthquake, when ground movements from surface faulting and liquefaction-induced lateral spreads, as well as strong shaking, led to the highest incidence of gas pipeline damage associated with any southern California earthquake.

There is a remarkable and consistent difference in the earthquake performance of pipelines of different ages. Pre-WWII pipelines constructed before 1930 show a damage rate associated with traveling ground wave effects nearly 100 times larger than that of post-1929 pipelines. Pipelines partially reconditioned by electric arc reinforcement at original oxy-acetylene welds show a damage rate nearly 20 times less than that of the pre-1930 pipelines. This damage rate is, nonetheless, five times larger than the overall average rate for post-1929 pipelines, which were not reconditioned.

A similar, consistent pattern of performance can be seen in the response of gas transmission and supply lines to surface faulting and liquefaction-induced ground deformation. There has been no occurrence of pipe rupture or direct disruption of gas transmission for post-WWII pipelines from earthquake-induced permanent ground deformation. In contrast, pre-1930 oxy-acetylene welded and 1931 electric arc welded pipelines have failed at locations of surface faulting and lateral spreads.

Pipe damage from traveling ground waves and permanent ground deformation has occurred predominantly as ruptures of oxy-acetylene welds. Poor weld quality appears to have played a key role in the relatively high incidence of weld damage. Although substantially better than their predecessors, the partially reconditioned oxy-acetylene welded pipelines appear to be more vulnerable to earthquake effects than post-1929 pipelines that did not require reconditioning.

Given the relatively high rate of earthquake damage associated with oxy-acetylene welded lines, it would be prudent to regard with caution all pre-WWII oxy-acetylene welded pipelines potentially subject to seismic intensities of MM VIII or larger. In contrast, pre-WWII electric arc welded pipelines have shown relatively low rates of damage in response to traveling ground wave effects.

The data associated with pipeline performance during past earthquakes are helpful because they point out that the predominant failure mode has been rupture at oxy-acetylene welds. They provide for an assessment of the relative vulnerability of pipelines constructed at different times to both transient and permanent ground movement, and thus can be incorporated directly into a risk assessment methodology for repair/replacement decisions.

SECTION 3

PERFORMANCE DURING 1994 NORTHRIDGE EARTHQUAKE

3.1 General Earthquake Characteristics

The 1994 Northridge earthquake occurred on January 17, 1994 at 4:31 a.m. PST. It has been assigned a surface wave magnitude of 6.6 [Earthquake Engineering Research Institute, 1994], and was felt over an area of approximately 230,000 km^2 (89,000 mi.^{2}), including southern California, southwestern Nevada, western Arizona, and northwestern Mexico [Dewey, 1994]. Maximum seismic intensities of MM VIII to IX were assigned to areas totaling approximately 750 km^2 (290 mi.^{2}) in the San Fernando Valley, Sylmar, Santa Monica, and Fillmore [Dewey, 1994]. The epicenter of the main shock was located in the northwestern end of the San Fernando Valley at geographical coordinates 34° 13'N latitude, 118° 32'W longitude [Porcella, et al., 1994]. The focal depth of the earthquake was approximately 18 km (11 mi.) [Porcella, et al., 1994]. Maximum horizonal ground acceleration exceeded 1 g in the epicentral area at several permanent stations. Duration of strong ground shaking (peak horizontal acceleration greater than 0.1 g) in the epicentral area was approximately eight seconds.

3.2 Liquefaction, Landslides, and Surface Faulting

Evidence of liquefaction was reported in the northern San Fernando Valley near the Jensen Filtration Plant, Juvenile Hall, Sylmar Converter Station, and Los Angeles Reservoir. These locations are approximately the same as those at which liquefaction was observed during the 1971 San Fernando earthquake, although the magnitude and extent of ground deformation triggered by liquefaction were considerably less than those in 1971. Liquefaction also was observed at Redondo Beach, Marina del Rey, Long Beach, Santa Monica, northeast of Culver City near the intersections of La Brea and La Cienaga Blvds. with Interstate 10, Potrero Canyon, and the Santa Clarita Valley along Highway 126 east of Fillmore [e.g., Moehle, 1994].

There were thousands of landslides in the hilly and mountainous terrain north and south of the epicenter, including the Santa Monica, Santa Susana, and San Gabriel Mountains. The great majority of landslides occurred in relatively remote locations. Landslides, however, did contribute to damage in several water transmission and trunk pipelines, highways in mountainous areas, and gas storage field facilities.

The location of the causative fault, as inferred from the aftershock distribution, does not correspond to a readily identifiable mapped feature. The pattern of aftershocks has disclosed a rupture plane dipping 40° to 50° to the southwest. Extensive field surveys have not provided any confirmed evidence of surface faulting.

There was extensive ground deformation in the Potrero Canyon on the north side of the Santa Susana Mountains near the northern edge of the aftershock zone. A series of discontinuous vertical offsets, some as high as 0.6 m (2 ft), and tensile cracks developed on both the north and south sides of the canyon, apparently in response to liquefaction-induced ground displacement towards the stream within the canyon.

Another area of prominent ground deformation cut across Balboa Blvd. between Rinaldi and Lorillard Sts. Ground movement at this location was responsible for breaks in one gas transmission and two water trunk lines, as discussed in the following section.

3.3 System Performance

The system performance statistics provided in this report were obtained approximately three months after the earthquake. It should be recognized that some changes in the statistics may occur in the future as additional information is collected and clarified by SoCalGas personnel.

There were approximately 151,000 gas outages as a result of the earthquake, of which 123,000 were customer initiated. Service was restored to approximately 84,000 customers within one week of the earthquake, and to almost 120,000 within one month of the earthquake. Service could not be restored to 9,100 customers because of structural property damage.

There were approximately 209 instances of damage to metallic distribution mains and services where no corrosion or construction-related damage was observed. There were 27 instances of damage to polyethylene pipes, the majority of which were at couplings and transition fittings. In addition, there were 563 instances of damage to metallic distribution piping where corrosion or material- and construction-related defects were observed or where damage was of unknown origin.

There were 35 non-corrosion related repairs in the transmission system, of which 27 were at cracked or ruptured oxy-acetylene girth welds in pre-1932 pipelines. Figure 3-1 shows a plan view of selected transmission pipelines in the area of most severe ground shaking. Locations of damage in the form of pipeline breaks and leaking flanges are shown in the figure.

Figure 3-2 is a map of the area just north of the earthquake epicenter, showing the Aliso Canyon Gas Storage Facility and the locations of two gas transmission line breaks on Balboa Blvd. The Aliso Canyon facility, which covers some 14.7 km^2 (3,600 acres) and 56 km (35 mi.) of access road, is used to store gas in an underground reservoir that once was used for oil production. Gas is injected during low demand summer months and withdrawn during high demand winter months. Earthquake effects in the facility included deformation of aboveground pipe supports, displacements of runs of injection and withdrawal lines, and structural damage to a fin fan unit used to cool compressed gas before its injection in storage wells. The supply of gas from Aliso Canyon was interrupted for five days.

As shown in Figure 3-1, there were 24 breaks at oxy-acetylene girth welds and one location of buckled pipe in Line 1001, which conveys gas between Newhall and Fillmore, many of which were in Pico and Potrero Canyons. Line 1001 was constructed in 1925, and was operated at the time of the earthquake at 1.7 MPa (245 psi) internal pressure. The pipeline is 300 mm (12 in.) in diameter, with 5.6-mm- (0.22-in.)-thick wall of unknown grade steel.

Of the 25 repairs in Line 1001, 18 were made in Potrero Canyon. Six breaks in oxy-acetylene welds were located in areas adjacent to the Santa Clara River east of Piru and west of Potrero Canyon. One oxy-acetylene weld ruptured at the eastern city limits of Fillmore, leaving a crater approximately 2.7 m (9 ft) deep

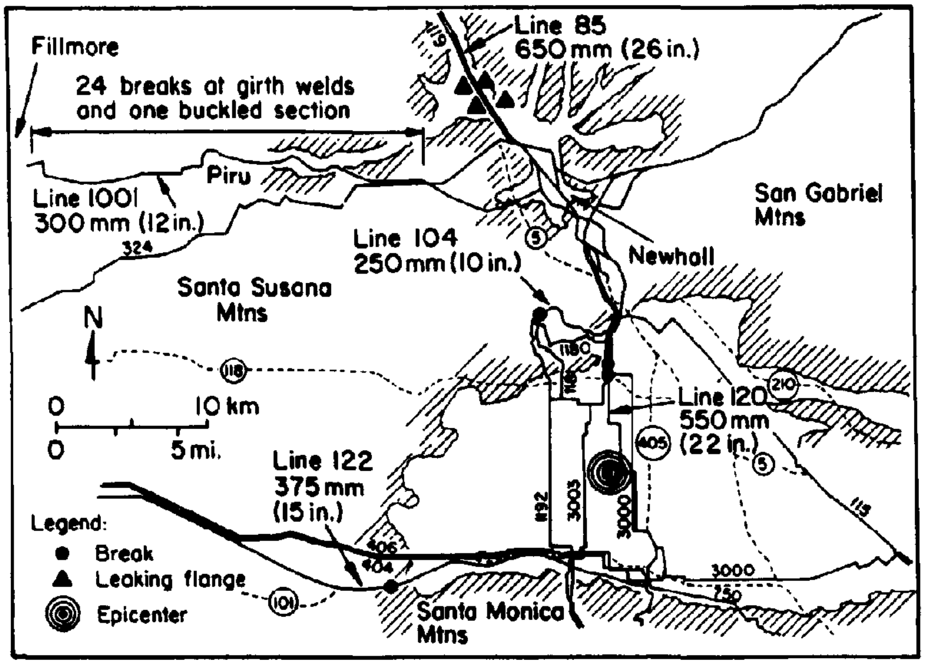


FIGURE 3-1. Map of Gas Transmission Pipelines in the Area of Strong Ground Shaking

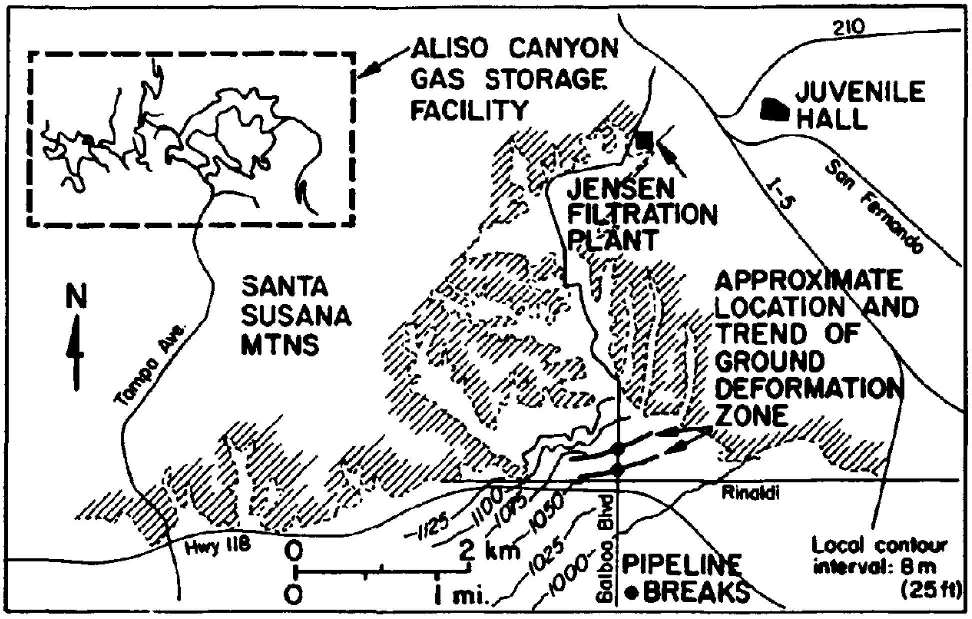


FIGURE 3-2. Map of the Area North of the Northridge Earthquake Epicenter

and 4.5 m (15 ft) by 6 m (20 ft) in area. Gas escaping at the location of this break under Highway 126 was ignited by a downed power line.

Figure 3-3 presents a photograph of a ruptured oxy-acetylene girth weld in pipe of Line 1001 taken from Potrero Canyon. Figure 3-4 shows a cross-section through the ruptured weld where there was poor weld penetration along the inside surface of the pipe. As discussed in Subsection 2.6, the main reason for the relatively high incidence of oxy-acetylene weld damage is inferior weld quality, as evinced by the poor root penetration shown in the photograph.

Flange leaks occurred at the four locations shown in Figure 3-1 at sections of aboveground piping. There was also a break in an oxy-acetylene weld in Line 85 at a location approximately 39 km (24 mi.) northwest of Newhall, which is not shown in the figure. Damage was mainly in the form of flange separation and leaking gaskets. One of the flanges shown in Figure 3-1 was fractured. At the damaged locations, Line 85 is a 650-mm- (26-in.)-diameter pipeline with a pipe wall 6.4 mm (0.25 in.) thick, of Grade A steel, operated at MAOP of 2.2 MPa (317 psi). The ruptured oxy-acetylene weld and four leaking flanges occurred in a partially reconditioned portion of Line 85, which is described in Subsection 2.3.3. The weld failure was at an original oxy-acetylene weld.

There was a break at a weld in Line 85 near Taft, approximately 120 km (75 mi.) north of the epicenter. This section of the pipeline was constructed in 1931 with electric arc welds, as described in Subsection 2.3.3. The line had an MAOP of 2.5 MPa (360 psi). There was a leaking flange at an above-ground section of Line 119 north of the area shown in Figure 3-1. This section of the 550-mm- (22-in.)-diameter pipeline was constructed in 1931 with a wall thickness of 7.9 mm (0.312 in.). There is no clear record of weld type. The SMYS of the steel and MAOP were 208 MPa (30,000 psi) and 2.5 MPa (360 psi), respectively.

A fractured oxy-acetylene girth weld was repaired in Line 122 at the location shown in Figure 3-1. Although this pipeline is not operated as a transmission line, it nevertheless is described in this report because of its relatively high operating pressure of 1 MPa (150 psi). The pipeline was installed in 1927 with oxy-acetylene girth welds, 6.4-mm- (0.25-in.)-thick wall, and steel of unknown grade.

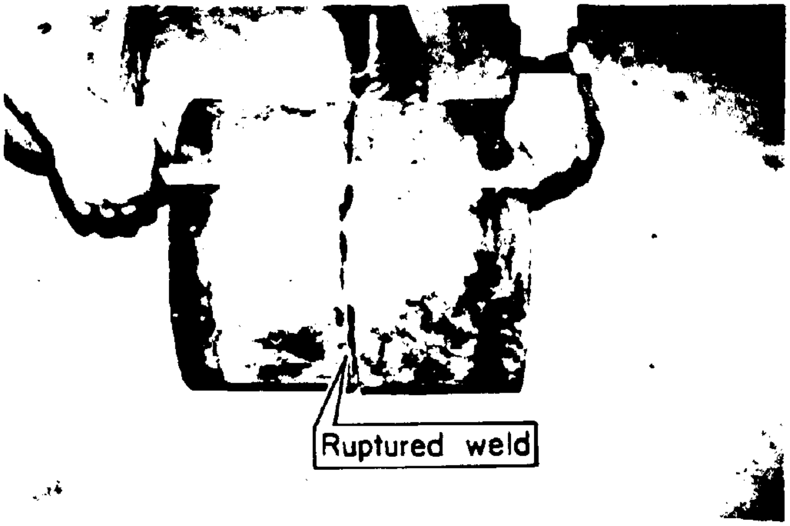


FIGURE 3-3. Ruptured Oxy-Acetylene Girth Weld in Line 1001

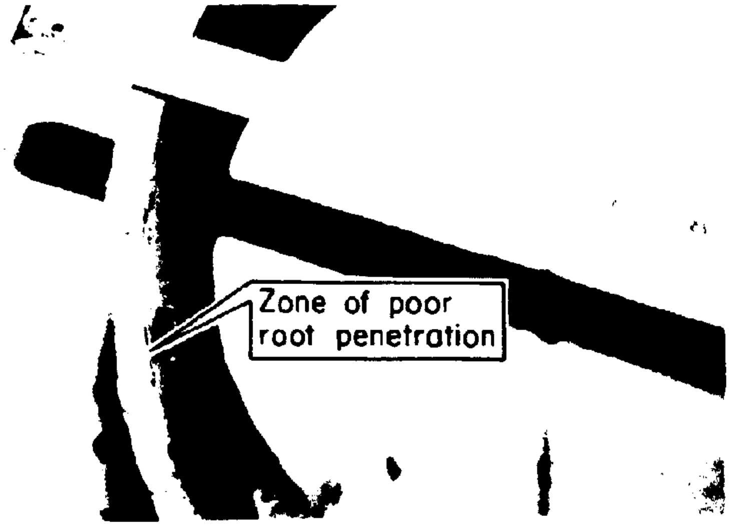


FIGURE 3-4. Cross-Section Through Ruptured Oxy-Acetylene Girth Weld Showing Poor Root Penetration of Weld

As shown in Figure 3-1, there was a break in Line 104 inside the Aliso Canyon Gas Storage Field. The pipeline is 250 mm (10 in.) in diameter and has an MAOP of 1.6 MPa (228 psi). It was constructed with electric arc girth welds in 1941. The pipe has a 5.2-mm- (0.203-in.)-thick wall of unknown grade steel.

Figure 3-5 shows a plan view of Line 104 in Aliso Canyon relative to the site topography. The rock in the area covered by the figures is highly fractured, friable siltstone and sandstone with 0.6 to 3 m (2 to 10 ft) of silty sand cover in many places. Pipe damage appears to be related to slope displacement perpendicular to the pipeline, which also caused an adjacent 100-mm- (4-in.)-diameter, steel fuel oil line to fail at an aboveground vertical bend. Slope displacement adjacent to the access road in the northeast part of the figure threatened Line 104, and the pipeline was excavated in the slope area to free it from the adjacent soil.

Three water tanks in the facility were damaged. The tank supplying water to the main plant was not damaged, but pipelines conveying water from the tank developed leaks, thereby cutting off supply. Of approximately 12 oil storage tanks in the facility, six were damaged. As shown in Figure 3-6, one tank collapsed and another at the same location sustained a split seam. Damage at other oil storage tanks was relatively minor and consisted of buckling and warping of steel plates. The fuel gas system used for heaters and plant instruments was disrupted in several locations. A number of transformers fell from poles, disrupting electrical service.

Because of failed water tanks and associated piping damage, water supply inside the facility was disrupted. Because of damage to Los Angeles Department of Water and Power trunk and distribution mains, water supply from outside the facility also was disrupted. Vacuum trucks were dispatched to locations of leaking trunk lines outside the facility, where water was collected and brought back for internal use.

There were numerous landslides throughout the facility. Figure 3-7 shows a landslide of approximately 380 m^3 (500 yd^3) which undermined an injection line near the top of the slope. Debris from the slide caused deformation of two withdrawal lines and an injection line, which are located adjacent to the roadway shown in

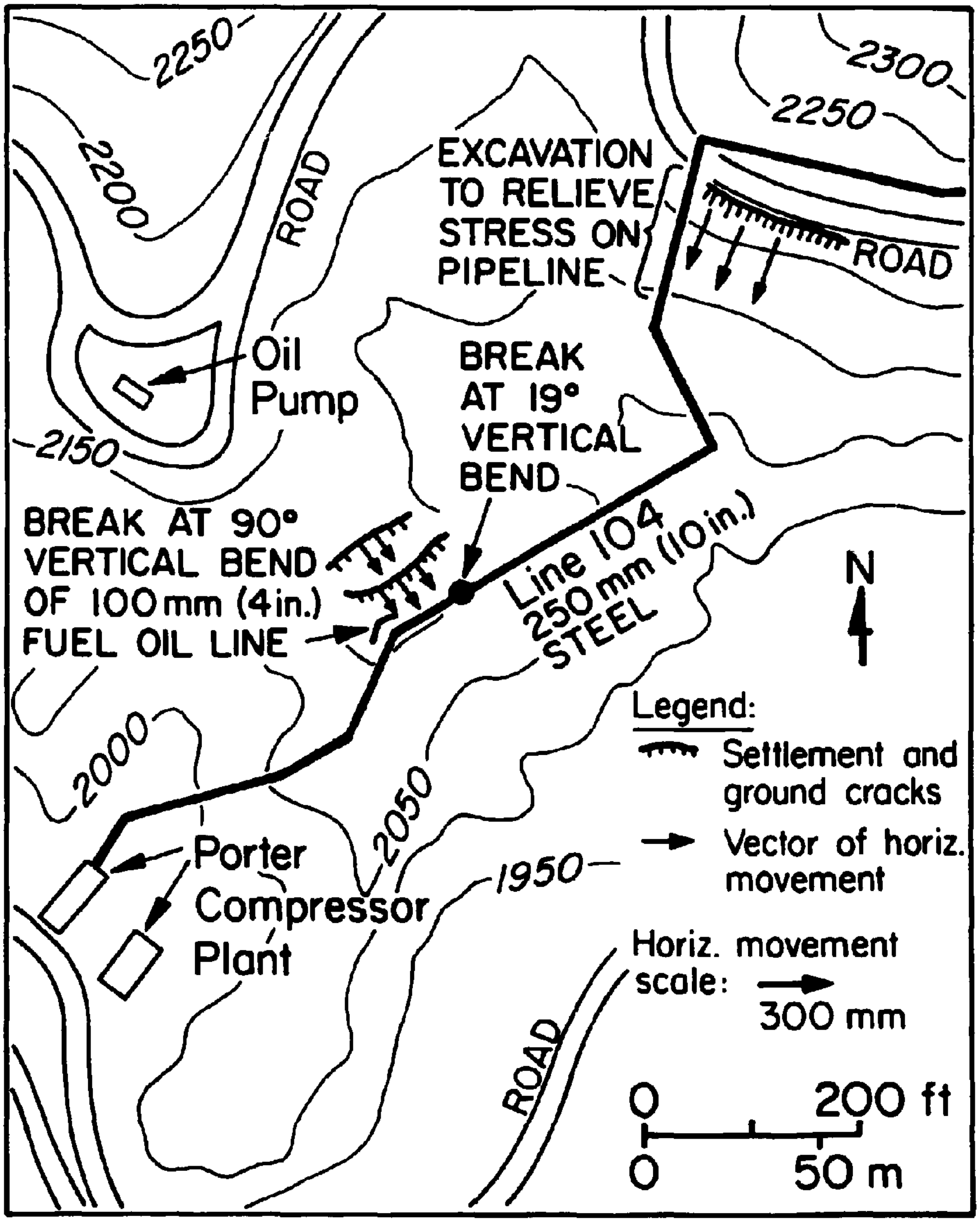


FIGURE 3-5. Plan View of Line 104 in the Aliso Canyon Gas Storage Field

FIGURE 3-6. Collapsed Oil Tank in the Aliso Canyon Gas Storage Field

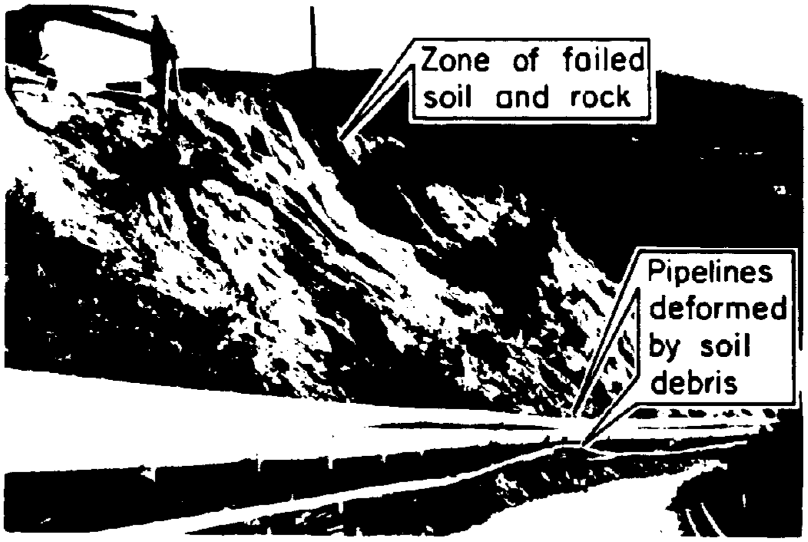


FIGURE 3-7. Local Landslide in Sandstone and Overlying Soil at the Aliso Canyon Gas Storage Field

the photograph. The landslide illustrated in the photo was typical of ground displacements in several locations. The slide was activated along joints dipping at approximately 60° subparallel to the 45° slope. The rock is friable sandstone of the Topanga Formation.

Figure 3-8 shows a plan view of surficial ground movement and gas facilities near the location of a leaking flange in Aliso Canyon. Downslope movement at the Wye structure caused tensile deformation at the flange of a withdrawal pipeline, thereby breaking the seal at the gasket. Local soil and rock failure exposed the drilled shaft foundations of aboveground pipeline supports north of the Wye structure. Withdrawal and injection lines along the access road were deformed by fallen debris in the landslide area at the eastern side of the figure. Figure 3-7 provides a photograph of the landslide. Elsewhere along the access road, several aboveground pipeline supports were twisted and deformed.

With the exception of a leaking flange in an area of slope movement, there were no leaks or ruptures of aboveground withdrawal and injection pipelines. Serious damage to aboveground pipes was scarce, even though there were many deformed pipe supports and sections of line undermined and distorted by local landslides. The presence of large ground cracks and the potential for further ground movement are likely to require continuing remedial action to stabilize slopes and protect vulnerable pipes.

Gas pipeline damage on Balboa Blvd. occurred in Line 120, a 550-mm- (22-in.)-diameter steel pipeline constructed in 1930 with unshielded electric arc girth welds. At the time of the earthquake, the line was operated at about 1.2 MPa (175 psi). The pipe had a wall thickness of 7.2 mm (0.281 in.) and was composed of Grade B steel. The pipeline failed in tension in a zone of tensile ground deformation about 300 m (900 ft) north of a zone of compressive ground deformation where the pipe failed by compressive wrinkling. As shown in Figure 3-2, the ground rupture zones occurred in the toe area of an alluvial fan and are oriented subparallel to the surface elevation contour lines. The pattern of ground deformation suggests that lateral spreading of the alluvial fan sediments took place. Nearby boreholes show loose silty sands at depths of 9 to 12 m (30 to 40 ft), although water levels are indicated at considerably greater depths in dense materials.

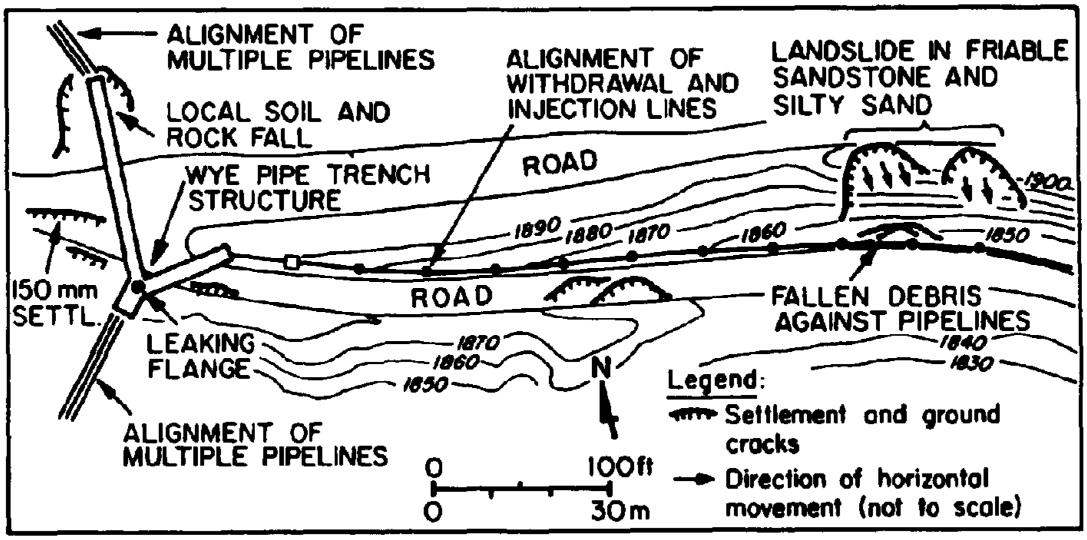


FIGURE 3-8. Plan View of Wye Pipe Trench Structure and Aboveground Pipelines Influenced by Local Landslide Activity at Aliso Canyon

Line 120 had been scheduled for replacement in the Granada Hills area. A new 600-mm- (24-in.)-diameter pipeline, with electric arc girth welds, X-60 steel, and 6.4-mm- (0.25-in.)-thick wall, had been constructed parallel to the older 550-mm- (22-in.)-diameter line along McLennan Ave. It had not been opened for gas flow at the time of the earthquake. Even though it crossed similar zones of tensile and compressive ground deformation, it was not damaged.

Figures 3-9 and 3-10 show maps of the pipelines in Balboa Blvd. near the zones of permanent ground deformation. In addition to numerous distribution mains, there were six transmission and water trunk lines at this site. There were two 750-mm- (30-in.)-diameter gas transmission lines constructed of X-52 steel in the 1950s which were not damaged. There was a 400-mm- (16-in.)-diameter petroleum pipeline, operated by the Mobil Oil Corporation, which was not damaged. The pipeline was composed of X-52 steel and installed in 1991. Two water trunk lines, the 1,240-mm- (49-in.)-diameter Granada and the 1,730-mm- (68-in.)-diameter Rinaldi Trunk Lines, failed in tension and compression in the tensile and compressive zones of ground deformation, respectively.

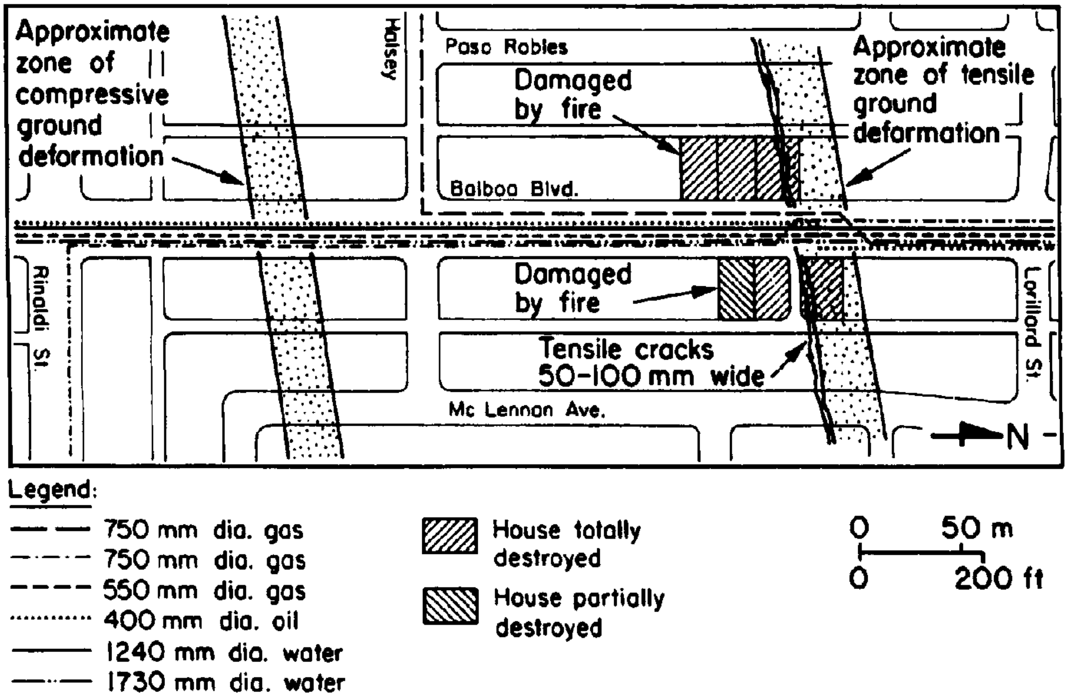


FIGURE 3-9. Map of Major Pipelines, Fire Damage, and Ground Deformation on Balboa Boulevard

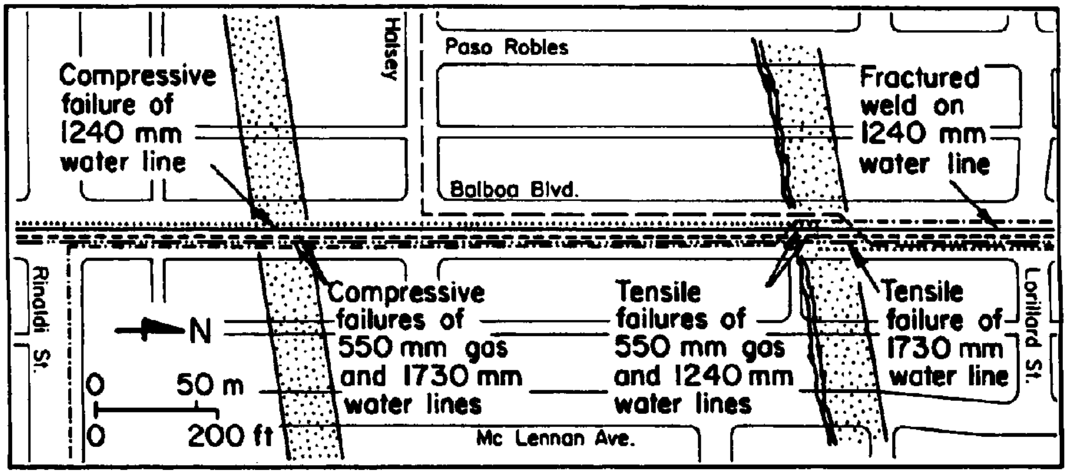


FIGURE 3-10. Map of Major Pipelines, Ground Deformation Zones, and Locations of Pipeline Damage on Balboa Boulevard

A 150-mm- (6-in.)-diameter gas distribution pipeline along the eastern side of Balboa Blvd. was ruptured in tension and compression in the tensile and compressive ground deformation zones, respectively. This pipeline was operated at a pressure of approximately 0.3 MPa (45 psi). Gas escaping from the tensile rupture caught fire.

The water trunk line damage in the figure represents locations where excavations were required for repair. In addition, there were three other locations where internal inspection disclosed damage of the Rinaldi Trunk Line, primarily as separations at welded slip joints, within a distance of two blocks north of the tensile ground deformation zone.

A detailed examination of sections of Line 120 and the Granada Trunk Line, which were removed from the compressive ground deformation zone, each disclosed a compressive shortening of approximately 250 mm (10 in.). In each case, the compressive shortening and line failure occurred at a welded joint. Observations of Line 120 in the tensile ground deformation zone showed a separation between the failed ends of the pipe of approximately 250 mm (10 in.). Failure occurred at a welded joint.

Figure 3-11 shows a view during repair of the Granada Trunk Line and Line 120 in the zone of tensile ground movement. Figure 3-12 shows tensile ground cracks in cementitious backfill covering the Mobil Oil pipeline in the zone of tensile ground deformation. Two prominent cracks, each 50 to 75 mm (2 to 3 in.) wide, can be seen in the photo.

Gas escaping from Line 120 was ignited by sparks from the ignition system of a pickup truck that had stalled in the area of tensile ground deformation flooded by the ruptured trunk lines. The gas fire spread to adjacent properties, destroying five houses and partially damaging an additional structure.

There was damage at the Honor Rancho Storage Field near Newhall, although the earthquake effects at this installation were considerably less than those at Aliso Canyon. There was disruption of the fire loop system, brine filtration equipment, and access roads. A 400-mm- (16-in.)-diameter water main, water tank, gas piping, and electrical transformer also were damaged.

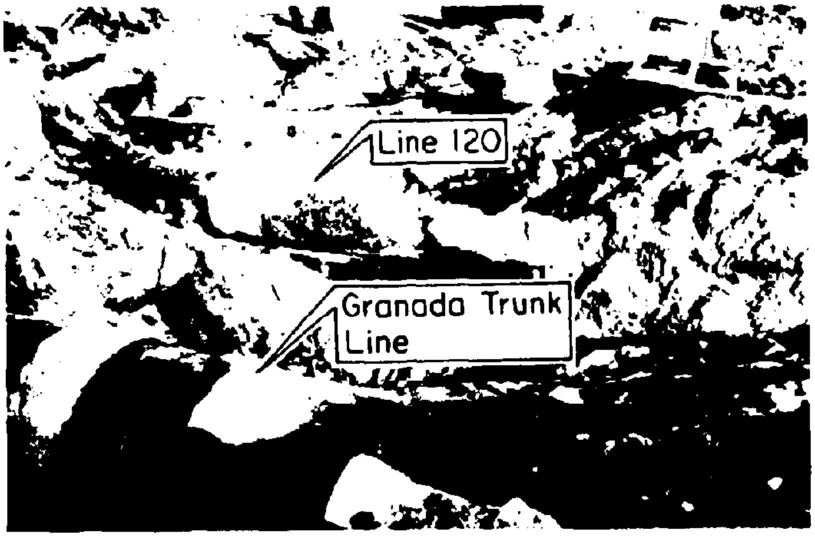


FIGURE 3-11. Damaged Water Trunk and Gas Transmission Pipelines at the Zone of Tensile Ground Deformation and Fire on Balboa Boulevard

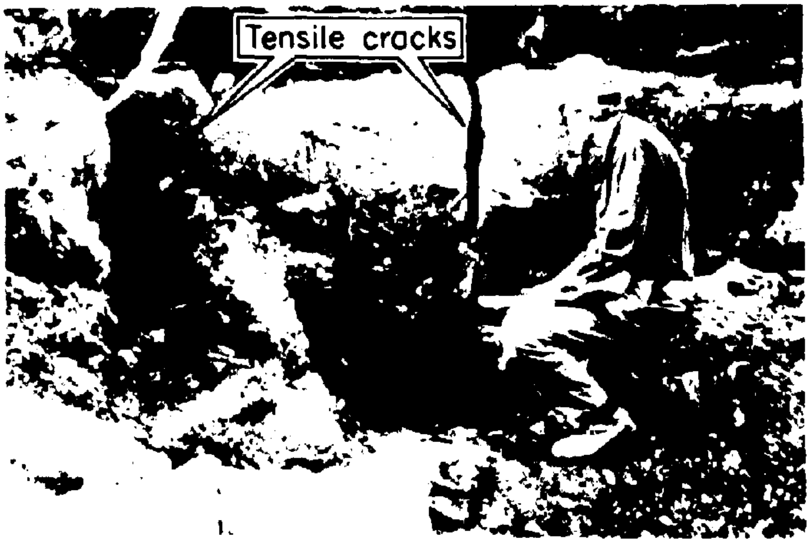


FIGURE 3-12. Subsurface Cracks at the Zone of Tensile Ground Deformation on Balboa Boulevard

3.4 General Characteristics of Pipeline Performance

Table 3-I provides a summary of pre-WWII transmission line response to traveling ground waves during the Northridge earthquake. Only pipelines which required at least one repair are included in the table. Similar to Table 2-III, the information is organized according to pipeline installation date, starting with the oldest lines. Repairs are reported separately for areas affected by seismic intensities greater than or equal to MM VIII and MM VII. Areas with MMI ≥ VIII were obtained from preliminary intensity maps developed by USGS [Dewey, 1994]. A single modification was made in the MMI ≥ VIII mapping reported by Dewey [1994] by extending the MM VIII zone at Potrero Canyon to include the area of recent alluvial deposits along the Santa Clara River to just east of Piru. Field observations in this area have disclosed evidence of sand boils and ground cracks which are indicative of liquefaction and consistent with MM VIII intensities. An intensity of MM VIII has been assigned to the city of Fillmore in both this report and the USGS mapping.

Table 3-II summarizes the transmission line response to permanent ground deformation triggered by the Northridge earthquake. The table is organized in a format similar to that of Table 2-IV. Only pipelines which required repair are included in the table.

In terms of general characteristics, the Northridge earthquake pipeline damage is consistent with and predictable relative to the trends in damage summarized in Section 2. The highest incidence of damage from traveling ground waves was at oxy-acetylene girth welds, with the preponderance of this damage occurring in a single pipeline, Line 1001. Approximately 91% of all traveling ground wave damage was in areas of MMI ≥ VIII, as compared with virtually all ground wave damage in previous earthquakes being assigned to areas of MM VIII or larger. Given the approximate nature of MMI, it is not surprising that relatively minor amounts of damage would be assigned to areas with MMI ≤ VII. Such variations are to be expected because of the variability in interpreting and mapping MMI. Moreover, some pipe components are likely to be relatively weak within a given category of piping and especially vulnerable to the small loading effects associated with lower earthquake intensities.

TABLE 3-I. Summary of Pre-WWII Transmission and Supply Line Response to Traveling Ground Waves as a Result of the 1994 Northridge Earthquake

Instal-lation Date	Line No.	Nominal Diam. mm (in.)	Wall Thickness mm (in.)	SMYS[f] MPa (ksi)	Welds	MMI ≥ VIII Distance Affected km (mi.)	MMI ≥ VIII Repairs	MMI ≥ VIII Repairs/km (Repairs/mi.)	MMI ≤ VII Repairs
1925	1001	300 (12)	5.6 (0.22)	172 (25)	oxy-acetylene	40 (24.9)	25	0.63 (1.0)	0
1927	122	380 (15)	6.4 (0.25)	NR	oxy-acetylene	19.3 (12.0)	1	0.05 (0.08)	0
1930	119	550 (22)	7.9 (0.312)	207 (30)	not recorded	3.2 (2.0)	0	0	1[b]
1930	120	550 (22)	7.1 (0.281)	241 (35)	electric arc[c]	29.6 (18.4)	0	0	0
1930	121	650 (26)	6.4 (0.25)	241 (35)	oxy-acetylene	1.1 (0.7)	0	0	0
1931	85	650 (26)	6.4 (0.25)	228 (33)	partially reconditioned[a]	3.2 (2.0)	4[b]	1.56 (2.5)	1
1931	85	650 (26)	6.4 (0.25)	228 (33)	electric arc[c]	NA[d]	NA[d]	NA[d]	1
1941	104	250 (10)	5.2 (0.203)	NR[e]	electric arc	3.7 (2.3)	0	0	0

[a] Originally oxy-acetylene; many welds reinforced in 1932 with electric arc welded bands and plates

[b] Leaking flanges

[c] Using belled end pipe and underlying steel ring

[d] Not applicable because this entire section of pipeline was outside MM VIII area

[e] Not reported

[f] Specified Minimum Yield Stress

TABLE 3-II. Summary of Transmission Line Response to Permanent Ground Deformation Triggered by the 1994 Northridge Earthquake

Installation Date	Line No.	Nominal Diam. mm (in.)	Wall Thickness mm (in.)	SMYS[a] MPa (ksi)	Welds	Pipeline Response and Ground Deformation
1930	120	550 (22)	7.9 (0.312)	240 (35)	Electric arc	One compression and one tension failure at ground deformation on Balboa Blvd. in Granada Hills
1941	104	250 (10)	5.1 (0.203)	Unknown	Electric arc	One break consisting of buckle and split at weld at an overbend in Aliso Canyon Gas Storage Facility

[a] Specified Minimum Yield Stress

The general trend shown by performance statistics in 11 major earthquakes, including the Northridge earthquake, is that the preponderance of gas transmission line damage from traveling ground waves is likely to occur in areas of MMI ≥ VIII. For planning and replacement decision purposes, the earthquake data substantiate MM VIII and higher as intensities at which the risk of damage to gas transmission piping with oxy-acetylene welds increases significantly.

Pipeline response to permanent ground movement during the Northridge earthquake is similar to that experienced in previous earthquakes. No breaks nor disruption of supply has been experienced in post-WWII gas pipelines constructed with quality welds. The table indicates that breaks were not sustained in modern electric arc welded pipelines, but were experienced in pre-WWII electric arc welded pipelines.

SECTION 4

CONCLUSIONS

A detailed and systematic review of the seismic performance of gas transmission lines prior to the 1994 Northridge earthquake shows that all repairs in pipelines affected by traveling ground waves occurred in areas which experienced seismic intensities of MMI ≥ VIII. A review of gas transmission line performance during the 1994 Northridge earthquake discloses a similar pattern of seismic response. Approximately 91% of all pipeline damage caused by traveling ground waves in the 1994 event occurred in areas with MMI ≥ VIII. The earthquake-related damage has been predominantly in the form of ruptures at oxy-acetylene girth welds. The potential for damage in such welds appears to increase considerably for seismic intensities equal to and greater than MM VIII.

Table 4-I summarizes all gas transmission pipeline repairs which can be related to earthquake effects, covering more than 60 years of earthquake experience in southern California, from the 1933 Long Beach to the 1994 Northridge earthquake. Figure 4-1 presents similar information in the form of a pie chart. During this time, there were 11 earthquakes with local magnitudes equal to or greater than 5.8 with epicenters inside the area of transmission facilities operated by SoCalGas. Evidence of transmission line damage could be found for only four of these events, including the 1952 and 1954 Kern County, 1971 San Fernando, and 1994 Northridge earthquakes. The table includes damage from traveling ground waves and permanent ground deformation. Damage is listed for breaks in both pre-WWII oxy-acetylene and electric arc welded pipelines, leakage at locations of corrosion, and leaking flanges.

To provide a comprehensive data set, leakage at locations of corrosion are included. It is interesting to note the relatively low incidence of corrosion-related earthquake damage in transmission lines, representing only 1.4% of the total number of repairs. The data set also includes the repaired oxy-acetylene weld in Line 122 after the Northridge earthquake. Even though this line was not operated as a transmission pipeline, its relatively high internal pressure is consistent with that of many transmission lines. Moreover, risks associated with

TABLE 4-I. Summary of Earthquake-Related Gas Pipeline Repairs

Type of Damage	Traveling Ground Wave Damage: Number of Repairs	Permanent Ground Deformation Damage: Number of Repairs
Break in pre-WWII oxy-acetylene girth welded pipeline	123[a]	4[e]
Break in pre-WWII electric arc girth welded pipeline	4[b]	10[e]
Leakage at locations of corrosion	2[c]	---
Leaking flanges	5[d]	---

[a] Refer to Tables 2-III and 3-I. Note that repairs to partially reconditioned Line 85 during the 1971 San Fernando earthquake were at oxy-acetylene welds and one of the repairs in Line 100 was at an oxy-acetylene weld. Repairs include damage to Line 122 during the 1994 Northridge earthquake.

[b] Refer to Tables 2-III and 3-I

[c] Includes leaks detected in Lines 80.90 and 1134 during the main 1952 Kern County earthquake

[d] Refer to Table 3-I

[e] Refer to Tables 2-IV and 3-II

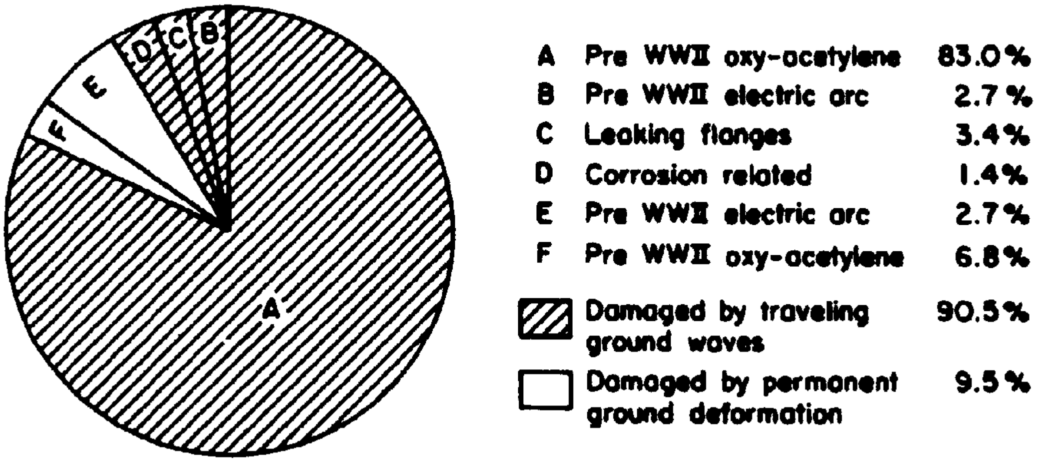


FIGURE 4-1. Pie Chart Showing Relative Proportions of Earthquake-Related Repairs Associated with Various Categories of Damage

damage to this type of facility are similar to that associated with transmission piping.

Table 4-I and Figure 4-1 have been developed on the basis of existing repair records. It should be recognized that the oxy-acetylene welded Line 1001 was so heavily damaged by the 1971 San Fernando earthquake that over 8 km (5 mi.) of the line were abandoned. Hence, an accurate account of repairs to this section of pipeline could not be included in the data set.

The type of pipeline most vulnerable to earthquake effects is the pre-WWII oxy-acetylene welded pipeline. Eighty-three percent of all earthquake-related repairs were caused by traveling ground wave effects in oxy-acetylene girth welded lines. The preponderant form of damage was rupture at the oxy-acetylene welds, which often are characterized by defects such as poor root penetration, lack of good fusion, and overlapping and undercutting at the toe. The worst performers among the oxy-acetylene welded lines have been those constructed before 1930, some of which have experienced damage at a relatively high rate of over 1 repair/km (1.61 repairs/mi). Oxy-acetylene welding for major transmission lines appears to have been discontinued by SoCalGas after 1931.

In contrast to oxy-acetylene welded piping, pre-WWII pipelines with electric arc welds have fared much better when influenced by traveling ground waves. Damage under these conditions accounts for only 2.7% of the total repairs, which is 30 times less than the traveling ground wave damage in oxy-acetylene welded lines. Prior to WWII, welding practices often involved the use of unshielded electric arc techniques, which exposed the molten weld directly to the atmosphere. Gas inclusions and uneven heating associated with this technique tended to produce a weld of inferior quality relative to the shielded electric arc welds produced according to standard procedures adopted during the WWII period.

Damage from permanent ground deformation associated with surface faulting, liquefaction-induced lateral spread, and landslides represents only 9.5% of the total repairs. This relatively low portion is associated with the relatively small percentage of surface area influenced by ground failure during an earthquake. Damage from permanent ground deformation can nonetheless be severe, resulting in some of the most conspicuous damage during a seismic event. Pipeline ruptures on Balboa Blvd. during the 1994 Northridge earthquake, and along Glenoaks Blvd. during the 1971 San Fernando earthquake, are examples. Permanent ground deformation damage during previous earthquakes has been confined entirely to oxy-acetylene and pre-WWII electric arc welded pipelines.

Post-WWII electric arc welded pipelines in good repair have never experienced a break or leak as a result of either traveling ground waves or permanent ground deformation during a southern California earthquake. A very small amount of damage can be attributed to leaks at pipe walls thinned by corrosion, such as the corrosion-related leakage detected after the main 1952 Kern County earthquake. Modern electric arc welded pipelines have been subjected to severe permanent ground displacement which has damaged adjacent welded water trunk lines, such as those subjected to 2.7 m (9 ft) of lateral spread next to the Jensen Filtration Plant during the 1971 San Fernando earthquake. Likewise, ground movement on Balboa Blvd. during the 1994 Northridge earthquake ruptured the pre-WWII electric arc welded Line 120, but did not damage two adjacent post-WWII electric arc welded transmission lines.

The lack of damage to post-WWII electric arc welded pipelines does not mean they are immune to permanent ground deformation. On the contrary, there is substantial experience with modern pipeline failures in areas of severe landslides. The repair record shows that modern electric arc welded gas pipelines in good repair are the most resistant type of piping, vulnerable only to very large and abrupt ground displacement, and generally highly resistant to traveling ground wave effects and moderate amounts of permanent deformation.

SECTION 5

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