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16. Abstract (Limit: 200 words)

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NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH

State University of New York at Buffalo

Feasibility Study of Replacement Procedures and Earthquake Performance Related to Gas Transmission Pipelines

by

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NOTICE

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Feasibility Study of Replacement Procedures and Earthquake Performance Related to Gas Transmission Pipelines

by

T.D. O'Rourke[1] and M.C. Palmer[2]

May 25, 1994

Technical Report NCEER-94-0012

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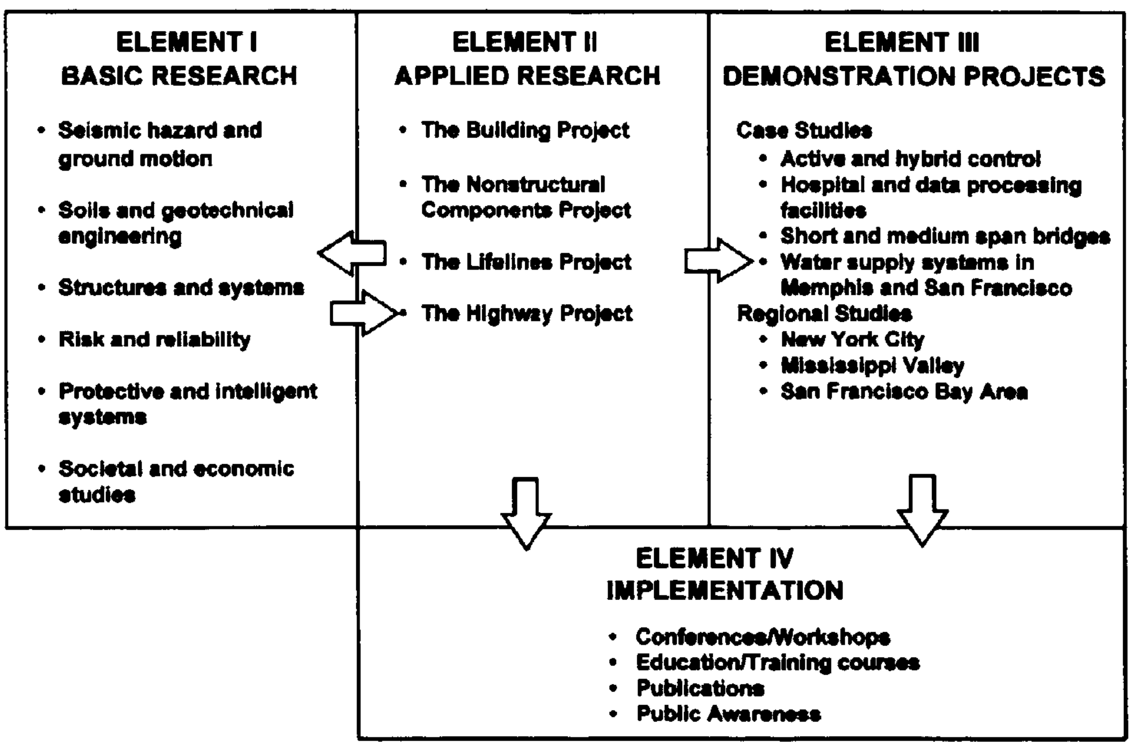
PREFACE

The National Center for Earthquake Engineering Research (NCEER) was established to expand and disseminate knowledge about earthquakes, improve earthquake-resistant design, and implement seismic hazard mitigation procedures to minimize loss of lives and property. The emphasis is on structures in the eastern and central United States and lifelines throughout the country that are found in zones of low, moderate, and high seismicity.

NCEER's research and implementation plan in years six through ten (1991-1996) comprises four interlocked elements, as shown in the figure below. Element I, Basic Research, is carried out to support projects in the Applied Research area. Element II, Applied Research, is the major focus of work for years six through ten. Element III, Demonstration Projects, have been planned to support Applied Research projects, and will be either case studies or regional studies. Element IV, Implementation, will result from activity in the four Applied Research projects, and from Demonstration Projects.



Research tasks in the **Lifeline Project** evaluate seismic performance of lifeline systems, and recommend and implement measures for mitigating the societal risk arising from their failures or disruption caused by earthquakes. Water delivery, crude oil transmission, gas pipelines, electric power and telecommunications systems are being studied. Regardless of the specific systems to be considered, research tasks focus on (1) seismic vulnerability and strengthening; (2) repair and restoration; (3) risk and reliability; (4) disaster planning; and (5) dissemination of research products.

The end products of the **Lifeline Project** will include technical reports, computer codes and manuals, design and retrofit guidelines, and recommended procedures for repair and restoration of seismically damaged systems.

The research described in this report plays an integral role in the Lifeline Project. The work was sponsored jointly by the Southern California Gas Company (SoCalGas) and NCEER, and thereby represents a cooperative undertaking with industry, which is an important feature of NCEER's program for implementation of research results. The work in this report has resulted in a definitive database for the seismic performance of a large and complex gas transmission system, spanning 61 years of earthquake records and including a detailed assessment of high pressure pipeline response to the Northridge earthquake. The report establishes a plan for identifying the most vulnerable high pressure gas pipelines, based on seismic and non-seismic considerations, and demonstrates the feasibility for implementing such a plan in a pipeline replacement program by an example application to part of the existing SoCalGas system.

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ABSTRACT

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 $\geq$ 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 $\geq$ 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.

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.

A general procedure for evaluating the relative risks from earthquake hazards to steel pipelines was developed. The procedure accounts for the influence of traveling ground waves, surface faulting, landslides, and soil liquefaction. The procedure utilizes information, acquired primarily through reconnaissance studies, on regional geology, groundwater conditions, aerial photos, and site-specific soil borings obtained principally through public agencies.

Two transmission pipelines, Lines 121 and 123, were selected for a feasibility study. Both lines were constructed in 1930, and therefore represent older, more vulnerable portions of the system which are joined with oxy-acetylene welds. Emphasis in this work has been placed on characterizing the geotechnical and earthquake hazards to these pipelines, especially the potential for surface faulting and large ground deformation caused by liquefaction.

A general replacement procedure is recommended. It involves a three-step process in which a system planning assessment is made, followed by a repair record cost assessment, with a risk assessment completing the evaluation. At each stage in the evaluation, a decision to replace or retain is made. If the pipeline is to be replaced at any of the three stages, the flow chart shows, by means of dashed lines, a return to specifying new pipeline characteristics and repeating the three-tier decision process. It is recommended that an economic assessment about the desirability of repair and retention versus replacement be made for steel pipelines. Low leakage rates may obviate the need to make such an evaluation for some pipes in the transmission network. It is recommended that the economically-based model (or derivative thereof), which has been developed in-house for distribution piping, be applied. Making an economic assessment based on repair records fits logically within a comprehensive procedure. By predicating part of the assessment on a review of the repair record, the procedure promotes a systematic collection and analysis of repair statistics which can have benefits in determining medium and long-term trends in performance.

ACKNOWLEDGEMENTS

This report has been prepared as part of a study undertaken by Cornell University and EQE Engineering and Design to develop a methodology to replace or retain current and future steel pipelines within the Southern California Gas (SoCalGas) system. Work performed by Cornell researchers focused on the gas transmission system, whereas efforts by EQE personnel were concentrated on the gas distribution system. Dr. Ronald T. Eguchi was the Principal Investigator for EQE, and was assisted by Hope Seligson and Doug Honegger, both of EQE.

This report was prepared with the cooperation of many personnel of the Southern California Gas Company. The continuous, detailed assistance of Rick Gailing and Jack McNorgan, in particular, is deeply appreciated. Others who deserve recognition for their help are, in alphabetical order: Claire Becker-Castle, Karen Clark, Sheri Conley, Fred Grande, Jim Haynes, Lou Minjares, Dennis Moore, Mark Saad, Tom Stevens, John Streich, and Ron Wilkenson. Gratitude is expressed for help during the Northridge earthquake reconnaissance activities from Doug Honegger and Ron Eguchi of EQE, Le Val Lund, John Sisk of the Mobil Oil Company, Charlotte Rodrigues and Hampik Deckermenjian of the Los Angeles Department of Water and Power, John Tinsley of USGS, and Ken Jackura of Caltrans.

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SECTION 1

INTRODUCTION

1.1 BACKGROUND

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 is 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.

Clearly, earthquake effects need to be considered in the management of such a large, diverse pipeline system, but the risks associated with earthquakes also need to be evaluated in light of the many other factors affecting performance. The expenditures associated with repair and replacement need to be prudently managed, and, at the same time, need to be allocated in such a way that the risks of damage and disruption are minimized throughout the system. Repair and replacement strategies also must be implemented with an awareness of changing regulatory policies, as well as the economics associated with natural gas distribution as a deregulated industry.

1.2 OBJECTIVES

This report has been prepared to help develop a strategy and overall procedure to replace current and future steel piping within the SoCalGas system. To accomplish this, the research program was divided into two phases, involving a feasibility and an implementation phase of the work. This report focuses on the feasibility phase in which a general methodology for making decisions about steel pipeline integrity has been developed and applied to a relatively small portion of the SoCalGas system. This feasibility phase is important for establishing the practicality of the process as well as the benefits which will accrue to SoCalGas from a system-wide implementation of the methodology. In the implementation phase, the general methodology will be refined, tested for additional portions of the system, and implemented with SoCalGas engineers as a continuing program to assess pipeline conditions and set cost-effective priorities for steel pipeline repair and replacement.

The objectives of the feasibility phase of the project are two-fold:

- Develop a general methodology for evaluating the integrity of steel piping within the SoCalGas system and for setting priorities regarding the repair and replacement of such piping. The assessment of repair and replacement needs should be formulated to optimize public safety, economics, system planning, and regulatory issues. The methodology needs to account for varying rates of deterioration, varying depths of cover and pipe exposure, soil conditions, internal pressure and hoop stress, proximity to populated areas and public facilities, age of piping, etc. The methodology will also account for earthquake hazards associated with strong ground shaking, surface faulting, liquefaction, landslides, and differential settlements.

- Assess the feasibility of applying the methodology by means of a cost/benefit analysis. The cost and time of developing databases, integrating these with appropriate risk and economic models, and applying these on a systematic basis to the SoCalGas steel pipeline network need to be evaluated and compared with the improved safety and cost savings expected to result from the more comprehensive and accurate assessments.

To accomplish these objectives, the following five tasks have been performed.

1. Review Current SoCalGas Programs

A review has been made of existing methodologies to set priorities for pipe replacement pursued by the SoCalGas Transmission and Storage and Distribution Departments. Input also has been received from the Engineering Design and System Planning Departments.

2. Improvements in Existing Programs

Work has been performed to develop a consistent, company-wide approach which involves the best elements of existing programs and input from all departments contacted. Special attention has been devoted to coordinating the best elements of current procedures with System Planning. The intention has been to produce an integrated approach to steel pipeline replacement and planning, which is derived by modifying and combining elements of the existing SoCalGas procedures.

3. Refined Economic and Risk Models

New modeling techniques have been examined, including statistical procedures for the time-dependent occurrence of leaks in distribution pipelines. These models have been tested for a small portion of the SoCalGas system, and used to show how economic decisions can be improved when based on a refined projection of future leakage events. The investigations, database, and model development for this part of the work has been performed by EQE, Inc. and is contained in a companion report.

Current SoCalGas models for identifying high-risk transmission and distribution supply lines have focused on pre-World War II (pre-WWII) pipelines, which are deemed vulnerable to earthquake effects at their girth welds. Concern for these types of pipelines has been generated by their performance during the 1971 San Fernando earthquake [Eguchi, 1983; 1986]. As part of this research, additional performance statistics for these facilities have been obtained by examining records of pipeline behavior during the 1971 and other earthquakes. The results of these investigations are summarized in Section 3 of this report.

4. Refined Seismic Hazard Models

The research has taken advantage of the substantial case history data and new findings resulting from research sponsored by the National Center for Earthquake Engineering Research (NCEER) on soil liquefaction, large ground deformation, and effects on lifeline facilities [O'Rourke and Hamada, 1989; 1991; 1992; Hamada and O'Rourke, 1992]. Specifically for the SoCalGas system, stereo pair aerial photos have been used to identify local geomorphological features which provide evidence for liquefaction potential and the likely patterns of ground deformation in the event of soil failure. This information has been used to ascertain whether or not, and with what pattern, ground deformation, such as lateral spread, might develop during a future earthquake. Aerial photo interpretation, in combination with geologic maps, groundwater studies, soil surveys, and select soil borings have been used to refine existing knowledge about the susceptibility of soil to liquefaction.

Two transmission pipelines, Lines 121 and 123, were selected for the feasibility study. Both lines were constructed in 1930, and therefore represent older, more vulnerable portions of the system which are joined with oxy-acetylene welds. Emphasis in this work has been placed on characterizing the geotechnical and earthquake hazards to these pipelines, especially the potential for surface faulting and large ground deformation caused by liquefaction. The feasibility study for these lines is summarized in Section 6 of the report.

5. Overall Methodology

The results from the previous four tasks have been combined to develop an overall methodology for the SoCalGas system to assess pipeline integrity and make economically viable decisions about pipeline replacements which promote safety under normal operation and future earthquakes. It should be emphasized that the feasibility phase has concentrated on developing a general methodology and demonstrating its potential. Additional refinements, testing, and feedback from gas engineers are needed during the implementation activities which follow from this work.

1.3 SCOPE

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.

This report is composed of eight sections of which the first provides introductory and organizational information. The second section reviews the factors affecting steel pipeline replacement, with emphasis on the transmission and distribution supply lines of the SoCalGas system. The third section summarizes and evaluates the performance of high pressure gas pipelines in previous southern California earthquakes. The statistics of pipeline damage caused by previous earthquakes are used to establish the relative risks associated with pipelines of different age when subjected to either traveling ground waves or permanent ground deformation. The fourth section summarizes the current procedures for replacing transmission and supply lines, and the fifth section proposes improvements in the current methods. The sixth section summarizes the results of a feasibility study for Lines 121 and 123. Lines 121 and 123 were originally constructed in 1930 with 650-mm- (26-in.)-diameter pipe; replacement pipe installed primarily in the 1950s and 1960s has introduced diameters as large as 750-mm (30 in.) in certain sections of the lines. A methodology for assessing risks, especially those associated with earthquake effects, is applied to these lines, and the results are compared on an economic basis with the consequences of the current replacement program. Conclusions and recommendations are presented in the seventh section, and references are listed in the eighth section.

SECTION 2

FACTORS AFFECTING STEEL PIPELINE REPLACEMENT

There has been considerable work performed on hazard identification and quantification [e.g., Ozog and Bendixen, 1987; Martinsen and Cornwell, 1991] in relation to both process and pipeline applications. In addition, specific procedures have been proposed for identifying and quantifying hazards and setting pipeline replacement priorities [e.g., Kulkarni, et al., 1988; Muhlbauer, 1991; Kiefner and Vieth, 1991; Day and Peck, 1992]. In all cases, the procedures for optimal management and replacement begin with a systematic evaluation of the factors most influential in the performance of a given system.

This section concentrates on transmission and distribution supply lines, which operate at higher pressures and larger diameters than pipelines in the distribution networks. In many cases, the supply lines constitute single sources of supply to large areas, many within the central portion of the Los Angeles region [Strang, 1986]. In contrast to distribution piping, (for which economic replacement is the driving force), transmission and supply lines are influenced most strongly by operational elements, such as future loads and supply for peak demands. Transmission and supply lines, because of their relatively high operating pressures, involve the potential for more serious consequences as a result of damage than do distribution lines, so that risks to public safety need to be minimized as a primary focus of the replacement program.

The factors affecting steel pipeline performance are reviewed in this section, starting with the principal parameters embodied in the Code of Federal Regulations [Office of the Federal Register, 1990]. The review is extended to pipeline proximity to buildings, hoop stress, brittle-to-ductile transition temperature, pipe wall thickness, longitudinal and circumferential welds, pipe diameter and pressure, corrosion, environmental factors, earthquake and natural hazards, traffic loads, depth of cover, and pipe age. The section concludes with a general scheme for organizing the factors affecting performance and selecting the most important ones for a systematic program of replacement.

2.1 FEDERAL REGULATIONS AND REPORTING REQUIREMENTS

The minimum standards for natural gas pipeline design and operation are specified by Title 49, Part 192 of the Code of Federal Regulations, "Transportation of Natural and Other Gas by Pipelines: Minimum Federal Safety Standards" [Office of the Federal Register, 1990]. These standards establish statutory obligations, and have been incorporated into all state public utility and service commission codes. Accordingly, the minimum federal standards are a logical starting point in the evaluation of factors affecting pipeline performance and of any pipeline replacement program derived thereof.

The primary design equation in Title 49, Part 192 of the Code of Federal Regulations calls for the determination of a design pressure, P, by:

$$P = \frac{2\,St}{D} \cdot F \cdot E \cdot T \qquad (2\text{-}1)$$

in which S is the specified minimum yield strength of the pipe steel (SMYS), t is the nominal pipe wall thickness, D is the nominal outside pipe diameter, F is the design factor, which depends on class location, E is the longitudinal joint factor, which depends on the welding and fabrication process of the pipe, and T is a temperature derating factor. Specific directions are provided for the selection of each factor.

The Federal Code defines a transmission line as "a pipeline, other than a gathering line, that operates at a hoop stress of 20% or more of the SMYS." Accordingly, the preponderance of SoCalGas distribution supply lines qualify as transmission lines. In some cases, portions of older supply lines that have been replaced with newer, higher strength pipe may operate at hoop stress less than 20% SMYS.

Title 49, Part 191 of the Code of Federal Regulations [Office of the Federal Register, 1990] requires that reports be filed as a result of leaks which are deemed significant by the operator, and/or comply with criteria set forth in the code. These criteria include events leading to fatalities, hospitalization, removing pipe from service, gas ignition, and damage exceeding a specified threshold. Before 1984, the property loss threshold was set at $5,000. After

1984, the minimum reporting value was $50,000, which contributed to a sharp decline in the reportable gas line incidents.

According to the Transportation Research Board (TRB) [1988], more than 10,000 incidents were reported between 1971 and 1986 in hazardous liquids and natural gas transmission and gathering lines. The great majority of reportable events were associated solely with property or product loss. Approximately 3% of all reportable events were accidents involving deaths and injuries [TRB, 1988]. More than 40% of the gas transmission and gathering line incidents occurred in the four south central states of Arkansas, Louisiana, Oklahoma, and Texas, which cover an area consistent with the highest density of transmission and gathering systems.

The reasons for pipeline failures are recorded in Department of Transportation (DOT) Annual Reports on Pipeline Safety as corrosion, outside force, defective material or construction, and other. These subject headings are quite general, and do not permit an in-depth assessment of cause. Outside force, for example, includes various causes of damage such as third party construction damage, undermining, vandalism, and natural hazards.

The breakdown of failure statistics for 1971-1986, based on TRB analysis [TRB, 1988], is illustrated in Figure 2-1. An additional illustration of the failure statistics for 1985-1989 is given in Figure 2-2, based on analysis of more recent DOT data. The most prominent factors contributing to pipeline incidents are outside forces, which account for roughly 40% of all reportable events in both reporting periods. Corrosion is the second most important factor contributing to pipeline failure. A conspicuous rise in the percentage of corrosion events can be seen in the 1985-1989 data set.

It is interesting to compare U.S. and European data. Information pertaining to European natural gas pipeline incidents has been summarized for six gas transmission companies [European Gas Pipeline Incident Group, 1988], including British Gas plc, N.V. Distrigaz S.A., Gaz de France, N.V. Nederlandze Gasunie, Ruhrgas AG, and SNAM S.p.A. The incidents involve loss of gas in onshore steel transmission lines, operating at pressures above 1.5 MPa (220 psi). The data were

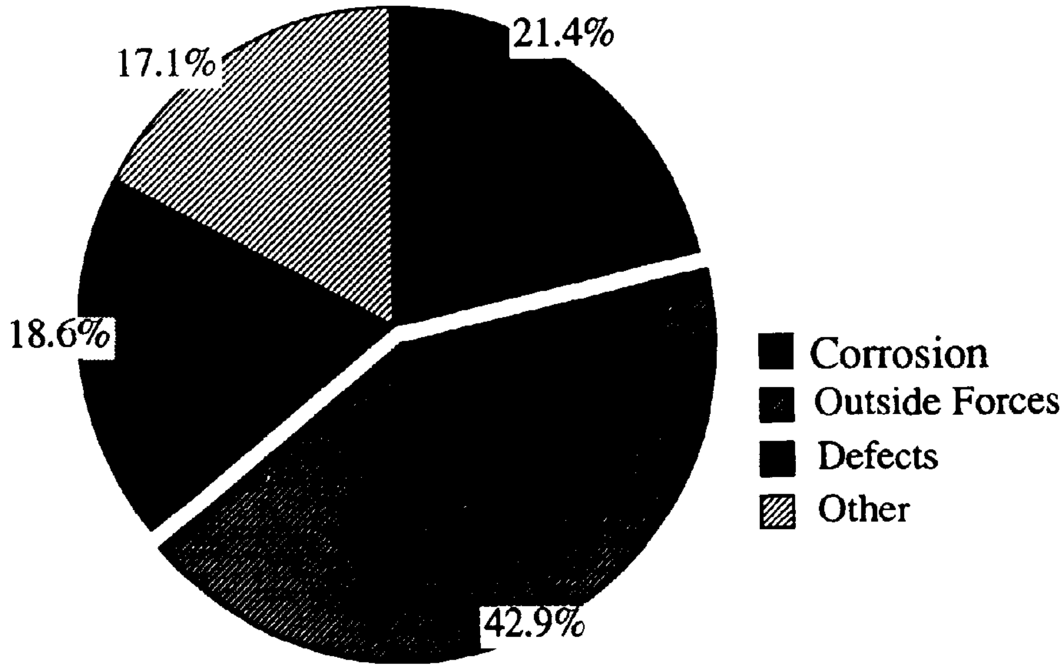


FIGURE 2-1. Breakdown of Causes of Incident for U.S. Hazardous Liquids and Natural Gas Transmission and Gathering Pipelines: 1971-1986 [after TRB, 1988]

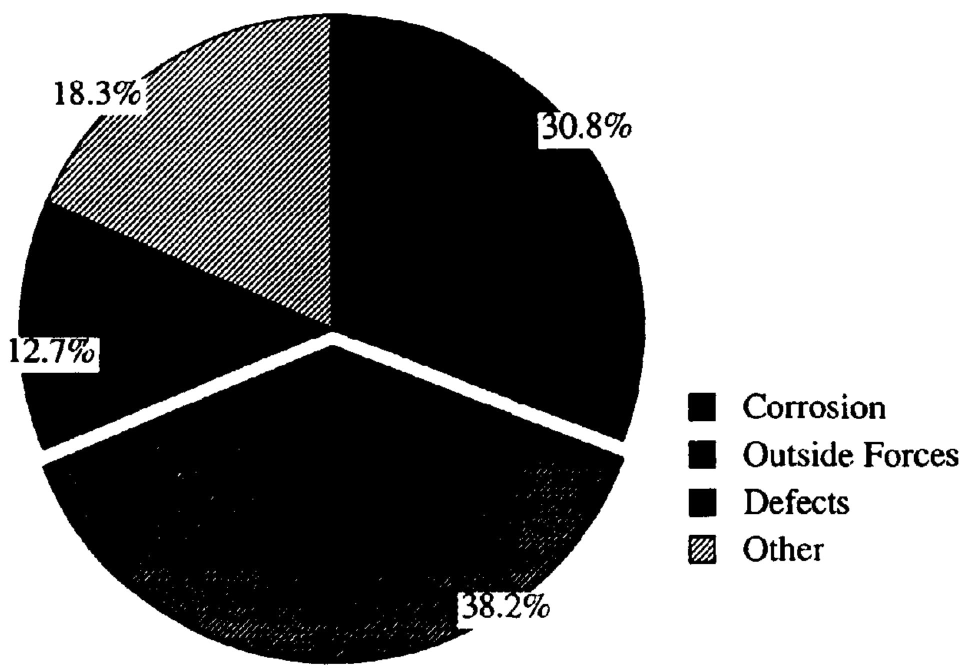


FIGURE 2-2. Breakdown of Causes of Incident for U.S. Hazardous Liquids and Natural Gas Transmission and Gathering Pipelines: 1985-1989

recorded since 1970, and are representative of approximately 970,000 km years (603,000 mi. years) of operation.

Incidents were divided into three categories of leak size, including: 1) pinhole/crack: equivalent defect diameter less than or equal to 20 mm (0.8 in.), 2) hole: equivalent defect diameter greater than 20 mm (0.8 in.) and less than or equal to pipe radius, and 3) rupture: equivalent diameter of defect greater than pipe radius. In estimating the equivalent diameter, a noncircular defect was converted to a circular one with the same area. The incidents were identified according to cause in terms of external interference, construction defect/material failure, corrosion, ground movement, hot tap by error, and other. Hot tap errors involve cutting or other penetration by gas company personnel of a live pipeline that was incorrectly identified.

Figure 2-3 shows the frequency of incidents by cause, in which frequency is expressed per km/year. Mechanical interference by external force is the main cause of accidents and is responsible for the majority of incidents involving large losses of gas, including ruptures. Approximately 50% of all incidents were attributed to this cause. Construction defect/material failure and corrosion are the second and third principal causes of failure, respectively. No ruptures were attributed to corrosion.

Because of different reporting procedures and variations in the ways of identifying causes of damage, it is not possible to make detailed comparisons among pipeline incident statistics for U.S. and European systems. Nevertheless, a general comparison, based on broad trends, shows consistent patterns. The European database indicates that approximately 50% of natural gas pipeline incidents are caused by factors which most probably would be grouped under outside forces in the U.S. reporting protocol for both liquid fuel and gas pipelines.

2.2 PIPELINE PROXIMITY

It is important to review the design factors associated with pipeline proximity, which are embodied in the primary design equation of the Federal Code. Building and population characteristics, type of transportation route, and whether a pipeline is cased or uncased are components used to choose the design factor. Four class locations are defined in accordance with Table 2-I, which reflect increases

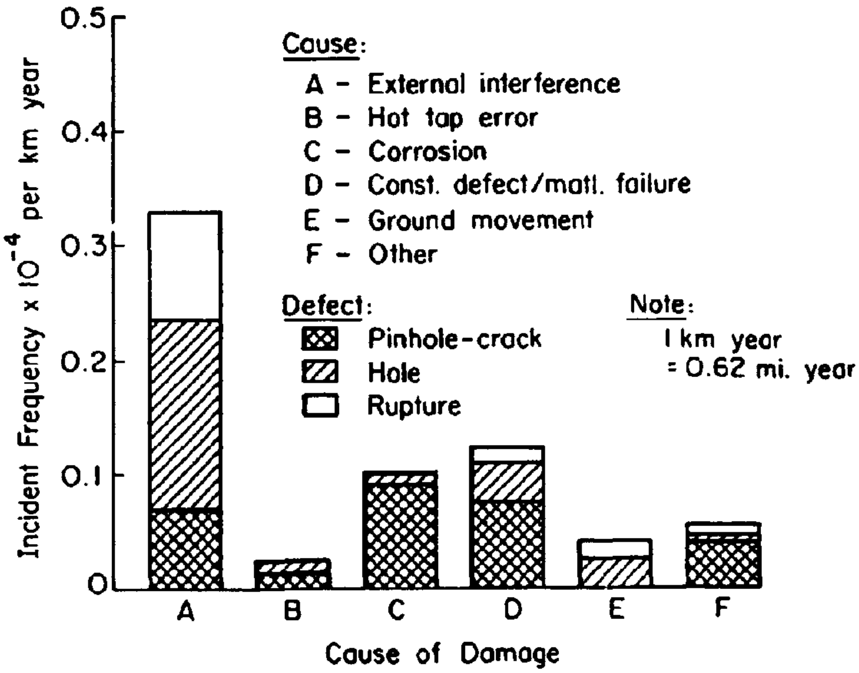


FIGURE 2-3. Incident Frequency According to Cause of Incident [after European Gas Pipeline Incident Group, 1988]

in building and population density as the class location number increases. The class location number is assigned on the basis of the number and types of buildings and areas of public congregation within a strip 0.4 km (1/4 mi.) wide and 1.6 km (1 mi.) long, centered on the pipeline. Consideration also is given to location within the rights-of-way of transportation routes. According to the class location number and proximity to transportation routes, the design factors may assume values of 0.40 to 0.72. The design factors associated with each class location and pipeline description are summarized in Table 2-II.

Although the class locations account for high density of occupied space, it may be advantageous to identify special locations within service areas where there is a high likelihood for people to congregate for significant periods of time. Candidate locations are pipelines beneath or adjacent to major thoroughfares and

TABLE 2-I. Class Locations for Gas Pipeline Design [after Code of Federal Regulations, Title 49, Part 192 (Office of the Federal Register, 1990)]

Class Location	Description
Class 1	Any class location unit[a] with 10 or less buildings intended for human occupancy
Class 2	Any class location unit[a] with more than 10 but less than 46 buildings intended for human occupancy
Class 3	Any class location unit[a] with more than 46 buildings intended for human occupancy, or an area where the pipeline is within 91 m (100 yds) of a building or small, well-defined outside area (e.g., playground, recreation area, etc.) occupied by 20 or more persons during normal use
Class 4	Any class location unit[a] where buildings with four or more stories above ground are prevalent

[a]An area which extends 20 m (220 yds) on either side of the centerline of any continuous 1.61-km- (1-mi.)-length of pipeline

TABLE 2-II. Class Locations and Associated Design Factors [after Code of Federal Regulations, Title 49, Part 192 (Office of the Federal Register, 1990)]

Occupancy, Traffic, and Exposure Classifications	Maximum Design Factor
Class 1	0.72
Class 1 with a steel pipeline that: a) crosses without a casing the right-of-way of an unimproved public road; b) crosses or makes a parallel encroachment without a casing of the right-of-way of a hard-surfaced road, highway, public street, or railroad; c) is supported by a vehicular, pedestrian, railroad, or pipeline bridge; and d) is used in a fabricated assembly	0.60
Class 2	0.60
Class 2 with an uncased steel pipeline that crosses the right-of-way of a hard-surfaced road, highway, public street, or railroad	0.50
Class 1 and 2 with a steel pipeline in a compressor, regulating, or measuring station; or on a platform offshore or in inland navigable waters	0.50
Class 3	0.50
Class 4	0.40

pipelines adjacent to schools, hospitals, shopping centers, and high density housing. These locations could be regarded as equivalent to Class 4 Locations.

2.3 HOOP STRESS

The hoop stress generated by pipeline operating pressure has been shown to affect the ductile rupture of pipe steel. Figure 2-4 presents a plot developed by Shannon [1974] in which hoop stress, as a fraction of SMYS, is expressed as a function of the size of a pipe wall defect. The defect size is given in dimensionless terms as $2C/\sqrt{Rt}$, in which 2C is the length of the defect, R is the pipe radius, and t is the pipe wall thickness. Test data are plotted in the figure for defects which were induced artificially by machining slots in the pipe wall, as well as defects which were induced either by corrosion in the field or under laboratory-controlled conditions.

As the internal pressure in the experimental pipe was increased, failure was initiated at the defect by plastic flow through the remaining wall thickness. If penetration of the full thickness occurred within the boundaries of the original defect, the resulting breach of wall was referred to as a leak. If a fracture was propagated beyond the boundaries of the original defect, ductile rupture of the pipe section occurred. Ductile rupture, as opposed to leak formation, may be regarded as a potentially catastrophic event because disruption of the wall spreads far beyond the confines of the original defect. Such rupture can result in an explosive release of energy from compressed gas, and may be accompanied by additional fire and explosion effects, if ignition takes place.

As illustrated in the figure, artificial defects led to ductile rupture at the lowest percentages of SMYS. Artificial defects are representative of gouging and scraping penetrations of pipe wall caused by third party damage, particularly direct hits by excavation and agricultural machinery. Corrosion defects show a different trend, with higher percentages of SMYS as the threshold for ductile rupture. The lines marking the thresholds of ductile rupture for artificial and corrosion defects are based on a theoretical formulation for the value of hoop stress at which defect penetration of pipe wall becomes unstable and produces a propagating rupture [Shannon, 1974].

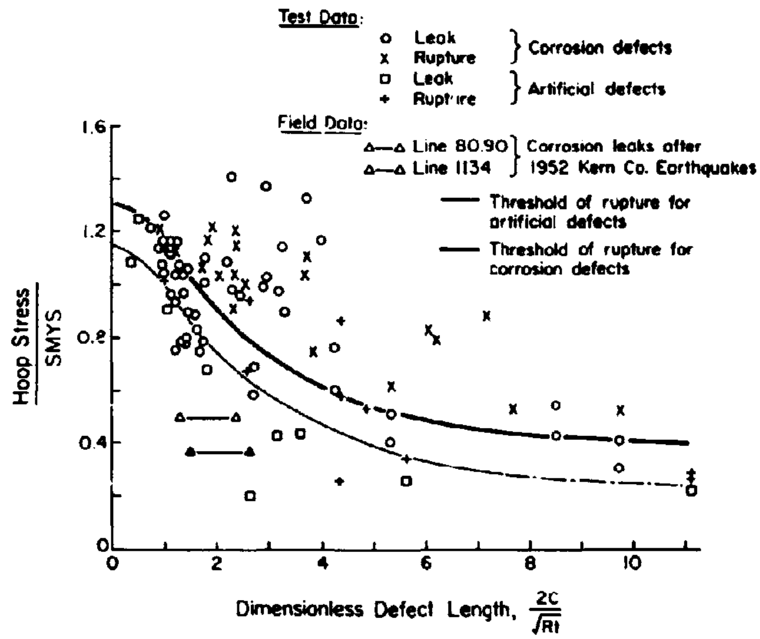


FIGURE 2-4. Hoop Stress as a Fraction of SMYS Expressed as a Function of Dimensionless Defect Length [after Shannon, 1974]

Figure 2-4 shows that even large corrosion defects have not resulted in ductile rupture at hoop stresses less than or equal to 50% SMYS. When large artificial defects are considered, a hoop stress less than or equal to 30% SMYS is required to prevent ductile rupture.

The experimental and theoretical results of Shannon [1974] have had a strong influence on practices in the United Kingdom (U.K.), where substantial emphasis has been placed on third party damage in the form of scraping and gouging buried pipelines. In essence, British recommended practice for transmission pipelines in suburban population areas calls for hoop stresses not to exceed 30% SMYS [Institution of Gas Engineers, 1984]. The adoption of this limitation on stress from oonsideration of brittle [Fearnehough, 1974] and ductile [Shannon, 1974] rupture is explained by Knowles, et al. [1978], and is the greatest single difference between U.S. and U.K. practice for natural gas pipelines. Practice in the U.S. emphasizes measures which prevent third party damage, including above ground markings, one call systems, and special protective devices.

Of particular interest for U.S. practice is the ductile rupture threshold for corrosion defects. As mentioned above, the experimental results show no evidence of rupture, even for large defects, given a hoop stress less than or equal to 50% SMYS. Most corrosion defects, however, are relatively small, and are confined to localized pits and limited areas of wall thinning. European data, representing over 970,000 km years (603,000 mi. years) of gas pipeline operation, indicate that corrosion defects are predominantly less than 25 mm (1 in.) in equivalent diameter [European Gas Pipeline Incident Group, 1988]. Even for the smallest diameters and thinnest pipe walls, the dimensionless lengths associated with these types of defects are likely to be less than 4. As mentioned in the previous section, no ruptures because of corrosion are found in the European data set.

Pipeline damage in previous earthquakes appears to corroborate the trends in Figure 2-4. As explained in Section 3, two gas transmission lines experienced damage in the form of leaking corrosion pits as a result of the main shock of the 1952 and 1954 Kern County earthquakes. Both Lines 80.90 and 1134 have a wall thickness of 6.4 mm (0.25 in.) and an SMYS of 241 MPa (35 ksi). Line 80.90 is 550 mm (22 in.) in nominal diameter, with a current maximum allowable operating pressure (MAOP) of 2.8 MPa (400 psi); Line 1134 is 450 mm (18 in.) in nominal diameter, with a current MAOP of 2.5 MPa (360 psi). It is assumed conservatively that the corrosion defects on these lines were 1 to 2 in. (25 to 50 mm) in equivalent diameter. The dimensionless hoop stresses and defect lengths for these pipelines, which are plotted in Figure 2-4, are well below the threshold of ductile rupture for corrosion defects.

2.4 BRITTLE-TO-DUCTILE TRANSITION TEMPERATURE

Brittle fracture occurs with relatively little deformation on specific metallurgical planes by a cleavage process. It differs from ductile rupture, which is accompanied by relatively large deformation in accordance with a shearing process. Brittle rupture can propagate a substantial distance, and thus represents a potential source of severe pipeline disruption and vigorous release of gas energy. The brittle-to-ductile transition temperature is a property of the pipe steel, which defines a thermal operating level below and above which brittle and ductile rupture, respectively, will occur. Most modern pipelines have relatively low brittle-to-ductile transition temperatures [below 0°C (32°F)], but older pipelines may not.

Work by Fearnehough [1974] has shown that brittle rupture not only depends on temperature, but on the level of stress in the pipe. Experimental data summarized by Fearnehough indicate that, if the hoop stress declines as a fraction of SMYS, the brittle fracture threshold will change to a temperature lower than the transition temperature, thereby extending the range of ductile behavior. Knowles, et al. [1978] show that ductile behavior can be extended to temperatures as low as 40°F (25°C) below the transition temperature, provided hoop stress is reduced from approximately 60 to 30% SMYS in direct proportion to the increasing temperature difference.

2.5 PIPE WALL THICKNESS

Pipe wall thickness may alternatively be viewed as providing a buffer against corrosion penetration, capacity to sustain permanent ground deformation, and resistance against impact by excavation and agricultural equipment. Given that wall thickness has been sized properly for the required percentage of SMYS, the principal benefit of increased wall thickness appears to be additional resistance to external interference and construction hits. This aspect of pipeline performance is well illustrated by the European data set discussed in Section 2.1.

Figure 2-5 shows the incident frequency for all pipelines damaged by external interference plotted as a function of pipe wall thickness. Please note that the incident frequency for pipe with wall thickness less than 5 mm (0.20 in.) exceeds the incident frequency for all external interference in Figure 2-3. There are a smaller number of thin wall pipes relative to others in the European systems. As a result, the km years associated with thin wall pipes are less than the 970,000 km years (603,000 mi. years) for the entire database, thereby yielding a higher frequency of incidents.

Figure 2-5 shows that the incident frequency decreases dramatically as a function of pipe wall thickness. The incident frequency for wall thickness between 5 and 10 mm (0.20 and 0.39 in.) is approximately 2.5×10^{-4} per km year. The incident frequency for pipe wall thickness exceeding 10 mm (0.39 in.) is very low. It

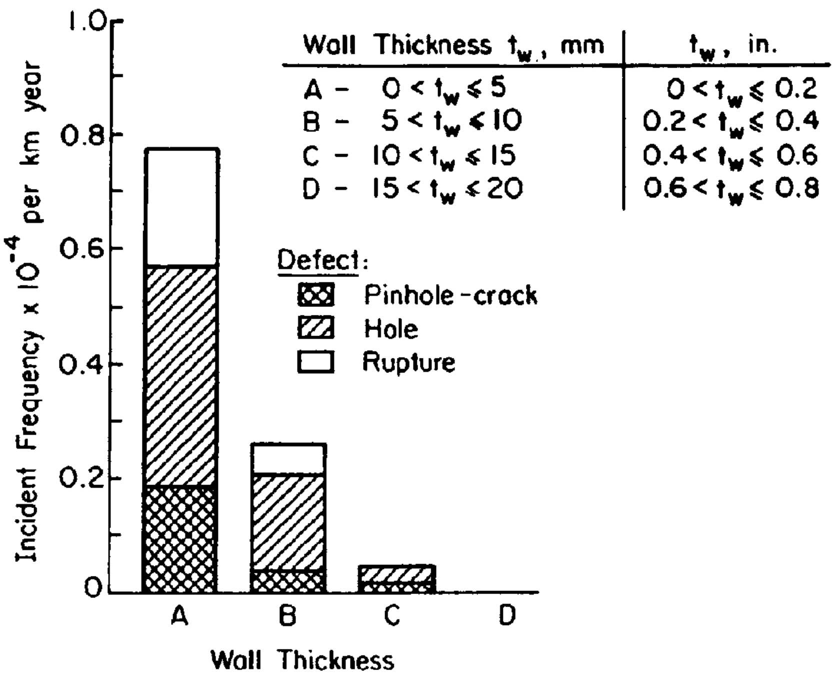


FIGURE 2-5. Incident Frequency Associated with External Interference According to Wall Thickness [after European Gas Pipeline Incident Group, 1988]

also is interesting to note that there are no ruptures associated with wall thickness equal to or greater than 10 mm (0.39 in.).

Research undertaken by the British Gas Corporation on the forces and associated construction equipment required to dent and fracture steel pipelines has been discussed by Knowles, et al. [1978]. Figure 2-6 summarizes some of the research results by showing the force required to dent pipe as a function of wall thickness. Forces associated with backhoe-type equipment, commonly used at the time the research was conducted, are marked on the figure. The denting force increases at an accelerating rate as the wall thickness increases. Because the force required to rupture the pipe exceeds the denting force, Figure 2-6 illustrates that wall thickness can be specified to reduce substantially the risk of third party damage leading to failure.

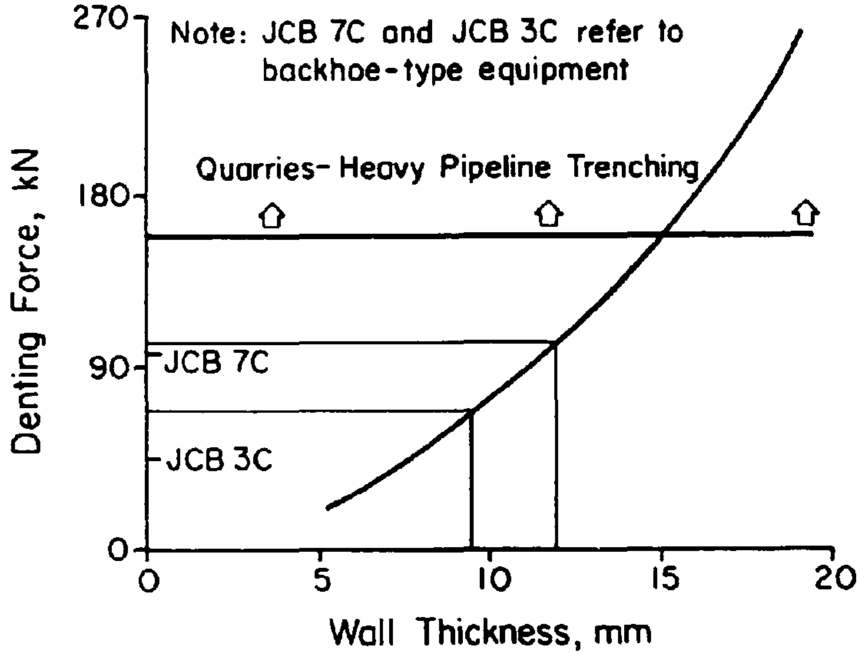


FIGURE 2-6. Force Required to Dent Pipe as a Function of Pipe Wall Thickness [after Knowles, et al., 1978]

Knowles, et al. [1978] provide the following comments:

> "The general conclusion has been reached that mobile diggers...cannot exert more forces than that required to dent a pipe 0.375 in. (9.52 mm) thick. It seems reasonably clear that either wall thicknesses greater than these, or special protective covers, will prevent the occurrence of any defect liable to fail the pipeline. By considering the effects of greater wall thickness, there is enough confidence to use a pipe wall of 0.469 in. (11.91 mm) instead of sleeves (casings)."

The wall thickness limits of 9.52 mm (0.375 in.) and 11.91 mm (0.469 in.) described by Knowles, et al. [1978] are the same as those for which special provisions are made in British recommended practices for natural gas pipelines, specifically IGE/TD/1: Edition 2 [Institution of Gas Engineers, 1984] and BS8010: Part 2, Section 2.8 [British Standards Institution, 1992]. For example, IGE/

TD/1: Edition 2 allows hoop stress to be as high as 50% SMYS in relatively close proximity to buildings, if pipe wall thickness exceeds 11.91 mm (0.469 in.).

Again, it should be emphasized that U.S. practice is oriented towards preventing third party damage. The risks associated with wall thickness are conditional and are derived from events which involve primarily third party damage.

2.6 LONGITUDINAL AND CIRCUMFERENTIAL WELDS

Welds can have a very important effect on pipeline performance because they are potential locations of flaws from which fractures may propagate, resulting in pipeline rupture. As discussed in Section 2.1, the primary design equation of the Federal Code [Office of the Federal Register, 1990] accounts for the quality of longitudinal pipe welds by means of a joint factor, E, which may reduce the allowable hoop stress to as little as 60% of that associated with a seamless pipe for any class location. Circumferential, or girth, welds require careful evaluation, depending on the type and date of the weld. A statistical analysis of pipeline rupture during past earthquakes, presented in Section 3, shows substantially increased vulnerability to traveling ground waves for pre-1930 oxy-acetylene welded pipelines, compared with unreconditioned post-1930 pipelines, which were constructed principally with electric arc welds.

2.7 INTERNAL PRESSURE AND PIPE DIAMETER

The internal pressure, P, and pipe diameter, D, contribute directly to the hoop stress, and thus are involved in the primary design equation of the Federal Code [Office of the Federal Register, 1990] (see Equation 2-1). For a given diameter, the design pressure is adjusted so that hoop stress will not exceed a percentage of SMYS consistent with the design factor for a given class location. Hence, the relative risk of exceeding SMYS should vary in direct proportion to the design factor. Risks, however, are more strongly influenced by the consequences of damage, and will be especially sensitive to pipeline proximity to buildings, public areas, and transportation routes. The consequences of damage also will depend on the cratering potential of the pipe, which in turn depends on the energy stored in the compressed gas. Should a rupture occur, either by longitudinal propagation from a pipe wall defect or by a circumferential break at a girth weld, the sudden release of energy from the pressurized gas can cause cratering and substantial outflow of gas.

In Appendix A, an equation is derived for the energy, W, per unit length of pipeline, which is liberated by pipe rupture, as:

$$W = 2.45 \; P \; D_i^2 \left[1 - \left(\frac{p_a}{P} \right)^{0.242} \right] \qquad (2\text{-}2)$$

in which D_i is the internal pipe diameter, P, is the internal gage plus atmospheric pressure, and p_a is atmospheric pressure.

Equation 2-2 provides a means of normalizing internal pressure and pipe diameter to express the relative potential for an explosive release of contents, should a rupture occur at a weld or along the pipe wall. In Section 5, it is explained how this equation can be used to judge the relative risks of pipelines subject to rupture at oxy-acetylene girth welds, and thus establish a means of setting priorities in a steel pipeline replacement program.

2.8 CORROSION

As evinced by the TRB and DOT data summarized in Section 2.1, pipeline corrosion is the second ranking cause of reportable leakage. The potential for corrosion depends on diverse factors, including those related to the pipeline environment such as soil type, location of groundwater, groundwater chemistry, soil moisture content, resistivity, pH, chloride content, presence of sulphides, sulphites, and sulphates, and stray currents. In some cases a standard index, known as Langelier's index, can be determined to provide an assessment of groundwater corrosivity in terms of its tendency to dissolve or deposit calcium carbonate. The condition of the pipeline also influences the potential for corrosion such that consideration needs to be given to the presence, absence, and efficiency of cathodic protection and pipeline coating.

Given the complex, multivariate factors influencing corrosion, it often is best to let the pipeline measurement and repair record provide data directly related to the location, frequency, and characteristics of corrosion. Checks on sacrificial anodes, transformer outputs, and pipe-to-soil potentials at test posts, casings, and ancillary equipment result in measurements which directly reflect the efficiency of the corrosion protection system. Closely spaced surveys of pipe-to-soil potentials [approximately on 15-m (50-ft) spacings] can provide detailed information in special areas. Repair records, if taken properly and evaluated systematically, provide a good means of assessing corrosion problems, because they are tuned to problem areas and collectively can provide a statistically valid sample for projecting future difficulties. A proper system of repair records and pipeline measurements is likely to be more finely focused and comprehensive than any data set on soil, groundwater, and associated chemistry.

The collection and use of repair records and pipeline measurements are discussed in Section 5 as part of an integrated package of improvements which should be considered for implementation in a pipeline replacement program. Direct observations of pipeline conditions should be recorded so that information is on file with respect to visible corrosion effects and quality or absence of pipe coating.

2.9 ENVIRONMENTAL FACTORS

Environmental factors have been discussed by Day and Peck [1991] with respect to transmission line replacement strategies developed in the San Francisco Bay region. In this report, environmental factors are defined on a broad basis with reference to Day and Peck [1992], and are taken to include proximity of special plants and wildlife, stream crossings, public parks and wetlands, potential locations of hazardous waste, and Native American burial grounds and other important cultural sites.

In some cases, replacement will not be feasible within an existing right-of-way (ROW) such that an alternative ROW needs to be used. The feasibility of replacement under these circumstances must be assessed carefully with respect to the potential for disturbing endangered plants and wildlife, cultural sites, and locations of buried hazardous waste. Especially in urban and suburban environments, a potential ROW may involve previous commercial and industrial areas.

Buried tanks at previous service stations are prime locations for potentially contaminated soil.

In a broad context, environmental factors may be taken to include current and future development over existing pipelines. Pipeline construction moratoriums because of recent or upcoming street paving can create a significant economic incentive either to avoid or schedule replacement in advance of the pavement construction.

2.10 EARTHQUAKE AND NATURAL HAZARDS

There are a variety of earthquake and natural hazards which can affect pipelines operated in southern California. The principal earthquake hazards generally are distinguished as being associated with traveling ground waves and permanent ground deformation. O'Rourke and McCaffrey [1984] and Hall and O'Rourke [1991] discuss these factors and note that the preponderance of pipeline damage from traveling ground waves in previous earthquakes has occurred in brittle materials or pipelines weakened by corrosion and other defects. With a single exception (O'Rourke, 1988), there are no documented instances of traveling ground wave damage to steel pipelines in good repair, constructed with modern welding techniques and quality control measures.

The principal earthquake hazards for steel transmission and supply lines are those which can cause large permanent ground movements. O'Rourke [1986] and O'Rourke and McCaffrey [1984] identify the principal causes of earthquake-induced permanent ground deformation as surface faulting, soil liquefaction, and landslides. Liquefaction effects are subdivided further into flow failures, lateral spreads, subsidence, loss of bearing capacity, and buoyancy effects.

Natural hazards affecting transmission and supply line systems include landslides, flooding, and erosion and undermining associated with heavy rainfall. As pointed out by O'Rourke [1986], the identification of potential landslide areas under static conditions is one of the first steps in evaluating the risk of landslide activity under seismic conditions.

In Section 5, a simplified method for evaluating earthquake hazards, particularly those associated with liquefaction, is proposed as a means of improving current replacement procedures. In Section 6, the method is applied as part of a feasibility study for deciding on retention or replacement of two pre-WWII transmission lines.

2.11 TRAFFIC LOADS

The three-dimensional stress system imposed in pipelines from internal pressure, soil load, and traffic-induced loading at highways and railroads has been evaluated in detail in recent work performed for the Gas Research Institute [O'Rourke, et al., 1988; Stewart, et al., 1991; Ingraffea, et al., 1992]. This work was undertaken in response to concerns expressed about the use of casings at highway and railroad crossings, and the consequent need to have a comprehensive methodology for evaluating pipeline stresses in the absence of casings. The analytical methodology could be applied in a rigorous way to the types of vehicular loading anticipated at road crossings in the SoCalGas operating region. On the basis of general experience with the methodology, however, it does not appear that longitudinal and circumferential stress increments from highway and street traffic will be sufficiently large to use traffic loading as an effective index for the system-wide performance of pipelines. As pointed out by O'Rourke, et al. [1988], the use of casings at highway and railroad crossings may introduce difficulties with respect to cathodic protection such that the risks from corrosion would be larger than those associated with traffic-induced stresses in an uncased pipeline. Highway and railroad crossings involve potentially greater consequences with respect to damage than pipe damage at other locations, and this aspect of potential response is reflected in the Federal Code [Office of the Federal Register, 1990] by means of reduced design factors for Class 1 and 2 locations.

2.12 DEPTH OF COVER

Minimum depth of cover requirements are set forth for transmission lines by the Code of Federal Regulations, Title 49, Part 192 [Office of the Federal Register, 1990] as varying from 762 to 914 mm (30 to 36 in.), depending on class location and crossing of transportation routes. Variations in depth of cover can be important when substantial reductions are planned because of new development or significant additional loading is anticipated because of embankment construction. These cases are special conditions, sometimes accompanied by a change in class location, which need to be evaluated on a site-specific basis. Accordingly, depth of cover is not an especially sensitive parameter for assessing pipeline system performance, and is likely to be of limited value when used on a recurrent basis for repair/replacement decisions.

2.13 PIPELINE AGE

Age provides a convenient means for identifying pipelines according to the amount of time they have been subjected to service loads, various deterioration processes, and externally applied loads. Age, in itself, is not a direct cause of difficulties, but an index which often can be correlated with exposure to processes having the potential to affect pipe integrity. Corrosion is an electro-chemical process leading to metallic deterioration which, if not corrected nor protected against, will result in increasing difficulty with age for pipelines in corrosive surroundings.

Hazardous liquid pipeline studies for the California State Fire Marshal (EDM Services, Inc., 1993) have shown a strong correlation between leak incident rates and age. This work indicates that pipe constructed before 1940 had a leak incident rate nearly twenty times that of pipe constructed in the 1980s. The report points out that modern pipeline coatings are more effective than older coatings, especially those installed before the 1940s so that the older pipe, based on this observation, would be more likely to experience a higher external corrosion rate. The report also shows that the trends in overall leak incident rates relative to age are very similar to leak rate trends for pipe affected by external corrosion.

A study commissioned by the Pipeline Research Committee of the American Gas Association (AGA) [Jones, et al., 1986] came to similar conclusions. This investigation includes an examination of the relationship between failures in gas transmission and gathering lines with age of pipe. Older pipelines, particularly those installed in the 1930s and 1940s, have the highest failure rates.

Age also is an indication of date of installation. The installation dates sometimes can be linked to a particular type of construction characteristic, such as the poorer quality of coating in pre-1940 pipelines mentioned in the work by EDM Services, Inc. (1993). As shown later in this report (see Section 3), the date of installation is used as an index of potential problems associated with the seismic performance of oxy-acetylene welded pipelines.

Age, therefore, can be used to make judgments about relative vulnerability, but its use should be conditioned by the recognition that age often reflects the potential severity of a specific process, such as corrosion. Accordingly, a more appropriate strategy for assessing risk may be to identify locations wherein repair statistics show the potential for corrosion and then use age as the index for evaluating replacement priorities on a more local basis. In other instances, dates of installation, rather tnan age, may provide a more effective parameter for deciding about repair/replacement measures.

2.14 REGULATORY ISSUES

Regulatory trends reflect the involvement of government, communities, and industry in ways which constantly change and are difficult to predict. Regulatory issues, however, can have a profound influence on the economies of pipeline system management and therefore should be part of the decision process when establishing a repair/replacement strategy. Because of the change inherent in regulatory issues, it is advisable to promote close communication and systematic input from the regulatory affairs personnel within the gas company. Only by establishing continuing interaction with the Regulatory Affairs Department or equivalent company group can an evaluation process be developed which responds to new measures and adjusts over time to governmental and community activities.

Although regulatory trends are difficult to forecast, there are two regulatory activities underway which are likely to influence public and governmental perceptions of hazardous pipeline systems and affect the economics of pipeline replacement. The first of these activities is specific to California and involves the Seismic Hazards Mapping Act (California State Legislature, 1990).

The Act calls on the State Geologist to prepare a time schedule and compile maps identifying seismic hazards zones, which are submitted to an oversight board and all affected cities, counties, and state agencies for review and comment. Cities and counties are to account for the effects of mapped seismic hazards when adopting or changing land use plans, and to require a geotechnical report delineating any seismic hazard before approval of a project located in a seismic hazard zone. Although little comment has been made to date about the effects of such mapping on the planning and operation of lifeline systems, these large, geographically extensive networks are likely to be influenced by the legislation in a variety of locations. Moreover, the locations of gas pipelines in mapped zones of seismic hazards are likely to change the perceptions of communities and governmental agencies with respect to the risks associated with nearby pipelines.

The California Seismic Safety Commission (1991) has developed an earthquake hazards reduction program, which specifically identifies the improvement of gas system earthquake performance as one of its goals. Program milestones include draft standards of acceptable performance levels and, if required, the enforcement of acceptable levels of risk, including seismic safety standards and emergency response and recovery plans.

A second regulatory issue of considerable interest for deciding on repair/replacement alternatives involves the Pipeline Safety Act of 1992 (U.S. Congress, 1992). The Act amends and adds to provisions in the original 1968 Act (U.S. Department of Transportation, 1980). Specifically, the 1992 Act calls for the identification of all transmission pipeline facilities in high-density population areas and increases the inspection requirements for them. A short summary of the recent legislation has been provided by AGA (1993):

> "This rule does not actually require pipelines to use smart pigs. The recently passed Pipeline Safety Reauthorization Act of 1992, however, does require DOT, in a separate rulemaking, to promulgate regulations requiring the periodic inspection of transmission lines located in high-density population areas. During the course of that rulemaking, DOT will examine the issue of whether to require smart pig use. DOT must promulgate that rule sometime within the next three years.
>
> The rule currently under consideration is required by section 108(b) of the Pipeline Safety Reauthorization Act of 1988. Section 108(b) requires that new and replacement transmission facilities or

equipment be designed and constructed to accommodate the passage of smart pigs, but only 'to the extent practicable'. DOT's Office of Research and Special Programs Administration (RSPA) is responsible for implementation of this rule."

The requirements being developed with respect to inspection by smart pigs can have a significant effect on repair/replacement strategies. The extent to which replacement transmission facilities are required to be designed and constructed to accommodate smart pigs affects cost and, therefore, the order of replacement priority assigned to various pipelines. Information regarding these emerging regulations needs to be integrated into the decision process.

SECTION 3

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.

3.1 SUMMARY OF MAJOR EARTHQUAKES

Table 3-I summarizes information pertaining to ten of the most severe earthquakes which have occurred in southern California prior to the Northridge earthquake. 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 3-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 3-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.

3.2 1933 LONG BEACH EARTHQUAKE

3.2.1 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].

3.2.2 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.

3.2.3 Locations of Liquefaction and Pipeline Damage

Figure 3-1 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 [1905] 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 3-1 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.

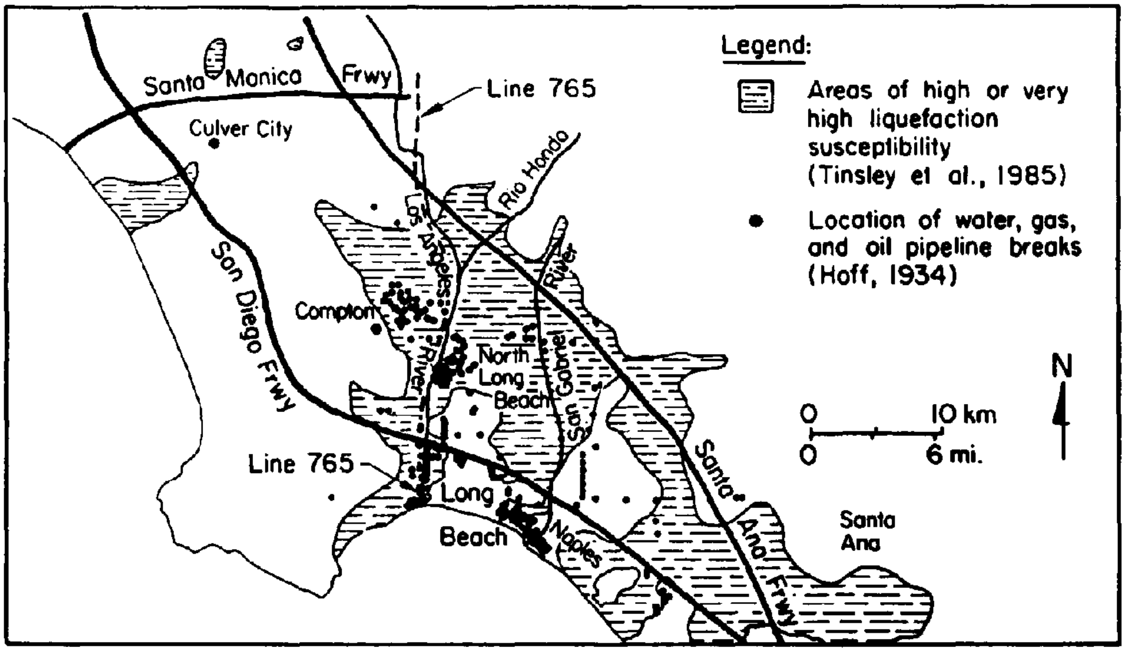


FIGURE 3-1. Pipeline Damage Caused by the 1933 Long Beach Earthquake [adapted from Hoff, 1934]

As shown in Figure 3-1, 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 3-1) 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.

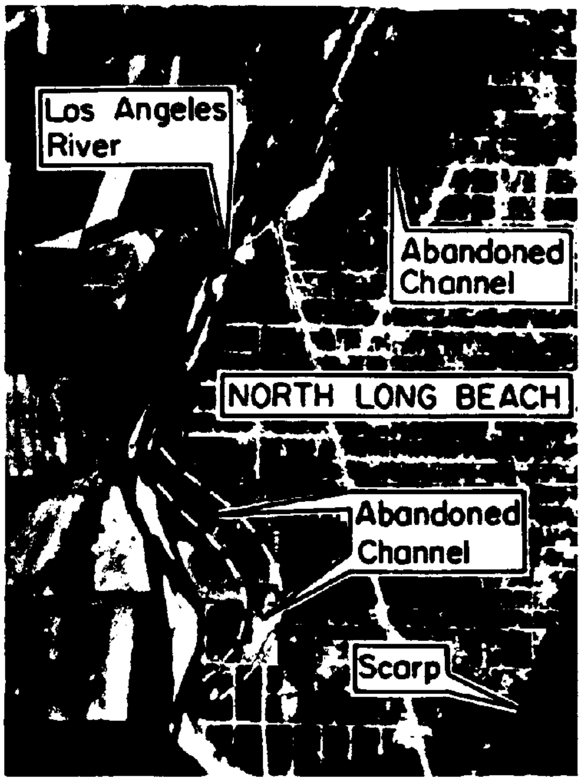
Figure 3-2 shows a portion of a 1928 aerial photo of North Long Beach. Several abandoned river channels are indicated by arrows. As discussed in the section of this work on improvements in pipeline replacement procedures, river channel deposits have been shown in previous earthquakes to be susceptible 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.

3.2.4 Pipeline Performance

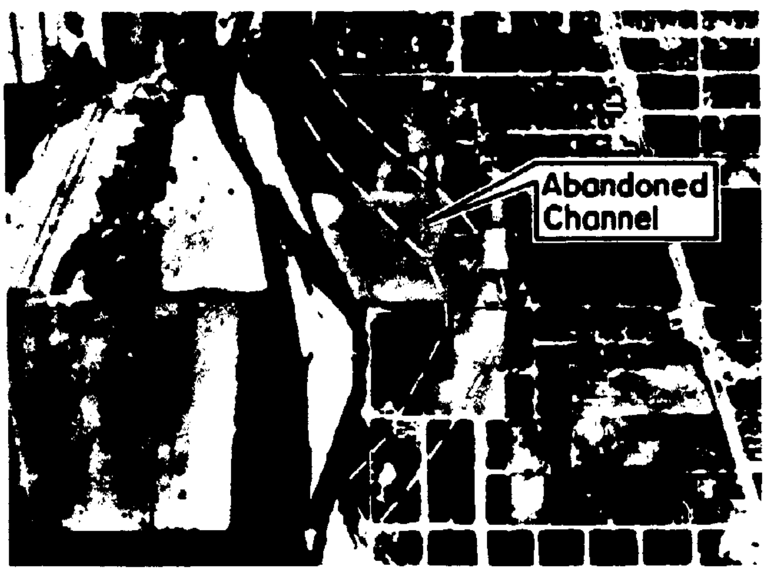
Pipeline damage caused by the 1933 Long Beach earthquake has been described by Bryant [1934] and Hoff [1934]. There were more than 500 main line breaks of water, gas, and oil lines in the areas of maximum seismic intensity [Hoff, 1934]. Within the City of Long Beach gas distribution system, there were 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



b) Close-up

FIGURE 3-2. 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].

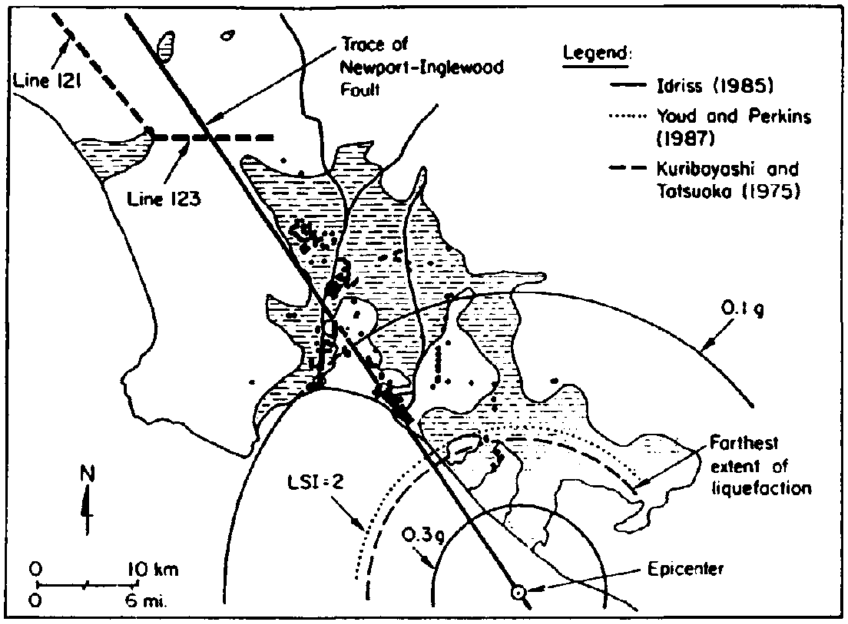
Other damage to the gas system included about 1,650 service risers broken off below ground at the elbow, and about 1,000 services sheared off at their connections to the mains. Over 90% of the main connection failures were located in the loose. artificially-filled ground in the Naples area [Bryant, 1934].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

3.2.5 Estimated Peak Acceleration and Liquefaction Potential

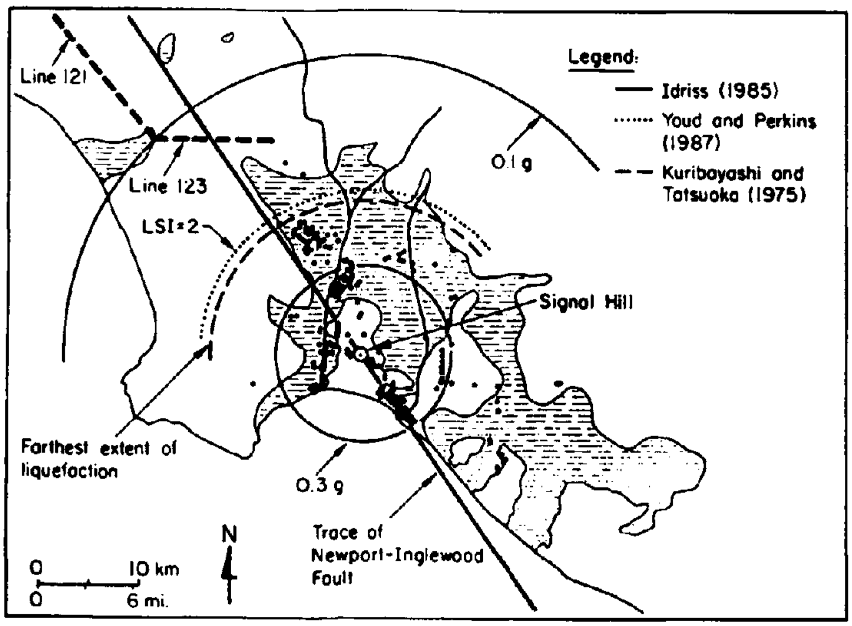
It is of interest to review the pipeline damage resulting from the 1933 earthquake in light of the estimated peak ground accelerations and the potential for soil liquefaction derived from empirical prediction procedures. Attenuation relationships developed by Idriss [1985] were used to estimate peak 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 3-3a 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 3-3. 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 [Toppazada, 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 3-3b 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.

Also shown in Figure 3-3a and 3-3b are the locations of Lines 121 and 123, which are the subjects of the feasibility study described in Section 6. Both lines were constructed in 1930, and company records indicate that neither was damaged as a result of the 1933 earthquake. By selecting the seismic source closest to the lines in Figure 3-3b, it can be seen that both pipelines fall well beyond the distance at which liquefaction would be anticipated and at a distance at which peak accelerations of approximately 0.1 g would be forecast.

3.3 1952 AND 1954 KERN COUNTY EARTHQUAKES

3.3.1 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.

3.3.2 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.

3.3.3 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 3-4 shows the locations of the damage relative to the epicenters of the main shock and the January 12, 1954 earthquake, which had a local 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 3-4). 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

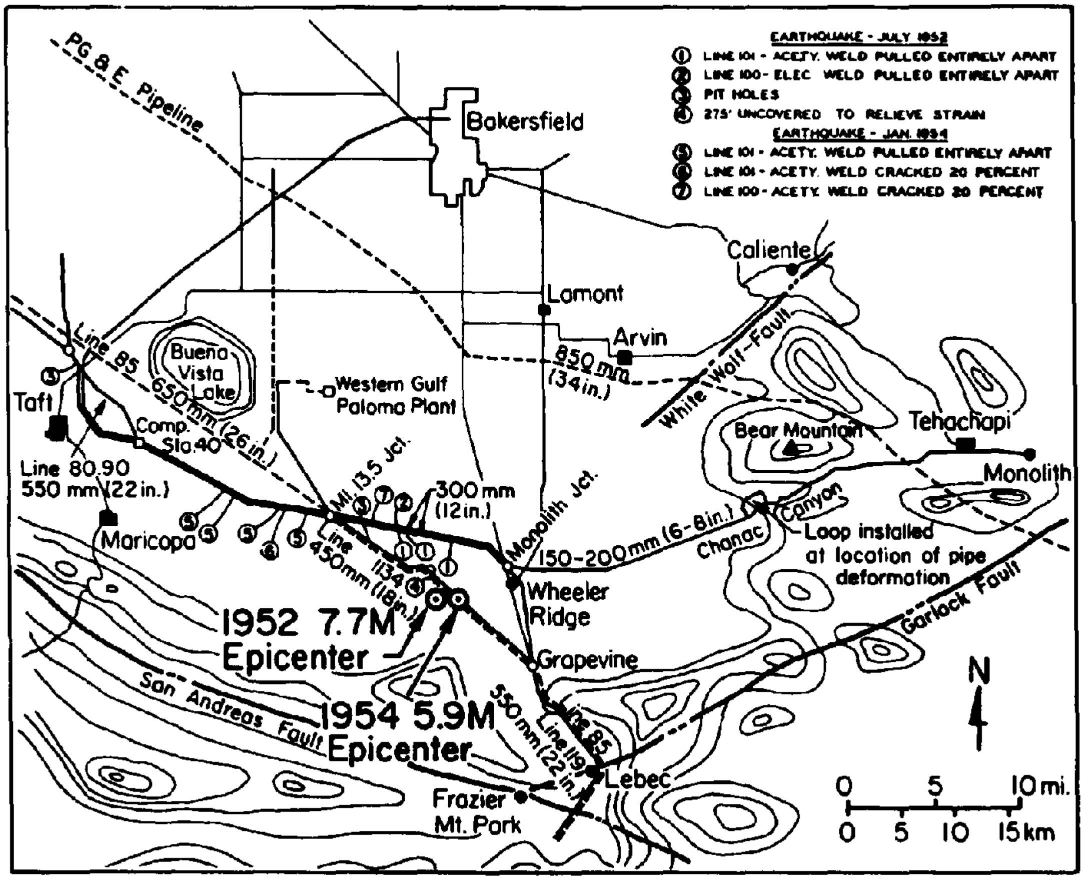


FIGURE 3-4. Gas Pipeline Damage Caused by the 1952 and 1954 Kern County Earthquakes [adapted from Newby, 1954]

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 3-4). 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 3-4, this quake parted the acetylene-welded line 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 3-4) 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 could not be found of the type of girth welds.

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 3-4. 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 3-4, 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.

3.4 1971 SAN FERNANDO EARTHQUAKE

3.4.1 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 MM X 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.

3.4.2 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].

3.4.3 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 3-5 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

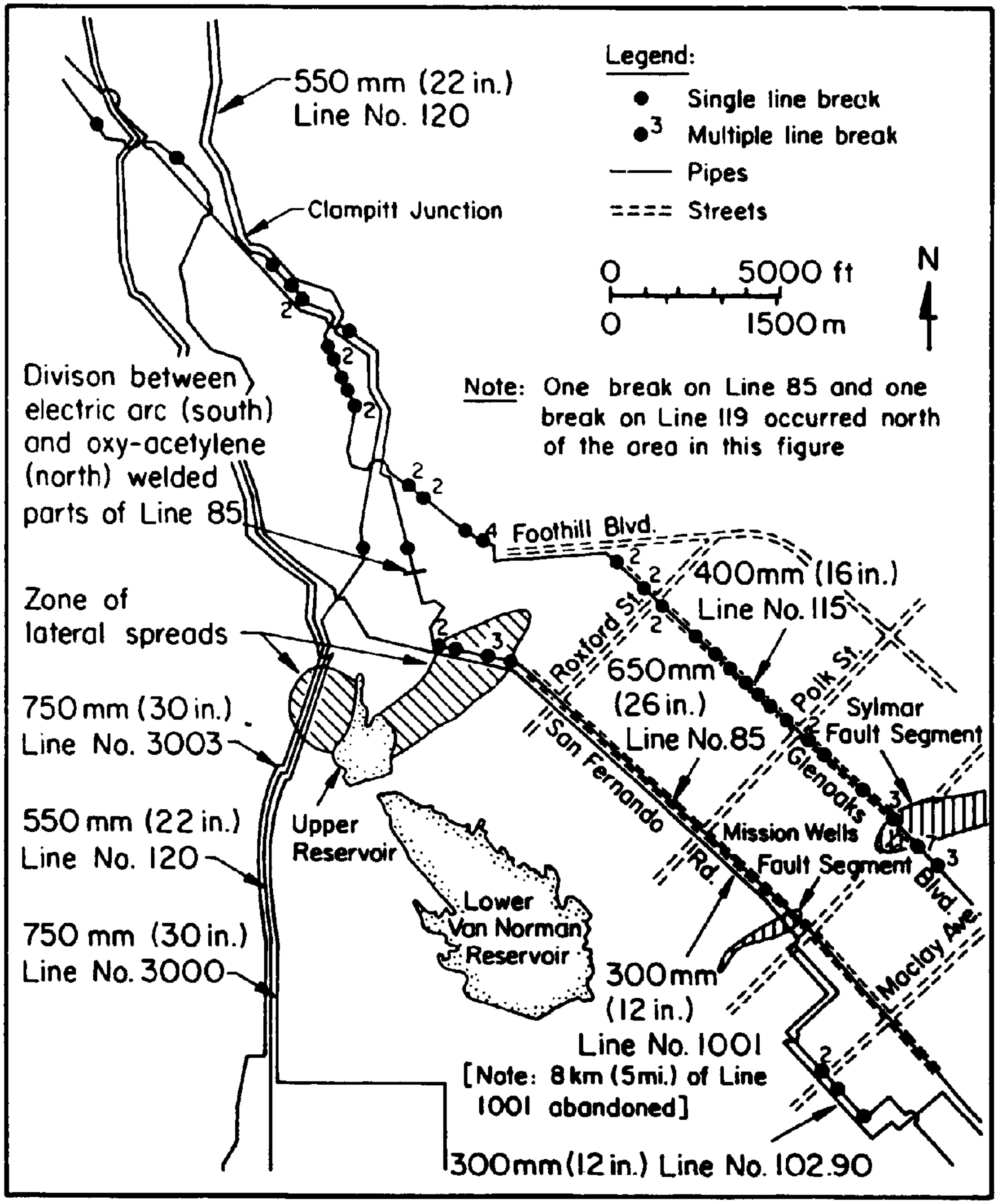


FIGURE 3-5. **Locations of Gas Pipeline Damage, Lateral Spreads, and Fault Segments Associated with the 1971 San Fernando Earthquake [adapted from Southern California Gas Company, 1973]**

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 3.3.3 dealing with the 1952 and 1954 Kern County earthquakes. In Figure 3-5, 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 in Subsection 3.3.3. 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 15° elbow.

3.5 1979 IMPERIAL VALLEY EARTHQUAKE

3.5.1 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].

3.5.2 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.

3.5.3 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 3-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. [1990] 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

TABLE 3-II. Characteristics of Pipelines Influenced by Fault Movements During the 1979 Imperial Valley Earthquake [after Dobry, et al., 1992]

Characteristics	Pipeline Location: 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

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 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 3-6. Between the time of installation and excavation after the earthquake, approximately 400 mm (16 in.) and 315 mm (12.6 in.) 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.

3.6 1994 NORTHRIDGE EARTHQUAKE

3.6.1 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 6.8 [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.

3.6.2 Liquefaction, Landslides, and Surface Faulting

Evidence of liquefaction was reported in the northern San Fernando Valley near

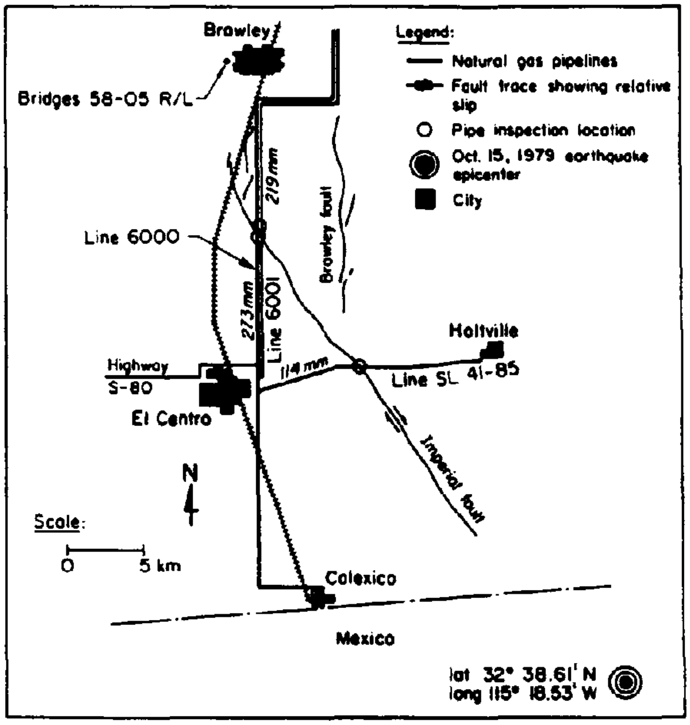


FIGURE 3-6. Locations of Gas Pipelines Crossing the Imperial Fault [adapted from Dobry, et al., 1992]

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.

3.6.3 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 3-7 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 3-8 is a map of the area just north of the earthquake epicenter, showing the Aliso Canyon Gas Storage Field 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 3-7, 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 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.

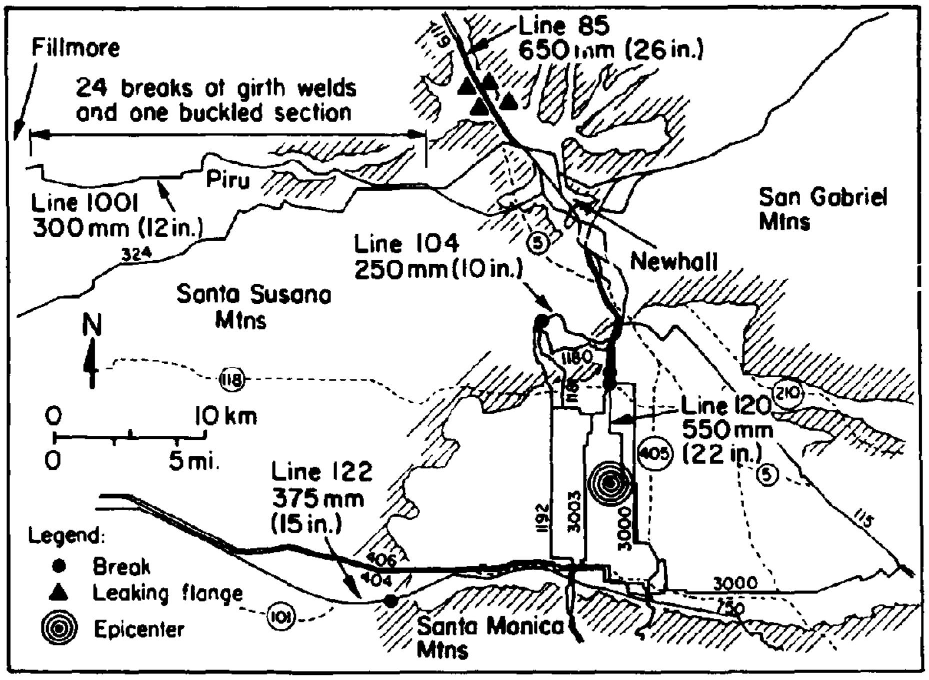


FIGURE 3-7. Map of Gas Transmission Pipelines in the Area of Strong Ground Shaking

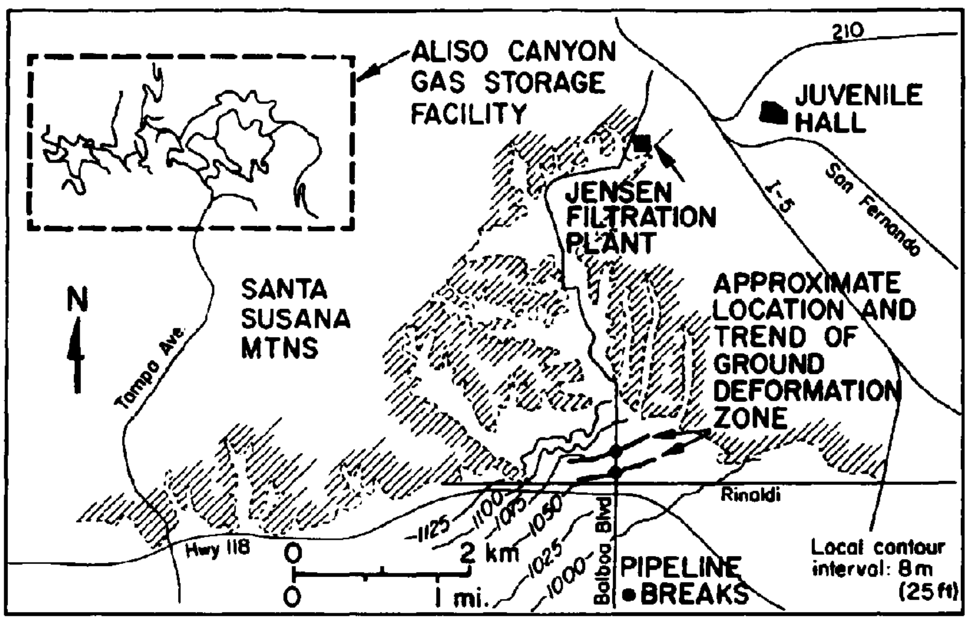


FIGURE 3-8. Map of the Area North of the Northridge Earthquake Epicenter

Flange leaks occurred at the four locations shown in Figure 3-7 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 3.3.3. 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 3.3.3. The line had an MAOP of 2.5 MPa (360 psi). There was a leaking flange at an aboveground section of Line 119 north of the area shown in Figure 3-7. 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 3-7. 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.

As shown in Figure 3-7, 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), but it is operated at 1.4 MPa (200 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 3-9 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

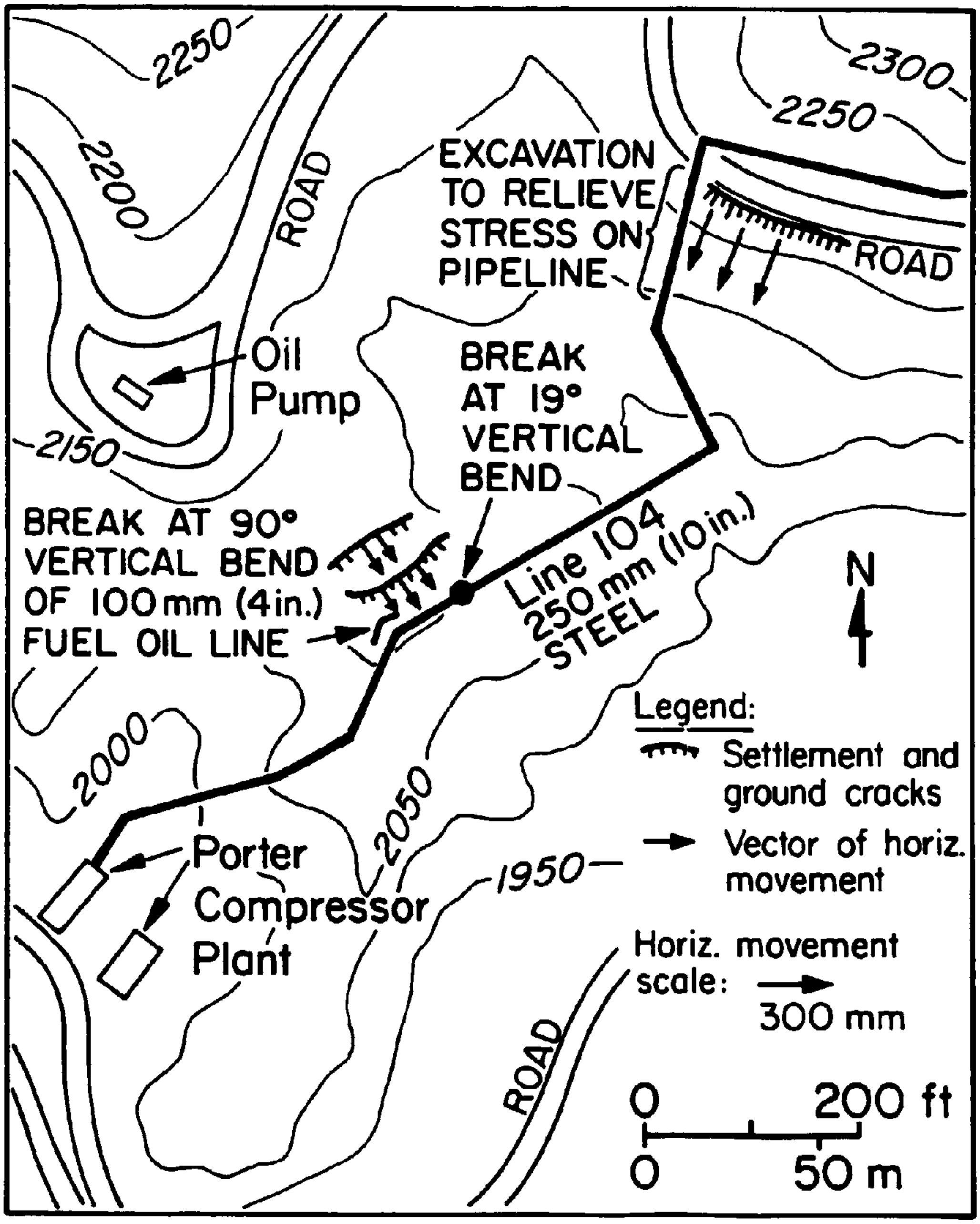


FIGURE 3-9. Plan View of Line 104 in the Aliso Canyon Gas Storage Field

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. 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. 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 3-8, 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.

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 3-10 and 3-11 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.

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.

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

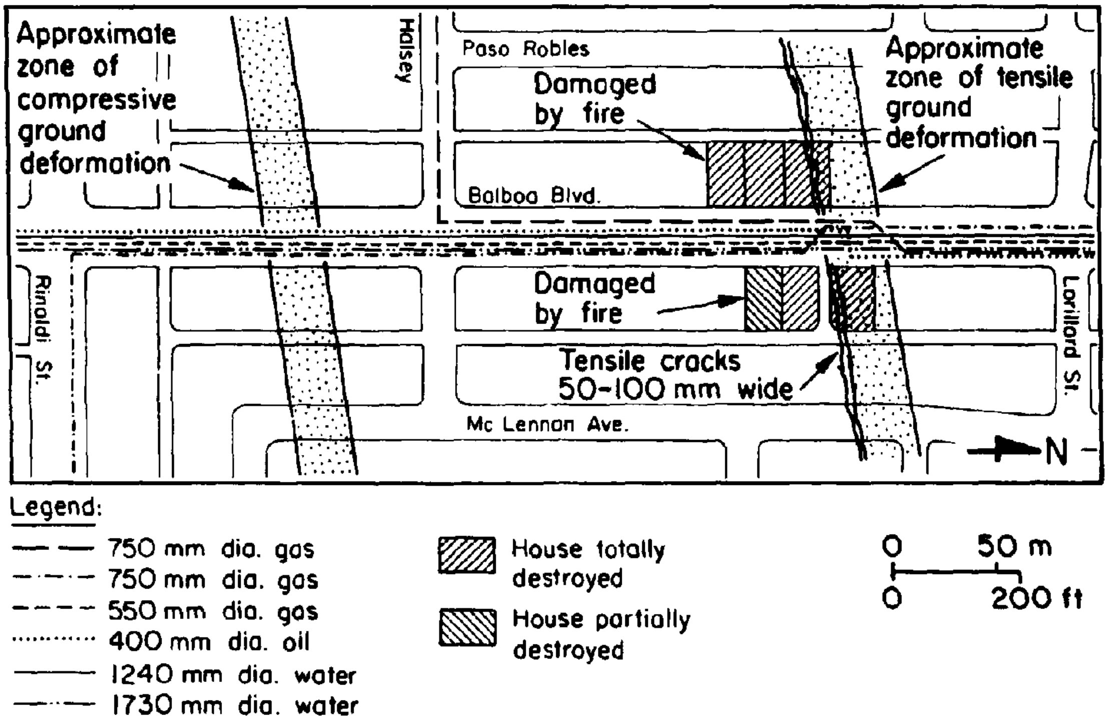


FIGURE 3-10. Map of Major Pipelines, Fire Damage, and Ground Deformation on Balboa Boulevard

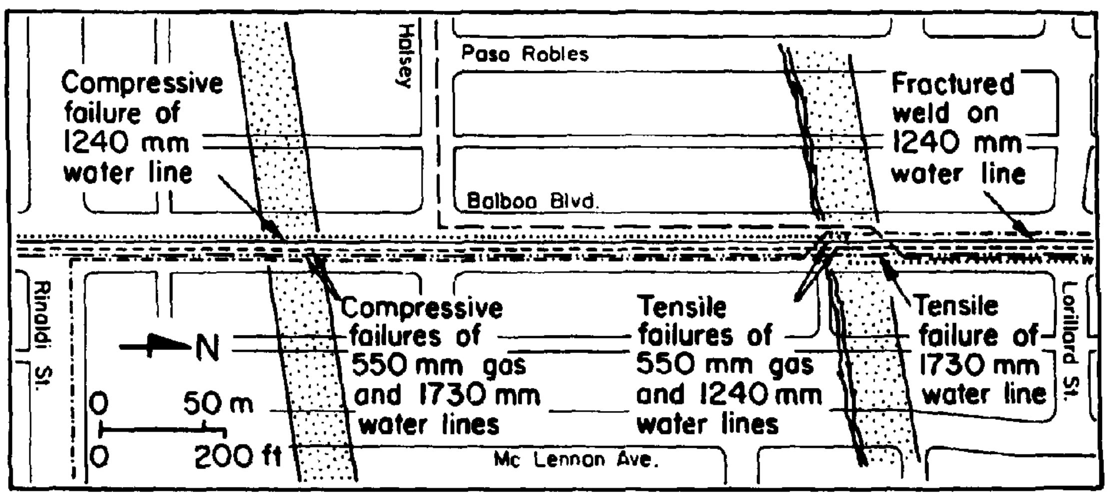


FIGURE 3-11. Map of Major Pipelines, Ground Deformation Zones, and Locations of Pipeline Damage on Balboa Boulevard

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.

3.7 GENERAL PIPELINE PERFORMANCE PRIOR TO NORTHRIDGE EARTHQUAKE

Table 3-III provides a summary of pre-WWII transmission and supply line response 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

TABLE 3-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
193[illegible]	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)	208 (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

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 3-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 3-12. 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

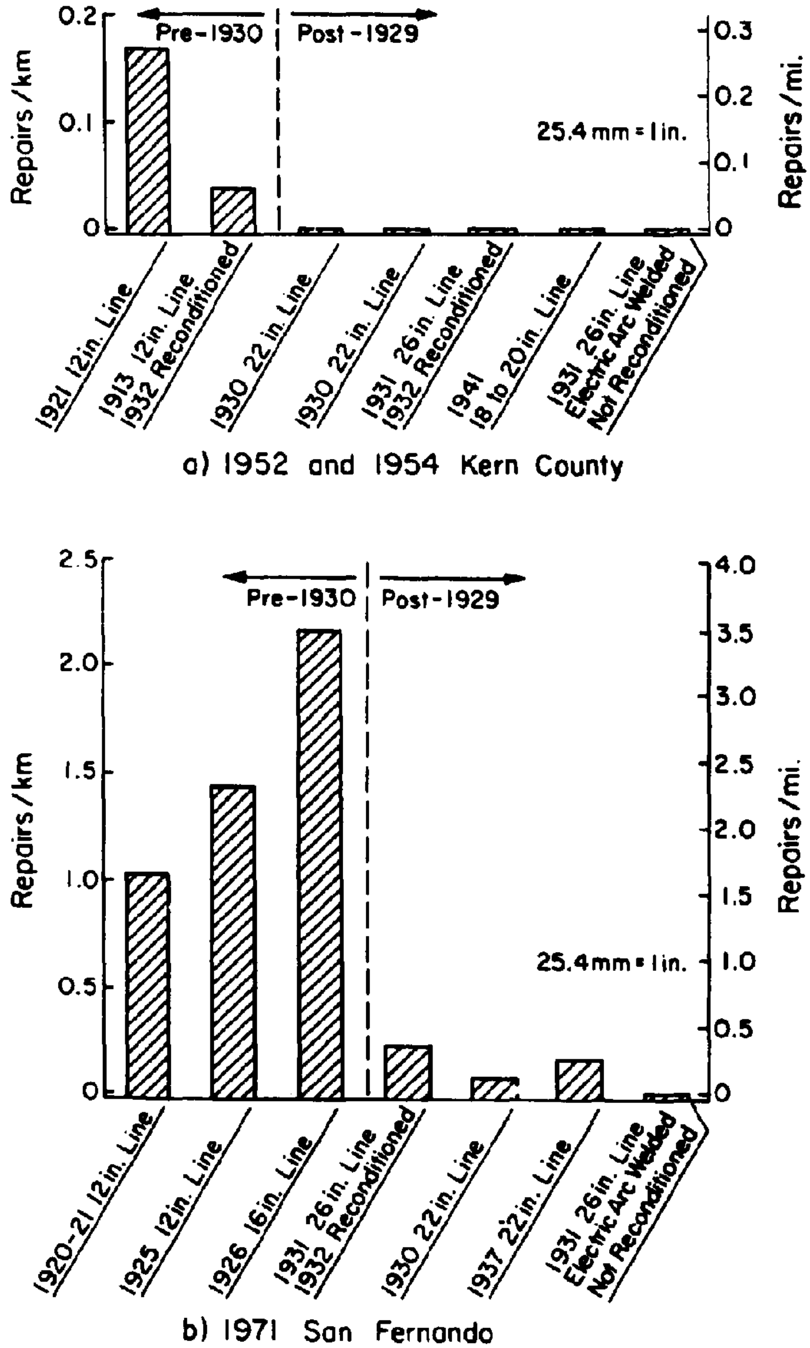


FIGURE 3-12. Damage Rates for Gas Transmission and Supply Lines Affected Predominantly by Traveling Ground Waves

two breaks associated with the 1913 pipeline, which was reconditioned in 1932 (see Figure 3-12a), 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 3-13 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 3-III was predominantly at oxy-acetylene welds. This observation does not mean 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

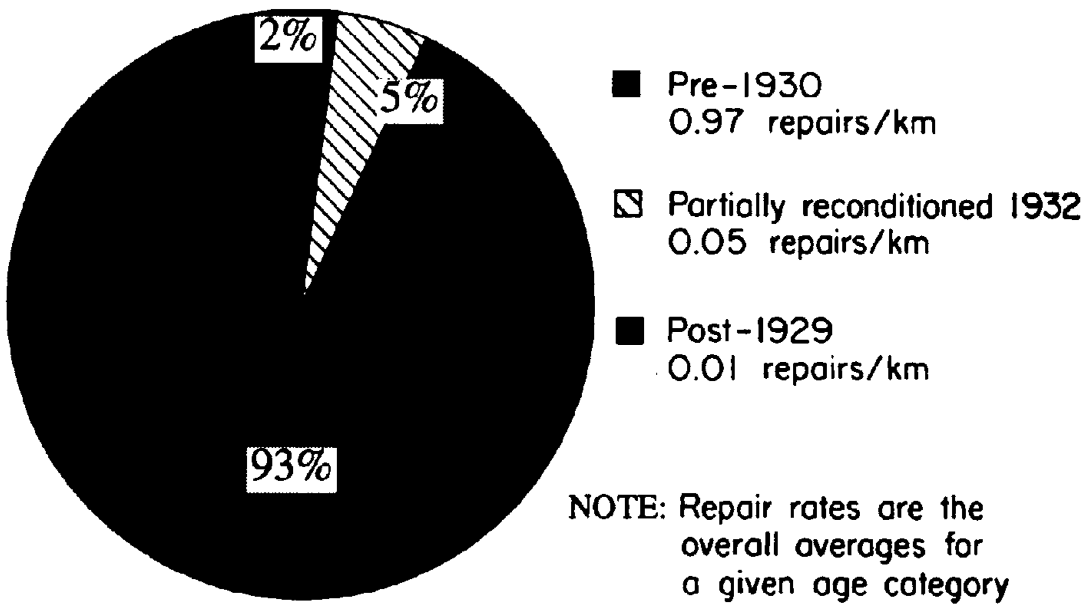


FIGURE 3-13. Pie Chart Showing Relative Proportions of Damage by Pipeline Age Category

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

3.8 GENERAL PIPELINE PERFORMANCE DURING NORTHRIDGE EARTHQUAKE

Table 3-V 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 3-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 $\geq$ VIII were obtained from preliminary intensity maps developed by USGS [Dewey, 1994]. A single modification was made in the MMI $\geq$ 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

TABLE 3-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

TABLE 3-V. 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[e]	oxy-acetylene	19.3 (12.0)	1	0.05 (0.08)	0
1930	119	550 (22)	7.9 (0.312)	207 (30)	NR[e]	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 recorded
[f] Specified Minimum Yield Stress

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-VI 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 3-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 the previous section. 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.

3.9 SUMMARY

A detailed review of gas pipeline performance prior to the Northridge earthquake 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

TABLE 3-VI. 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

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.

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.

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 4

CURRENT PIPELINE REPLACEMENT PROCEDURE

The current procedure for replacement of transmission and distribution supply lines has evolved from two proprietary studies undertaken by SoCalGas. In the first study [Strang, 1986], five families of pipe were identified as posing the most serious risk, and 12 pipe classifications were defined and ranked according to their relative hazards. The ranking set priorities for replacement, and a plan was developed for removing the highest through lowest priority piping in sequential order. In the second study, a procedure referred to as Value Chain Analysis (VCA) was used to refine the first program of replacement [Mansdorfer, et al., 1991]. This section reviews the two studies, and summarizes the current replacement procedure for transmission and supply lines. The section ends with a brief discussion of the replacement/repair decision model which has been developed for the distribution pipeline system.

4.1 REPLACEMENT ASSESSMENT

An assessment of the entire underground piping system (transmission and distribution) was undertaken in an effort to control and manage system deterioration, which is an inevitable consequence of aging and time in service [Strang, 1986]. Five families of pipe were identified as posing the highest risk:

- Cellulose acetate butyrate (CAB) plastic services
- Copper mains and services
- Cast iron mains
- Bare steel mains installed inside older mains
- Pre-WWII transmission lines and distribution supply lines located in urban areas

In identifying these families, emphasis was placed on public safety. The pipe families of CAB plastic and copper involved materials which were known to deteriorate at a relatively rapid rate. Repair statistics for cast iron and bare steel mains in older mains showed high leak development rates. Some pre-WWII urban supply lines were known to have poor girth welds, making them vulnerable to earthquakes. The potential for substantial gas release, should a welded joint rupture, and the difficulties in maintaining local community supply, should shutoff occur, were factors which made these lines prime candidates for replacement.

From the five families, 12 priority categories were identified after considering statistical performance data and eliciting the engineering judgment of gas company personnel. The priority categories were organized in order of descending risk, with the greatest risks assigned to CAB services, copper mains and services, and bare steel in conduit in Class 4 locations. Replacement of the first three categories associated with CAB and copper piping was completed in 1987. Continued replacement of pipelines and above-ground facilities associated with the remaining categories is pursued under a program known as the Special Pipeline Replacement Program (SPRP).

In the 1986 study, it was noted that both welding and coating practices had evolved to reliable, consistent procedures by about 1940. Accordingly, this date was suggested for replacement planning. It was recognized further that these older pipelines had experienced difficulties during earthquakes in the form of ruptured oxy-acetylene girth welds. As a result of this assessment, all pre-WWII transmission and supply lines were considered as replacement candidates. Pipelines of this vintage, operating at a hoop stress exceeding 20% SMYS in Class 3 and 4 locations, were assigned the highest priorities for replacement.

4.2 VALUE CHAIN ANALYSIS

The purpose of the Value Chain Analysis (VCA) study [Mansdorfer, et al., 1991] was to determine how to provide the best value to the customer by minimizing both the risks associated with remaining pipelines and the costs of replacement. The study was focused on pre-WWII transmission lines, but because of their similarity to pre-WWII distribution supply lines, the results of the VCA are considered to be relevant for both [Gailing, 1992].

Evaluation criteria were based on consideration of public safety, reliability of energy delivery, and total cost to customer. Risk was assessed, primarily on the basis of experience and judgment, as the product of the probability and consequence of failure. The mechanisms influencing the probability of failure in pre-WWII pipelines were considered to be corrosion-induced loss of pipe wall and weld-related rupture. The consequences of failure were regarded as location-related and pipeline-related. Consideration also was given to reliability of energy delivery and potential increases in cost to customer.

The study [Mansdorfer, et al., 1991] pointed out that the Transmission Department had emphasized cathodic protection of its pipelines, with the result that:

> "...for the eight-year period ending in 1990, the number of leaks on the whole Transmission system averaged 24 per year. With replacement of some of the pre-WWII pipe in the late 1980s, the leakage rate declined to only 14 in 1990. Moreover, not all of the leaks were on pre-WWII pipe. The average number of leaks on pre-WWII pipelines that still will be in service as of December, 1991 was 7.9 leaks per year for the period 1983-1990. This amounts to a leakage rate of only 0.0165 leaks per mile per year (0.0102 leaks per km per year)."

The potential corrosion-related failure modes of leakage and rupture were assessed, and it was concluded that rupture constitutes a very low risk for the system because virtually all pre-WWII transmission pipelines are operated at hoop stress below or very near 50% SMYS. Research sponsored by the British Gas Corporation [e.g., Shannon, 1974] was cited as substantiating the conclusion of low rupture risk. The low leakage rate and the fact that none of the pre-WWII transmission lines in populated areas are operated at hoop stress likely to cause rupture, led to the additional conclusion that the threat to public safety from corrosion-related failure is very low.

Weld-related ruptures were assessed by reviewing several loading conditions, such as thermally-induced tension from exposure to the atmosphere, heavy loads from construction equipment, train derailments, and earthquake effects. Of these, earthquake effects were regarded as posing the greatest threat to girth weld integrity. The performance of oxy-acetylene welded, pre-WWII pipelines during the 1971 San Fernando earthquake was reviewed. The conclusions put forward regarding oxy-acetylene girth weld integrity are as follows:

> "Because the probability of failure of welds on pre-WWII pipelines during an earthquake is such an unknown, the VCA team was forced to rely on intuition in evaluating alternatives in regard to this. We

assumed that these pipelines are likely to fail within seismic hazard areas during a great earthquake, and that failure outside these areas is much less likely, but is a definite possibility."

Locations where pipeline failures would have the greatest consequences on public safety were identified as "high consequence areas." They include: 1) pipelines in major thoroughfares, and 2) pipelines adjacent to schools, hospitals, high density housing, shopping centers, and other locations where high densities of people frequently congregate.

The influence of larger diameter, higher pressure pipelines was considered with regard to flame radiation potential. Nominal pipeline diameters of 400 mm (16 in.) and larger were considered as having a high flame radiation potential.

On the basis of an assessment using weighting criteria for public safety, reliability, and cost, various replacement scenarios were examined to establish priorities. It was concluded from this examination that the pre-WWII pipelines with highest priority for replacement are those in high consequence areas, seismic hazard zones in Class 3 locations, and in Class 3 locations with high flame radiation potential. Seismic hazard zones are regarded as locations where pipelines cross active faults, liquefaction zones, and landslide areas [Gailing, 1992]. All transmission and supply lines outside these categories, therefore, are no longer in the SPRP. Instead, they are evaluated as part of the Routine Pipeline Replacement Program (RPRP).

The nine replacement classifications in the SPRP as of 1992 were consolidated into five, following the recommendations of the VCA study. Three of the remaining categories pertain to cast iron, bare steel mains in conduit in Class 4 locations, and steel mains in conduit in annual leakage survey areas. The first two of these three are scheduled for full replacement in 1993, and the third category will be similarly disposed as of 1996. The highest priority pre-WWII pipelines identified above make up the two remaining categories of the five-category program.

The VCA study also encouraged consideration of alternative system planning that could eliminate the need for some pre-WWII pipelines by upgrading or extending distribution supply lines, increasing pressures in other pipelines, and additional compressors. It was recommended that teams be assembled from various departments to pursue these alternatives.

4.3 ROUTINE REPLACEMENT PROGRAM

The Routine Pipeline Replacement Program (RPRP) involves relocation due to development, upgrades, abandonments, and class location changes. These replacements are made in close coordination with personnel responsible for system planning. As mentioned above, the low leak rates associated with the transmission system are not regarded as a significant risk to public safety. From an economic perspective, repair rathe. than replacement is most advantageous under such conditions.

The replacement of distribution piping is based substantially on economic considerations in conjunction with the results of annual leak surveys. In the past, the decision to repair or replace was made at the division level, primarily on the basis of the judgment and experience of division personnel in interpreting trends indicated by the records. Currently, a computerized, economically-oriented model for replacement/repair decisions is being tested in the company divisions.

Statistical analyses of leak records and the choice of appropriate models for incorporation in replacement/repair decisions is the subject of a companion report by Eguchi, et al. [1993]. Establishing an optimal basis for collecting and interpreting repair records is an important aspect of a pipeline replacement program, and is a key feature of the work being conducted by EQE researchers as part of the overall research program on steel pipeline replacement procedures sponsored by SoCalGas and NCEER.

SECTION 5

RECOMMENDATIONS FOR IMPROVED REPLACEMENT PROCEDURES

This section provides recommendations for improved replacement procedures by first examining the VCA approach and using the structure of this process to derive a flow chart for general retain/replacement decisions. The damage statistics associated with earthquake effects on oxy-acetylene lines, as developed in Section 3, are used to set priorities for replacing the most vulnerable lines. A semi-empirical method for assessing the cratering potential of a ruptured line is presented and used to provide additional guidance for setting replacement priorities. Earthquake hazards are evaluated in terms of traveling ground wave effects and permanent ground deformation. Models are proposed for identifying locations where traveling ground wave effects may damage the most vulnerable lines, and permanent ground deformation sources of potential pipeline damage are evaluated in terms of surface faulting, landslides, and liquefaction. Replacement priorities are recommended for pre-WWII oxy-acetylene pipelines.

5.1 REVIEW OF VCA

The VCA approach is illustrated in Figure 5-1 in the form of a flow chart. The procedure involves initial consideration with respect to system planning, followed by a risk assessment with evaluations of 1) damage exposure, 2) damage susceptibility and potential, and 3) proximity to buildings and places of public gathering. In the VCA approach the relative exposure to damage is judged in terms of earthquake hazards, with emphasis on potential sources of permanent ground deformation. The pipe susceptibility to damage and the potential for damage and injury in areas adjacent to the pipe are taken into account by identifying pre-WWII pipelines with diameters larger than or equal to 400 mm (16 in.). The proximity characteristics of the pipeline are judged relative to class location and nearness to high consequence areas.

As described in Section 4, the VCA approach was developed after considering the leakage history of transmission pipelines and concluding that leakage rates were so low that economics would support repair rather than replacement in virtually

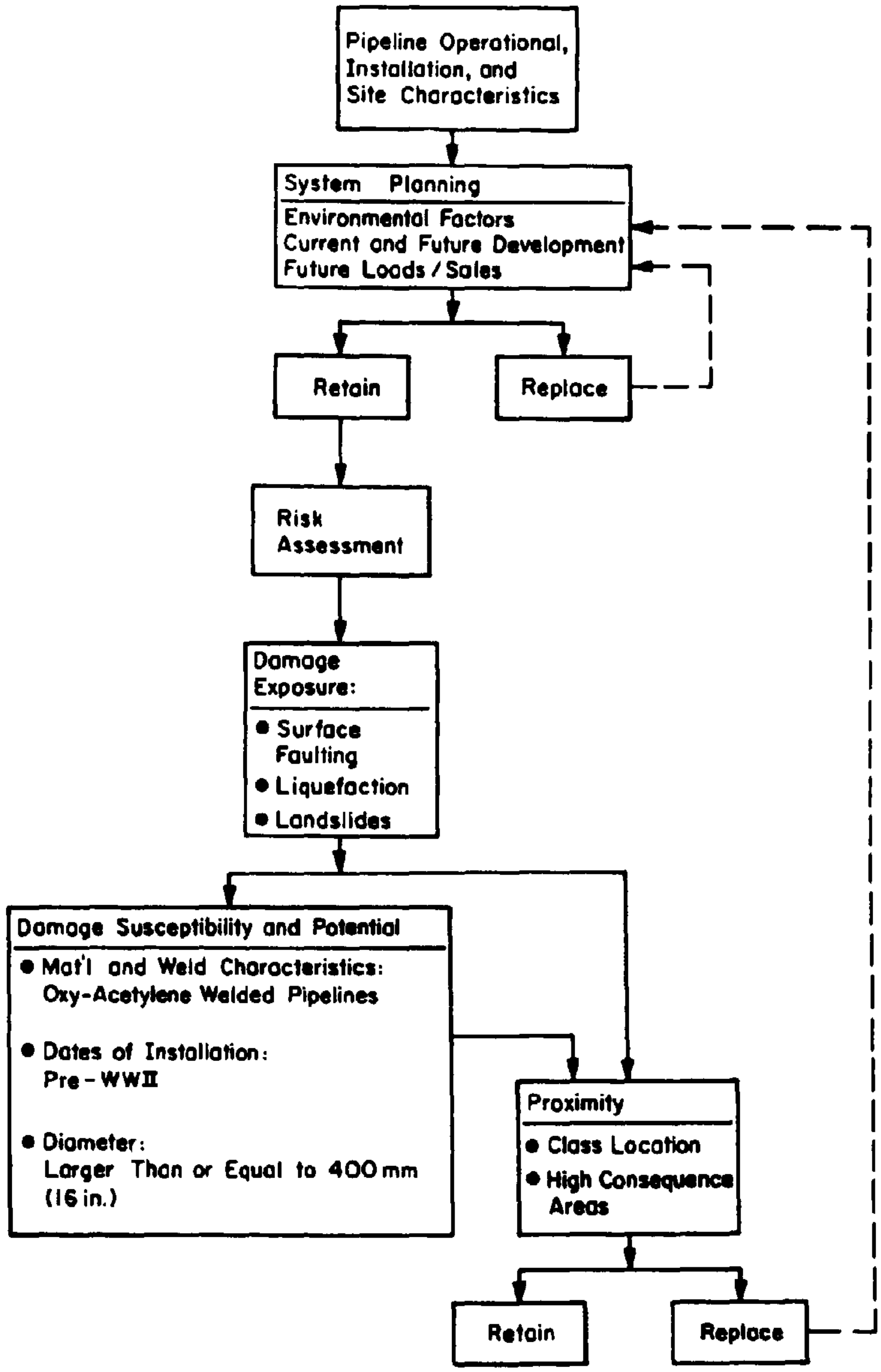


FIGURE 5-1. Flow Chart for Evaluation Procedure in the Value Chain Analysis Approach

all circumstances. Accordingly, economic estimates based on repair statistics are not included in the procedure.

5.2 RECOMMENDED REPLACEMENT PROCEDURE

After considerable discussion with SoCalGas personnel and a thorough review of the VCA approach, a general replacement procedure is recommended in the form of the flow diagram in Figure 5-2. Although the flow chart has been developed so it is amenable to either transmission or distribution pipelines, its primary advantage for SoCalGas will be its application to the company's supply line system.

The flow chart shows a three-step process in which a system planning assessment is made, followed by a repair record cost assessment, with a risk assessment completing the evaluation. At each stage in the evaluation, a decision to replace or retain is made. If the pipeline is to be replaced at any of the three stages, the flow chart shows, by means of dashed lines, a return to specifying new pipeline characteristics and repeating the three tier decision process.

As illustrated in Figure 5-3, risk assessment is performed in a three-step process, similar to the procedure followed in the VCA approach. Damage exposure represents the major hazards which need to be considered, including third party damage, corrosion, earthquake hazards, and natural hazards, such as flooding and landslides. Third party damage is defined as damage compromising pipe wall, welds, coating, connections, attachments, and associated devices, and is the result of forces and deformations imposed on the pipe by external activity, such as construction, agricultural work, subsurface exploration, and abnormally heavy surface loads. Some of the best measures to reduce third party damage involve clear surface markings to identify the paths of potentially hazardous pipelines at transportation crossings and the locating of pipelines near sites of intended construction or exploration by means of a one call system. Effective measures against third party damage may also involve protective concrete slabs installed above sections of pipe at risk from surface loads or direct hits by construction, agricultural, and subsurface exploration equipment. Pipeline replacement may be warranted in areas of future construction, provided that significant loss of

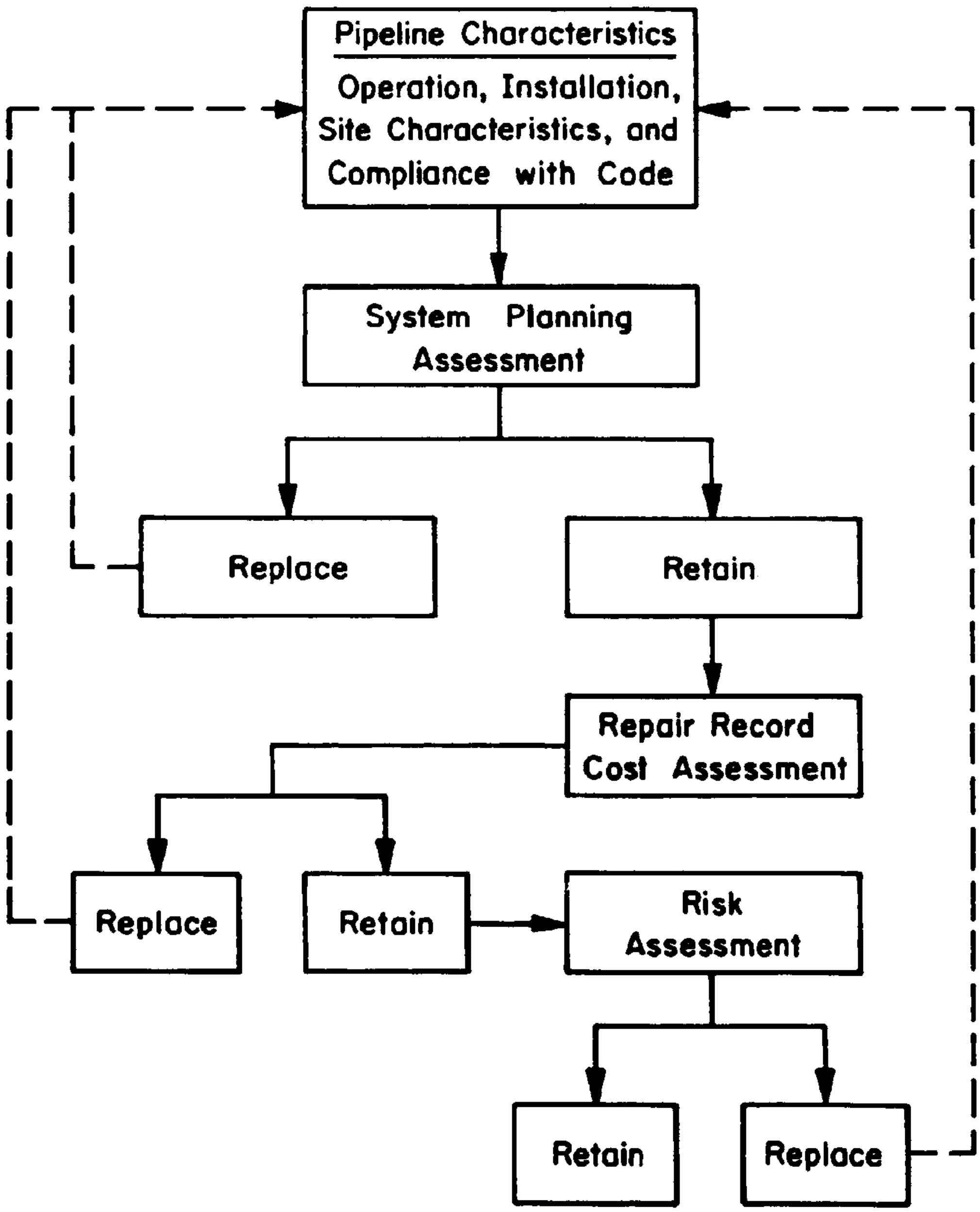


FIGURE 5-2. Flow Chart for Retention/Replacement Decisions About Steel Gas Pipelines

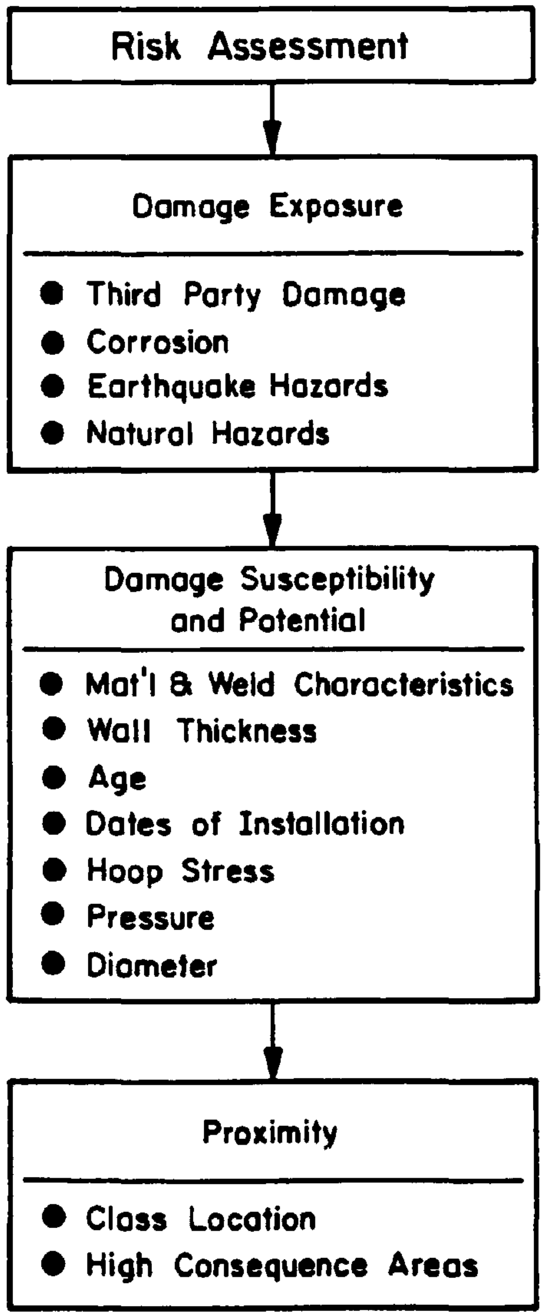


FIGURE 5-3. Risk Assessment Procedure

cover, risk of direct hit, or increased loading is likely to result from the construction activity.

After the potential hazards have been considered, an evaluation of vulnerability is made by weighing the factors which reduce pipeline capacity to sustain internal and external loads, as well as those which increase the potential for damage and/or injury in the area surrounding the pipeline. The factors influencing damage susceptibility and potential have been discussed in Section 2, and are listed within the diagram.

The final evaluation in a systematic risk assessment involves consideration of how many people are exposed to injury in the event of pipeline damage. The highest relative risk associated with proximity is accorded to pipelines in Class 4 locations and high consequence areas.

Some important factors of the proposed methodology are discussed under the following subheadings:

5.2.1 Repair Record Cost Assessment

It is recommended that an economic assessment about the desirability of repair and retention versus replacement be made for steel pipelines. As discussed previously, the low leakage rate associated with the transmission system may obviate the need to make such an evaluation for pipe in the transmission network. It is not clear, however, if a similar conclusion can be drawn for the supply line system. It may be advantageous to apply the economically-based model discussed in Section 4.3 (or derivative thereof) to the supply lines. Making an economic assessment based on repair records fits logically within the procedure. By predicating part of the assessment on a review of the repair record, the procedure promotes a systematic collection and analysis of repair statistics which can have benefits in determining medium and long-term trends in performance.

5.2.2 Damage Exposure

It is proposed that damage exposure be evaluated with major emphasis on earthquake hazards, which is consistent with VCA conclusions, as well as consideration of natural hazards involving landslides, flooding, and erosion/undermining.

Recent flooding and landslide activity in southern California encourage a more systematic review of natural hazards, and the general procedure recommended for earthquake hazard assessment in Section 5.5 includes some discussion of appropriate risk assessment methods for natural hazards.

5.2.3 Damage Susceptibility and Potential

Consistent with VCA recommendations, the damage susceptibility of older pipelines with oxy-acetylene welded joints is emphasized. The pipeline performance review in Section 3 provides statistics that are used to establish priorities for replacement, as discussed in Section 5.3. Pipeline pressure and diameter influence both the cratering potential, disregarding ignition, and the heat radiation distance, should ignition occur. These matters are discussed with reference to pipeline behavior during previous earthquakes in Section 5.4.

It is recommended that susceptibility to damage from external mechanical interference be considered with regard to pipe wall thickness. As indicated by the general statistical trends in Section 2.5, pipelines with wall thickness less than 5 mm (0.20 in.) are most prone to puncture, whereas pipelines with wall thickness exceeding 10 mm (0.40 in.) show high resistance to puncture.

5.2.4 Proximity

Consistent with the Code of Federal Regulations [Office of the Federal Register, 1990], the consequences of damage should be regarded as increasingly more severe as the class location number increases. High consequence areas, defined in the VCA, are locations in which pipeline damage would have the highest potential for harm, based on density of people and traffic. Class 4 locations and high consequence areas are to be given the highest priority with regard to the potential effects of pipeline damage.

5.3 OXY-ACETYLENE WELDED PIPELINES

In the 1986 replacement study [Strang, 1986], all pre-WWII transmission pipelines were regarded as candidates for replacement. Subsequent refinements in the VCA study [Mansdorfer, et al., 1991] have focused attention on pre-WWII pipelines in high consequence areas, seismic hazard zones in Class 3 locations, and Class 3 locations with high flame radiation potential. Seismic hazard zones are taken as locations where pipelines cross active faults, liquefaction zones, and landslide areas [Gailing, 1992]. Considerable uncertainty was expressed in the VCA study about the potential for failure from earthquake effects outside the seismic hazard zones.

On the basis of the earthquake performance review in Section 3, it is possible to clarify two issues regarding 1) pipelines which have failed most frequently during past earthquakes, and 2) earthquake effects which have caused damage. The repair statistics summarized in Section 3.6 show that pipelines constructed before 1930 have a damage rate nearly 100 times higher than that of post-1929 pipelines, with the exception of partially reconditioned lines. The damage rate for partially reconditioned lines is five times larger than the overall average rate for post-1929 pipelines. Virtually all pipelines in the post-1929 unreconditioned category are known to have been electric arc welded. Most traveling ground wave damage was sustained at oxy-acetylene welds at locations assigned a seismic intensity of MM VIII or higher.

As discussed in Section 3.7, a 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.

Given the statistical evidence, it is recommended that pre-WWII pipelines with oxy-acetylene welds, including partially reconditioned oxy-acetylene welded lines, be considered a relatively high priority for replacement when located in areas potentially vulnerable to earthquake effects. The earthquake effects should include permanent ground deformation and traveling ground waves. The highest priority for earthquake-related replacement should be pre-WWII oxy-acetylene welded pipelines in areas of potentially large permanent ground deformation, including locations of surface faulting, landslide zones, and areas of liquefaction. The next highest priority should include pre-WWII oxy-acetylene welded pipelines in areas of potentially strong traveling ground wave effects. Evidence from previous earthquakes suggests that such areas include locations of MM VIII or larger. The next highest priorities for replacement should include reconditioned oxy-acetylene welded pipelines in the following order: 1) areas of potential surface faulting, landslides, and liquefaction, and 2) areas of MM VIII or larger.

The proposed strategy for replacement places strong emphasis on pre-WWII oxy-acetylene welded pipelines and reconditioned oxy-acetylene welded lines. In contrast, earthquake repair statistics show a dramatic drop in damage for post-1929 pipelines which have not required substantial reconditioning. Most post-1929 pipelines and all post-1931 pipelines, 400 mm (16 in.) and larger in diameter, were constructed with electric arc welds. The relatively low rate of repair of the pre-WWII electric arc welded pipelines implies that they represent a significantly lower risk than the above-mentioned facilities.

As previously mentioned, electric arc welding was first introduced during 1929 for SoCalGas transmission lines. Between 1929 and 1932, 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 on lines equal to or larger than 250 mm (10 in.) in diameter now incorporated in the transmission and supply lines of the system.

It is interesting to note that the steel pipeline replacement program of the Pacific Gas and Electric Company has emphasized replacement of pre-1931 pipelines [Day and Peck, 1991]. The decision to identify these lines as a high priority for replacement was based, in part, on repair records which indicated a relatively high incidence of repair to pre-1931 oxy-acetylene girth welds [Savage, 1993].

5.4 CRATERING POTENTIAL

When a high pressure pipeline is ruptured, there may be a significant energy release, which will cause cratering in the absence of ignition. Cratering was observed after the 1971 San Fernando earthquake at locations where oxy-acetylene-welded transmission and supply lines failed by girth weld rupture [O'Rourke and McCaffrey, 1986]. The potential for cratering is related to the amount of energy or work expended by rapidly expanding gas. As explained in Section 2.7 and Appendix A, an equation has been derived for the energy per unit length of pipeline under adiabatic gas expansion. This expression is for a gas expanding under ideal conditions, and is used in this work as an index for the potential energy release of pipelines with different diameters and internal pressures.

Figure 5-4 presents a family of curves developed from Equation 2-2 which show how the energy per unit pipeline length varies as a function of pressure for various nominal diameters. Five points are plotted on the figure, which represent pipeline diameters and operating pressures associated with the girth weld rupture of transmission and supply lines during the 1971 San Fernando and 1994 Northridge earthquakes. Cratering after the 1971 San Fernando earthquake was observed at locations of girth weld failure in Line 115 [400-mm- (16-in.)-diameter] and Line 85 [650-mm- (26-in.)-diameter], whereas heaved and shattered soil and pavement were observed at locations of failure in Line 1001 [300-mm- (12-in.)-diameter]. No surface manifestations of rupture were reported for Line 102.90 [300-mm- (12-in.)-diameter]. Records exist for the MAOP and actual operating pressures in 1971 and 1994, respectively. It is recognized that using the MAOP may result in a somewhat higher operating pressure than that at the time of the earthquake. This simplification, however, does not affect the conclusions drawn, nor the method proposed here for relative risk assessment. Cratering after the 1994 Northridge earthquake was observed at multiple locations of failed oxy-acetylene girth welds along Line 1001, including the large crater and ensuing fire at Highway 126 at the eastern outskirts of Fillmore. Evidence of cratering was not used for the rupture of Line 120 on Balboa Blvd. because it is not possible to determine the extent to which water trunk line failures at these locations contributed to soil and pavement disruption.

The incidents of cratering associated with the San Fernando and Northridge earthquakes apply primarily to pipe buried between 1.2 and 1.5 m (4 and 5 ft) below ground surface. The cratering in San Fernando and Fillmore is associated with pipelines buried beneath paved roadways with underlying compact base course and subgrade soils. Cratering could occur at pipelines with lower pressures and smaller diameters for shallow depths of cover and loose backfill conditions. Accordingly, the scenario adopted in this report's evaluation of cratering applies to burial in compact soil beneath paved roadways at depths generally equal to or exceeding 1.2 m (4 ft).

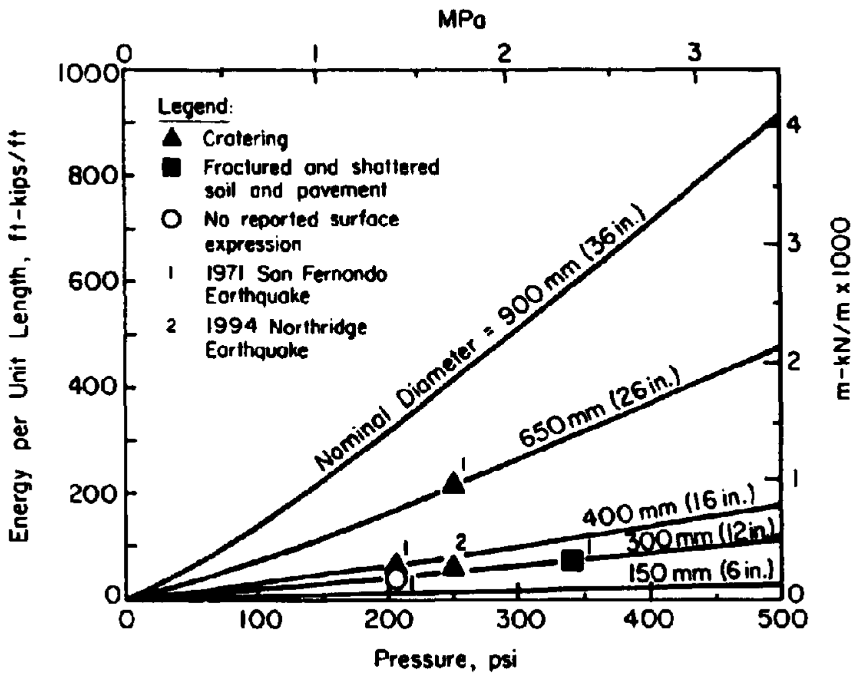


FIGURE 5-4. Energy per Unit Length of Pipeline as a Function of Pressure and Diameter

The figure allows for the superposition of energy associated with various pipelines and the occurrence of cratering or severe surface disturbance in the field. The onset of cratering and shattered soil correlates approximately with an energy of 276 m-kN/m (62.1 ft-kips/ft). This value is used as a reference energy, W_N, in Figure 5-5, which shows a family of dimensionless curves in which energy is normalized with respect to the reference value.

Figure 5-5 is expressed in a matrix format in Figure 5-6. This latter figure shows the normalized values of energy according to a row and column structure, organized with respect to nominal pipe diameter, as given by API 5L [API, 1987], and level of operating pressure. The matrix shows the energy levels for various pressures and diameters scaled according to the reference energy that correlates with cratering and severe surface disturbance in the field.

The diagonal of the matrix includes values close to one. The part of the matrix

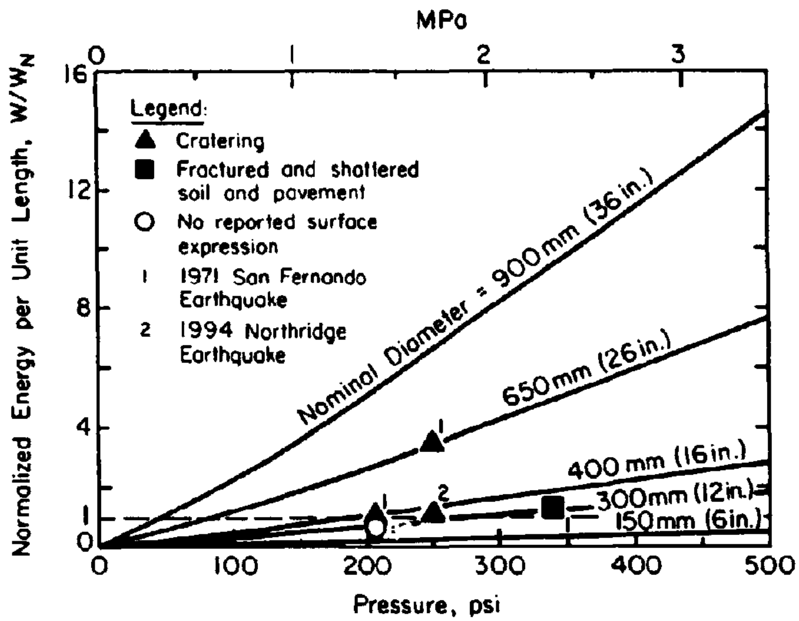


FIGURE 5-5. **Normalized Energy per Unit Length of Pipeline as a Function of Pressure and Diameter**

Nominal Diameter mm (in.)	Internal Pipeline Pressure, MPa (psi)								
	0.69 (100)	1.03 (150)	1.38 (200)	1.72 (250)	2.07 (300)	2.41 (350)	2.75 (400)	3.10 (450)	3.45 (500)
150 (6)	0.07	0.11	0.15	0.20	0.24	0.29	0.34	0.39	0.44
200 (8)	0.12	0.19	0.27	0.35	0.43	0.51	0.60	0.69	0.77
250 (10)	0.19	0.30	0.43	0.55	0.68	0.82	0.95	1.09	1.23
300 (12)	0.27	0.43	0.61	0.79	0.98	1.17	1.36	1.56	1.76
350 (14)	0.32	0.52	0.74	0.96	1.19	1.42	1.65	1.89	2.14
400 (16)	0.43	0.69	0.97	1.26	1.56	1.87	2.18	2.50	2.82
450 (18)	0.54	0.88	1.24	1.61	1.99	2.38	2.78	3.18	3.59
500 (20)	0.67	1.09	1.54	2.00	2.47	2.96	3.45	3.95	4.46
550 (22)	0.82	1.33	1.87	2.43	3.01	3.60	4.20	4.80	5.42
600 (24)	0.98	1.54	2.23	2.90	3.59	4.30	5.02	5.73	6.48
650 (26)	1.15	1.87	2.63	3.42	4.23	5.05	5.90	6.75	7.62
700 (28)	1.33	2.16	3.03	3.94	4.88	5.83	6.80	7.78	8.79
750 (30)	1.53	2.48	3.49	4.54	5.61	6.71	7.83	8.96	10.12
800 (32)	1.75	2.83	3.98	5.18	6.41	7.66	8.94	10.22	11.55
850 (34)	1.98	3.20	4.50	5.85	7.25	8.67	10.11	11.57	13.06
900 (36)	2.22	3.60	5.06	6.58	8.13	9.73	11.35	13.00	14.66

FIGURE 5-6. **Matrix Showing Normalized Energy, W/W_N, as a Function of Nominal Pipe Diameter and Pressure**

above the diagonal represents combinations of pressure and diameter with decreasing energy and potential for cratering. Similarly, the part of the matrix below the diagonal represents an increasing potential for cratering.

In Figure 5-7, the matrix of normalized energy is re-expressed in terms of relative potential. Cratering potential is given as moderate, high, and very high with respect to the potential for cratering should a girth weld rupture occur.

Various studies have been conducted to determine the radius of a given heat flux rate from an ignited ruptured pipeline [Knowles, et al., 1978; Fearnehough, 1985]. In British codes of practice, such as BS 8010: Part 2, Section 2.8 [British Standards Institution, 1992] and IGE/TD/1: Edition 2 [Institution of Gas Engineers, 1984], the consequences of pipeline failure and the ignition of escaping gas are accounted for by estimating the distances at which the heat radiation is equal to or less than 10,000 BTU/ft^2 hr (32 kW/m^2 sec). As Fearnehough [1985] points out, this heat flux has been correlated with 1% fatalities of those so exposed for 10 seconds. The distances associated with this heat flux are plotted by Fearnehough for various combinations of pressure and nominal pipe diameter.

In Figure 5-6, various combinations of pressure and nominal pipe diameter with the potential for cratering can be identified by values of W/W_N close to one. As such, it is possible to determine the distances associated with a heat flux of 10,000 BTU/ft^2 hr (32 kW/m^2 sec) and relate them to the diameters and pressures at which cratering may be anticipated. In general, the lowest levels of pressure and nominal diameter with potential for cratering have heat flux distances of approximately 21 to 26 m (70 to 85 ft), based on the threshold value 10,000 BTU/ft^2 hr (32 kW/m^2 sec). The heat flux distances increase for W/W_N greater than one. For relatively low W/W_N associated with the moderate cratering potential zone of Figure 5-7, the heat flux distance will decrease. Because cratering is not anticipated in the low to moderate risk category, not only is the opportunity for ignition diminished, but any ignition which does occur will not burn from direct exposure of the pipe.

5.5 EARTHQUAKE AND NATURAL HAZARDS

Figure 5-8 presents a flow chart of the methodology followed in this report to

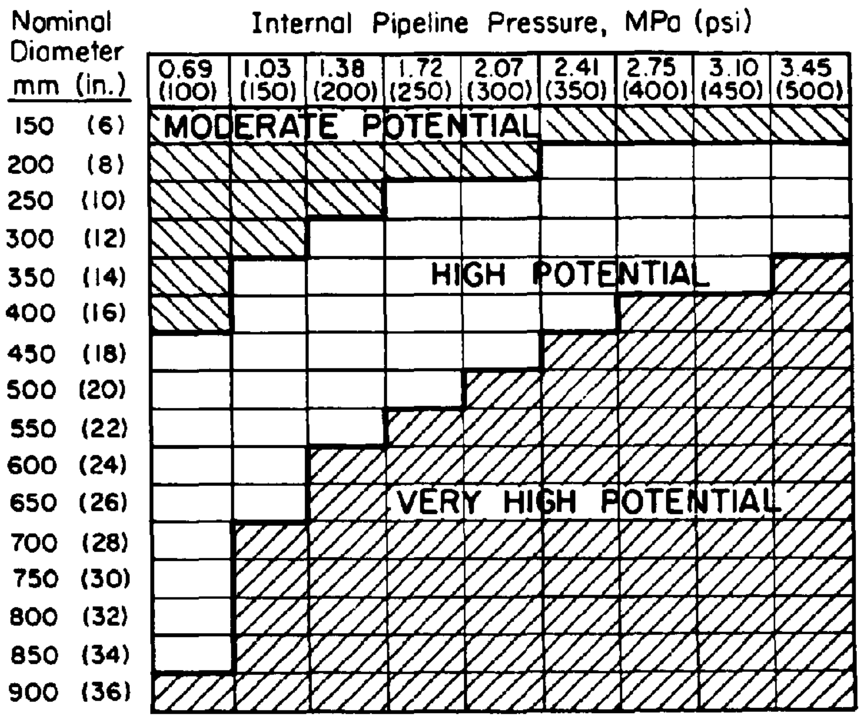


FIGURE 5-7. Cratering Potential as a Function of Nominal Diameter and Pressure

assess earthquake hazard effects on steel pipelines. The use of the methodology is demonstrated in Section 6 by means of its application to two existing supply lines. It is recommended that the general approach outlined in Figure 5-8 be followed in assessing the relative seismic risk to other transmission and supply lines. The methodology is based largely on reconnaissance information. The synthesis and interpretation of such information should be performed by one who is experienced and qualified to make geotechnical engineering evaluations.

The procedure begins with a comprehensive review of pipeline characteristics, routing, and repair records. Next, the regional geologic conditions are assessed. In southern California, it is helpful to evaluate regional conditions as they pertain to various groundwater basins, and reference should be made to publications of the California Department of Water Resources, such as bulletins [e.g., DWR, 1961] and Watermaster reports. Maps of surficial geology and regional hazards also are valuable at this stage. The characteristics of select

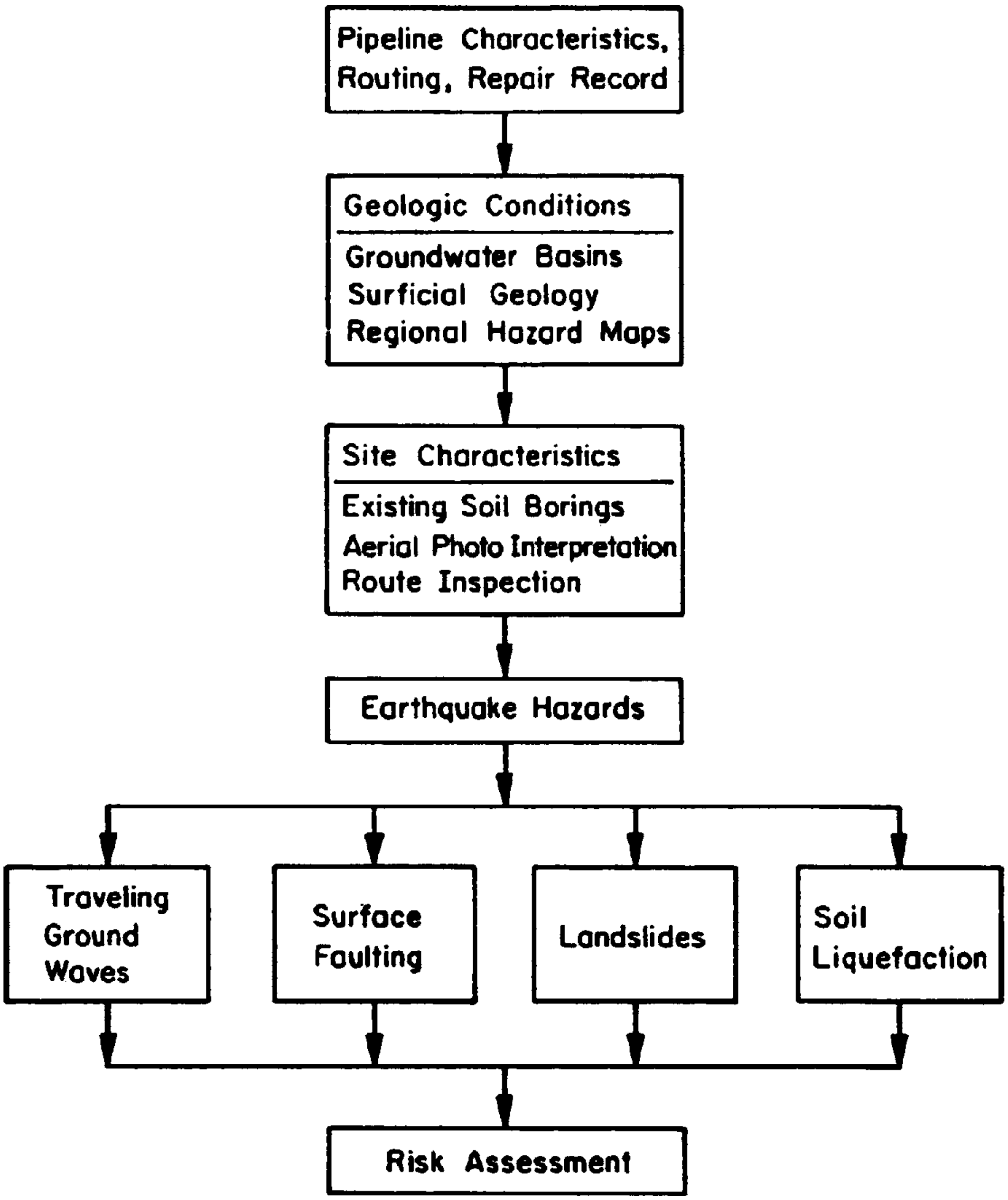


FIGURE 5-8. Flow Chart for Assessing the Relative Risk of Earthquake Hazards to Steel Pipelines

locations near the pipeline route are evaluated by air photo interpretation and collection of existing soil borings. Soil borings are available from various public agencies, such as Caltrans and municipal governments. Information often can be obtained from consulting reports for public utility companies, property owners, and companies which have constructed buildings in the vicinity of a pipeline route. It may be advantageous to make direct observations at select sites along the pipeline.

Given the preceding sources of information, earthquake hazards are assessed for traveling ground waves, surface faulting, landslides, and soil liquefaction. Information pertaining to regional geologic and site conditions is very important for evaluating liquefaction and landslide hazards, and provides useful background data for judgments about traveling ground wave effects and surface faulting.

As discussed in Section 5.3, repair records show that pre-WWII oxy-acetylene welded pipelines have been damaged by traveling ground waves in areas which experienced a seismic intensity of MM VIII or higher. Accordingly, the identification of lines at risk with respect to traveling ground wave effects should be based on the prediction of MM VIII or higher for future earthquakes on various active faults in the Los Angeles area. For example, the maximum credible earthquake on a particular fault could be chosen, and the areas of MM VIII or greater evaluated by means of existing models, such as the one developed by Evernden, et al. [1981]. The Evernden model has been used in a comprehensive study sponsored by the Federal Emergency Management Agency (FEMA) of the vulnerability and potential seismic disruption of lifeline systems in the coterminous U.S. [Applied Technology Council, 1991], and has been applied for general hazard assessment in the Los Angeles area [Evernden and Thomson, 1985]. Work sponsored by FEMA on the potential consequences of lifeline collocation [Lowe, et al., 1991] indicate that the Evernden model may underestimate MMI near the seismic source. Computer output based on the Evernden model should be scrutinized for intensities near the causative fault.

Areas of potential surface faulting can be evaluated by means of State of California Special Studies Zones maps. The maps delineate traces of hazardous faults to establish Alquist-Priolo Special Study Zones [Hart, 1978]. The maps provide information which affects the construction of buildings for human occupancy, and represent a well known and easily accessible source of information regarding zones of potential soil and rock deformation along major active faults.

As pointed out by the Committee on Gas and Liquid Fuel Lifelines [1984], quantifying the hazards associated with earthquake-induced landslides generally begins with the identification of slopes which are potentially unstable under static conditions. The assessment of earthquake-induced landslides, therefore, involves a systematic consideration of landslide potential under nonseismic conditions. Records of previous landslide activity, air photo interpretation, and regional landslide hazard maps prepared by state or federal agencies are sources of information important for the evaluation of both natural and earthquake hazards. In cases where there is potential for mud and debris flows triggered by intense rainfall, procedures relating rainfall and landslide initiation [e.g., Keefer, et al., 1987] should be incorporated into the overall approach for natural hazard assessment.

A method for estimating the effects of earthquake-induced landslides on buried pipelines was presented by the Applied Technology Council [1985] in a document referred to as ATC-13. The method was derived from slope failure intensity matrices, developed originally by Legg, et al. [1982], in which the probabilities of various slope failure states are correlated with MMI. The method characterizes the dynamic slope stability with respect to the critical acceleration of a slope, which is defined according to the dynamic stability models and field assessment procedures summarized by Wilson and Keefer [1985]. An advantage of this method is that it provides an assessment of potential slope deformation relative to MMI, which can be predicted by the Evernden model, thus providing a consistent basis for evaluating traveling ground wave and landslide effects.

Similar procedures for assessing liquefaction hazards for lifelines have been proposed [Lowe, et al., 1992] which are based on a regional assessment of potential liquefaction severity. In this work, a methodology is described for evaluating the potential for large liquefaction-induced deformation on a more local basis, as required for a specific pipeline route. The methodology is explained by means of its application to two supply lines in Section 6.

5.6 RECOMMENDED REPLACEMENT PRIORITIES

Based on the review of factors affecting steel pipeline performance in Section 2, the earthquake performance statistics in Section 3, and the foregoing material in this section, it is possible to refine and enhance the VCA approach to provide an improved ranking of pipelines having the highest priority for replacement. As discussed in Section 4, pipelines identified for replacement in the SPRP include cast iron mains and bare steel mains in conduit. These pipelines should remain in the highest priority categories without modification. The highest priority candidates for replacement among pre-WWII pipelines, however, should be modified to take advantage of the database on earthquake response and recommended risk assessment procedures developed in this study.

The earthquake performance review in Section 3 indicates that the highest risk of girth weld failure is associated with pre-WWII oxy-acetylene welded and partially reconditioned oxy-acetylene welded pipelines. Previous earthquake behavior indicates that these lines are especially vulnerable to permanent ground deformation from surface faulting, landslides, and soil liquefaction. These pipelines also are vulnerable to traveling ground wave effects in areas of MM VIII or higher. Consistent with the VCA approach, primary emphasis should be placed on the potential consequences of failure, particularly with regard to pipeline proximity to buildings and places where people congregate frequently. Pipelines vulnerable to damage in Class 4 locations and high consequence areas should be assigned the highest priority on the basis of potential for harmful effects on people. Similar pipelines in Class 3 locations should be assigned the next highest priority for replacement.

The highest replacement priorities identified in this study pertain to pre-WWII oxy-acetylene welded and partially reconditioned oxy-acetylene welded pipelines. It would be advantageous to rank the replacement of these pipelines according to their location with respect to human occupancy and congregation, as well as their susceptibility to damage and potential for harmful consequences. Accordingly, the ranking for replacement priority is as follows: 1) Class 4 locations and high consequence areas, 2) Class 3 locations and zones of seismically-induced permanent ground deformation or intensity of MM VIII or higher, and 3) Class 3 locations with very high and high cratering potential (see Figure 5-7).

TABLE 5-I. Comparison of Replacement Priorities from Value Chain Analysis and This Study

Value Chain Analysis Approach for Pre-WWII Pipelines	Highest Replacement Priorities Identified in This Study for Pre-WWII Oxy-Acetylene, Including Partially Reconditioned Oxy-Acetylene, Welded Pipelines
• High consequence areas[1]	• Class 4 locations and high consequence areas[1]
• Class 3 locations and zones of seismically-induced permanent ground deformation[2]	• Class 3 locations and zones of seismically-induced permanent ground deformation,[2] or MM VIII or higher seismic intensity
• Class 3 locations with high flame radiation potential[3]	• Class 3 locations with very high and high cratering potential, as given in Figure 5-7

[1]High consequence areas: major thoroughfares and areas adjacent to schools, hospitals, high density housing, shopping centers, and other locations where high densities of people frequently congregate. There were no transmission or distribution supply lines in Class 4 locations at the time of the VCA study

[2]Zones of seismically-induced permanent ground deformation: areas of surface faulting, landslides, and liquefaction

[3]High flame radiation potential: pipeline with diameter $\geq$ 400 mm (16 in.)

Table 5-I provides a comparison between the replacement priorities from the VCA approach and this study. Whereas the VCA approach targeted all pre-WWII pipelines as potential replacement candidates, this study recommends focusing on pre-WWII oxy-acetylene welded pipelines. The VCA approach linked earthquake hazard with zones of potential surface faulting, landslides, and liquefaction. This study identifies earthquake hazards as all of the foregoing zones plus areas likely to experience MM VIII or higher. The VCA approach drew attention to pipelines with diameters equal to or larger than 400 mm (16 in.), whereas this study utilizes the very high and high cratering potential categories established in Section 5.4 to identify various combinations of nominal diameter and operating pressure as the primary candidates for replacement.

SECTION 6

APPLICATION OF PIPELINE REPLACEMENT PROCEDURE

In this section, the pipeline replacement procedure proposed in the previous section is applied to two transmission lines, Lines 121 and 123. These pre-WWII pipelines represent a good opportunity for evaluating the benefits that are derived by using a more refined and geotechnically-oriented methodology, which then is evaluated with respect to the costs required to obtain and interpret the additional information needed for implementation.

The section begins with a description of Lines 121 and 123, and then provides information regarding the geologic conditions which influence the pipelines. The traveling ground wave, landslide, surface faulting, and liquefaction hazards in the vicinity of the pipelines are discussed. Special attention is focused on the liquefaction hazards, with a review of soil boring data and stereo pair aerial photographs. The information and data are used to assess pipeline risks and to recommend a course of action in the form of retention or replacement. The costs and benefits of the procedure are summarized.

6.1 CHARACTERISTICS OF LINES 121 AND 123

Lines 121 and 123 were commissioned in 1930. The lines were originally constructed with 650-mm-(26-in.)-diameter, Grade B steel [SMYS = 241 MPa (35 ksi)] pipe, with oxy-acetylene welds and wall thickness of 6.4 mm (0.25 in.). Replacement pipe installed in the 1950s through 1970s has introduced diameters as large as 750 mm (30 in.) in several locations. The current MAOP of both lines is 1.6 MPa (228 psi), which results in maximum hoop stresses from internal pressures of 34% SMYS. The routings of both lines are shown in Figure 6-1.

Line 121 is 11.4 km (7.09 mi.) in length and runs from about 122 m (400 ft) north of Rimerton Rd. on Sepulveda Blvd. to the intersection of Tennessee Ave. and Sepulveda Blvd. The coating of this line is reported to be generally poor, and the depth of cover varies from approximately 0.75 to 1.2 m (2.5 to 4 ft). No leaks have been reported for this line. Line maps provided by SoCalGas show cathodic protection on this line beginning about 1000 m (3400 ft) north of

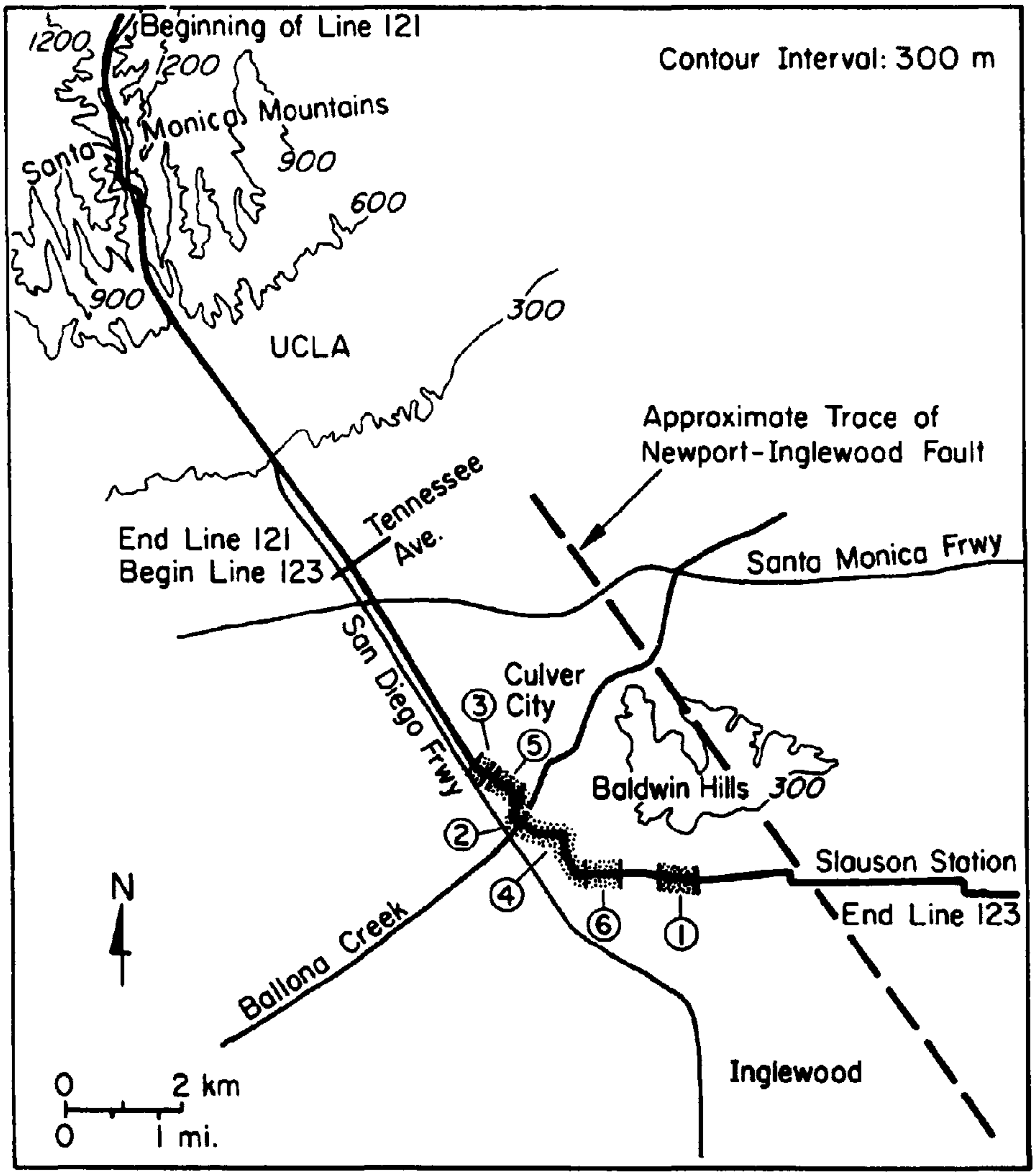


FIGURE 6-1. Location of Lines 121 and 123

Wilshire Blvd. and continuing through to the end.Line 123 is 14.6 km (9.07 mi.) in length and begins at the end of Line 121. The line proceeds down Sepulveda to Lucerne Ave., and then along Lucerne Ave., Sawtelle, Hannum, Slauson, Buckler, 59th, Arlington, and 60th Sts., and ends at Slauson Station. The coating on this line is reported to be poor, and records indicate a relatively high leak rate. The depth of cover varies approximately from 0.75 to 1.2 m (2.5 to 4 ft). The line maps show the first cathodic protection anodes are located where the line crosses Ballona Creek. These continue at irregular spacing to the end of the line at Slauson Station.

Several sections of Line 123 have been replaced since 1930. Table 6-I lists the replaced sections according to key dimensions, year, length, and approximate location of replacement pipe. Roughly 4.3 km (2.7 mi.), or approximately 28%, of Line 123 has been replaced with higher strength pipe constructed with modern electric arc welding procedures. Figure 6-1 shows the approximate locations of replaced line in conjunction with the numbering system listed in Table 6-I. At MAOP, the replaced sections of pipelines operate with maximum hoop stress from internal pressure between 15 and 28% SMYS.

6.2 GEOLOGIC CONDITIONS

The geologic conditions affecting Lines 121 and 123 are described in this work with reference to the groundwater basins in the Los Angeles area and the surficial geology. The groundwater conditions in the basins have an influence on the potential for soil liquefaction, and the surficial geology provides information pertaining to the nature and age of the soils in which the pipelines are constructed.

6.2.1 Groundwater Basins

Figure 6-2 is a map of the groundwater basins in the Los Angeles area, on which are superimposed the approximate locations of Lines 121 and 123. Lines 121 and 123 lie mainly within the Santa Monica Groundwater Basin, with portions of Line 123 located across the western and southern limits of the Baldwin Hills and the West Coast and Central Groundwater Basin. A brief commentary about each basin is provided. The groundwater basins and prominent physiographic features were described by the California Department of Water Resources (DWR) [1961], and the

TABLE 6-I. Summary of Replaced Sections of Line 123

Year	Diameter mm (in.)	Replacement Steel	Wall Thickness mm (in.)	Approximate Location	Replaced Length m (ft)	Section Number[c]
1949	650 (26)	X-42[a]	7.9 (0.312)	Slauson Ave.	599 (1964)	1
1953	650 (26)	X-42[a]	6.4 (0.25)	Lucerne Ave.	483 (1583)	2
1954	650 (26)	X-52[b]	7.1 (0.281)	Sepulveda Blvd.	149 (488)	3
1958	750 (30)	X-52[b]	9.5 (0.375)	Hannum Ave. and Sawtelle Blvd.	2007 (6584)	4
1967	750 (30)	X-52	8.7 (0.344)	Sepulveda Blvd.	627 (2039)	5
1973	750 (30)	X-52	8.7 (0.344)	Slauson Ave.	415 (1350)	6

[a]SMYS = 290 MPa (42 ksi)
[b]SMYS = 359 MPa (52 ksi)
[c]Refer to Figure 6-1 where number shows approximate location of replaced section

information related to these subjects in this work is taken mainly from this source.

<u>Santa Monica Basin</u>. All of Line 121 and half of Line 123 lie within this groundwater basin, which is bounded by the Santa Monica Mountains to the north, the Ballona Escarpment to the south, the Pacific Ocean to the west, and the Newport-Inglewood fault to the east. In the vicinity of the pipeline, there are two prominent physiographic features, the Sawtelle Plain and Ballona Gap. Holocene alluvium covers the Sawtelle Plain with a thickness of 10 to 13 m (30 to 45 ft). In Ballona Gap, the alluvium attains a maximum thickness of 30 m (90 ft).

There are three principal sedimentary units underlying the pipelines: the Bellflower aquiclude, the Ballona aquifer, and the Silverado aquifer. The Bellflower and Ballona units are recent Holocene alluvium, which extend to depths as great as 30 m (90 ft). Near Line 123 in Ballona Gap, maps prepared by DWR [1961] show the Bellflower aquiclude to be the shallowest deposit, underlain at a depth of approximately 6 to 9 m (20 to 30 ft) by the Ballona aquifer. The deeper Silverado aquifer, which consists of sand and gravel with small amounts of clay, is

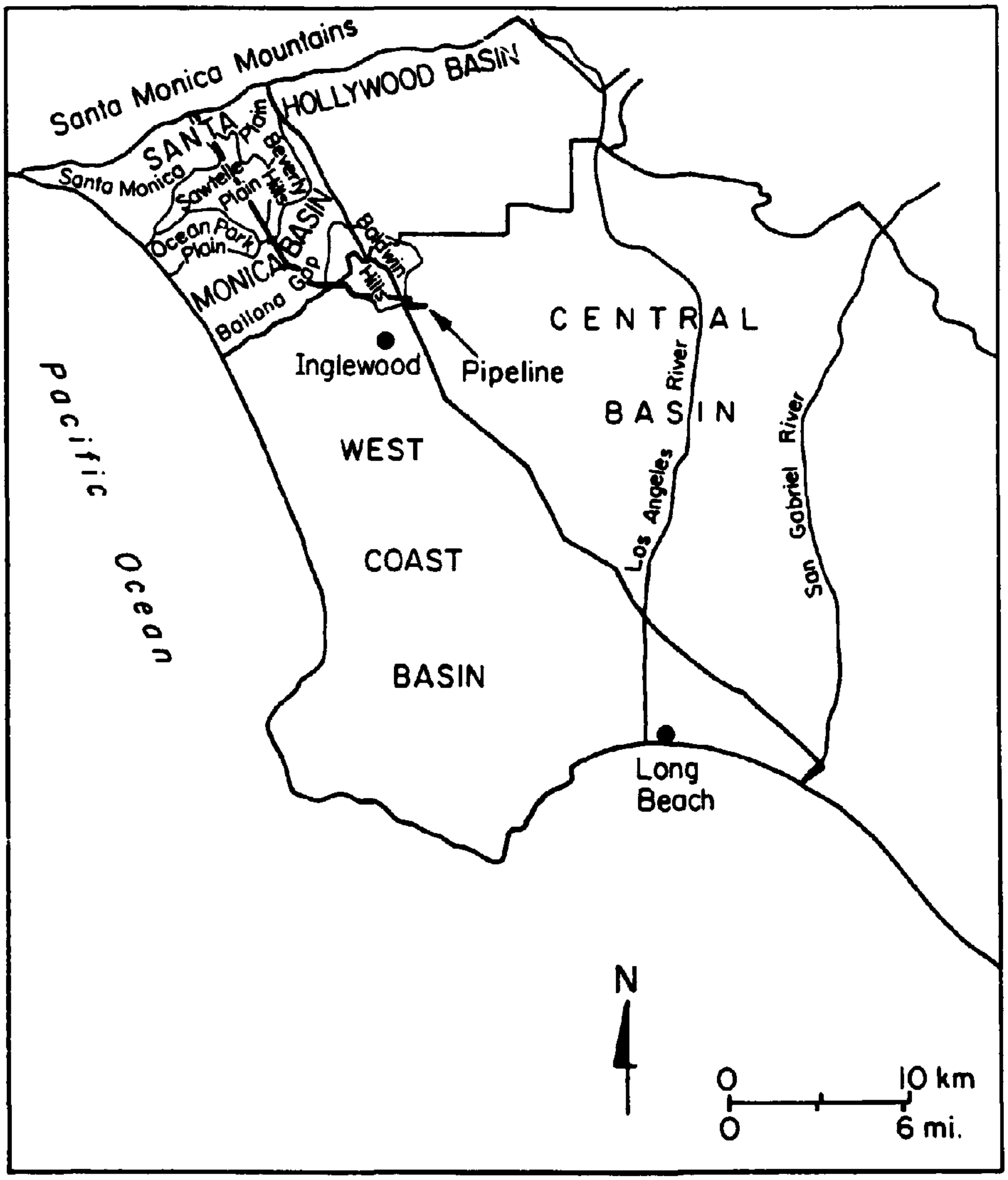


FIGURE 6-2. Line 121 and 123 Locations Relative to Los Angeles Area Groundwater Basins [adapted from DWR, 1961]

30 to 85 m (100 to 280 ft) thick at depths as great as 140 m (450 ft) below ground surface.

It has been reported [DWR, 1961] that water levels in the Holocene alluvium of the Sawtelle Plain are much higher than water levels which penetrate the older sediments, suggesting that perched or semi-perched groundwater exists in the Ballona aquifer in this area. Maps prepared by DWR also show that the Ballona and underlying Silverado aquifers merge west of the Charnock fault, approximately 1 km (0.62 mi.) west of the location where Line 123 crosses Ballona Gap.

The Los Angeles Department of Water and Power (LADWP) [1991] reports that the City of Santa Monica pumps municipal water from the Silverado aquifer through several wells at depths of 25 to 170 m (80 to 544 ft). The contact between the Ballona and Silverado aquifers implies that pumping from the Silverado could influence water levels in the shallower alluvium.

The City of Beverly Hills had municipal production wells in the Hollywood Basin until 1976 [LADWP, 1991], when pumping was discontinued. Since that time, there has been an increase in the level of the phreatic surface, with noticeable effects near abandoned wells [Lund, 1992]. Any recharge associated with the termination of this pumping should have no effect on water levels within the Santa Monica Basin.

West Coast Basin. Line 123 cuts through the extreme northeast corner of the West Coast Groundwater Basin. This basin is bordered by the Ballona Escarpment to the north, the Newport-Inglewood fault to the east, and the Pacific Ocean to the west and south. Reports prepared by DWR [1970; 1972; 1982; 1991] were examined for this basin. The elevation of the pipeline route at the edge of the Baldwin Hills is too high to be affected by the groundwater.

Central Basin. As indicated in Figure 6-2, only about 1 km (0.6 mi.) of Line 123 is in the Central Basin. This part of the pipeline is in the Central Basin Pressure Area, which receives its name from the fact that the aquifers in the basin are confined by relatively impervious layers of clay and silt over most of the area [DWR, 1961]. Measurements at select observation wells indicate a rise in water level from approximately 85 to 75 m (280 to 250 ft) below the ground surface since 1976 [DWR, 1990] near the location where the Santa Monica Freeway crosses the Los Angeles River. A similar rise in groundwater elevation from 60 to 50 m (190 to 160 ft) was observed during the period of 1981 to 1987 at the eastern boundary of the Central Basin near the intersection of Century and Western Blvds. In the vicinity of the pipeline, the groundwater in the surficial alluvium appears to be generally deep [depth greater than 16 m (50 ft)]. It is unlikely that variations in the water levels of the deep aquifers has had a significant effect on the groundwater in the surficial alluvium.

6.2.2 Surficial Geology

Figure 6-3 shows a surficial geology map on which are superimposed the locations of Lines 121 and 123. Approximately half the length of Line 121 is in the Santa Monica Mountains and foothills, which are shown on the map as the Santa Monica Slate and the Modelo Shales. Between the Santa Monica Mountains and the Baldwin Hills, virtually the entire length of the pipeline (including Lines 121 and 123) is in Holocene alluvium. To the southeast of the Baldwin Hills, most of Line 123 is in Pleistocene deposits.

It is well known that liquefaction susceptibility is highest in saturated late Holocene deposits of fluvial origin [Youd and Perkins, 1978; Tinsley, et al., 1985]. Accordingly, those portions of the pipeline in Holocene sediments with the potential for a relatively high water table require special consideration. As discussed in the previous section, perched groundwater has been observed in the Sawtelle Plain, and a relatively high groundwater level would be anticipated in the vicinity of Ballona Creek.

6.3 EARTHQUAKE HAZARDS

In this section, earthquake hazards are treated with respect to traveling ground waves, landslides, surface faulting, and liquefaction. Each hazard is discussed under a separate subheading which follows.

6.3.1 Traveling Ground Waves

By assuming a 7.2 magnitude earthquake, as recommended by Toppozada, et al. [1989], on the portion of the Newport-Inglewood fault nearest Lines 121 and 123, peak ground accelerations between 0.4 and 0.5 g are estimated using attenuation

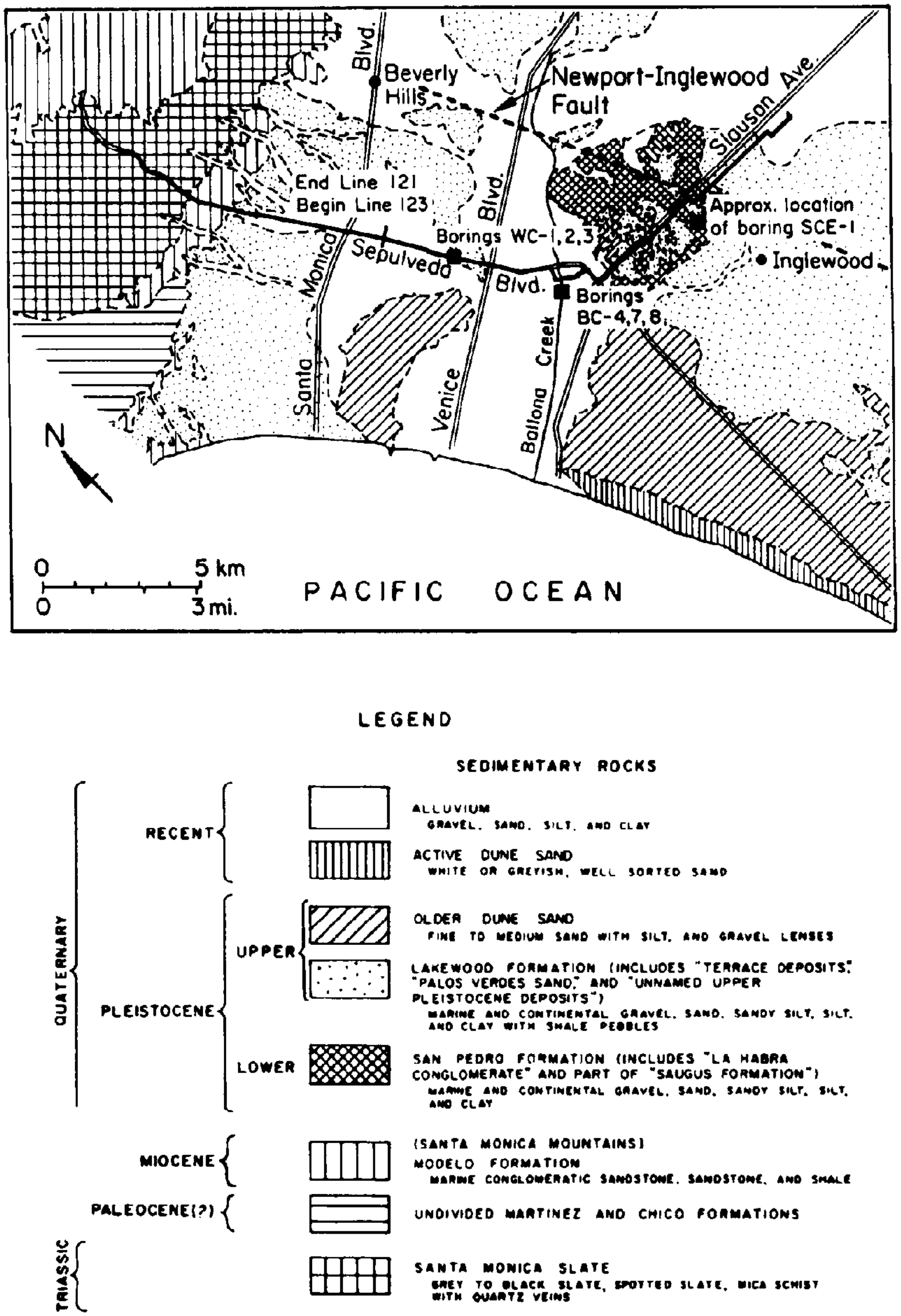


FIGURE 6-3. Line 121 and 123 Locations Relative to Surficial Geology [adapted from DWR, 1961]

relationships commonly applied for California earthquakes [e.g., Idriss, 1985; Joyner and Boore, 1988]. These estimated levels of acceleration are consistent with strong ground motion measurements and estimated MMI in the areas most severely affected by ground shaking during the 1933 Long Beach, 1952 and 1954 Kern County, and 1971 San Fernando earthquakes. Accordingly, pipeline performance as summarized for these earthquakes in Section 3 offers a reasonable scenario from which the response of similar pipelines to traveling ground wave effects can be extrapolated.

6.3.2 Landslides

The routing of Line 121 proceeds through the Santa Monica Mountains by way of Sepulveda Canyon. The Santa Monica Mountains are an anticlinal fold that consist primarily of two formations in the vicinity of the pipeline: Santa Monica Slate and Modelo Formation Shale. The floor of Sepulveda Canyon consists of Holocene alluvium originating in the Santa Monica Mountains [Dibblee Geological Foundation, 1991; DWR, 1961].

Santa Monica Slate is a dark blue to black Jurassic, metamorphosed rock. The section of the Modelo formation near the pipeline, also known as the Monterey Formation, is a thin bedded, platy siliceous shale of Miocene Age.

The walls of Sepulveda Canyon were significantly laid back during the construction of the San Diego Freeway (I-405). Discussions with California Department of Transportation (Caltrans) personnel indicated that there have been no major landslides in Sepulveda Canyon in the vicinity of the pipeline [Lisiewicz, 1993]. Heavy rains in February, 1993 caused soil and debris to wash off exposed slopes near the construction site of the Getty Museum. Although the debris was washed onto a part of the freeway, this type of ground movement is representative of shallow displacement and did not involve deep-seated displacements which influence the pipeline. In addition, SoCalGas repair records do not indicate any repair to Line 121 that would have been required as the result of landslide-induced damage.

Shallow disrupted failures (soil slides, rock falls, and rock slides) are the predominant landslide types predicted for the Santa Monica Mountains in the event of an earthquake with moment magnitude of 6.5 along the northern part of the Newport-Inglewood fault zone [Ziony, et al., 1985]. It is unlikely that such shallow failures will result in ground deformation which actually intersects the pipeline.

6.3.3 Surface Faulting

The potential for damage to Lines 121 and 123 caused by surface faulting was evaluated using State of California Special Studies Zones maps. Figure 6-4 shows a map of these zones superimposed on a map of Line 123 along Slauson Ave. and 59th St. These zones, also called Alquist-Priolo Special Studies Zones, first were established in 1972 and delineate traces of hazardous faults [Hart, 1978]. Regulations prohibit construction of structures for human occupancy within the zones. Zone boundaries on early maps were positioned about 60 m (200 ft) from fault traces to accommodate imprecise fault location and the possibility of unknown active branch faults. Later maps show zone boundaries as close as 60 to 100 m (200 to 300 ft) from the fault trace [Hart, 1978].

Line 123 crosses one of these zones on its routing along Slauson Ave. between Fairfax Ave. and Overhill Dr. Another Alquist-Priolo Zone reaches to within two blocks of the pipeline on its routing along 59th St. between Edgemar and Alviso Aves. Toppozada, et al. [1989] predicted that for an earthquake with an approximate magnitude of 7.2, the maximum surface displacement would be 2 m (6 ft), and the average displacement would be half of that, or 1 m (3 ft). Toppozada, et al. [1989] assumed the displacement would be predominantly right lateral and would occur along the Alquist-Priolo fault traces. For an earthquake with moment magnitude of 6.5, Ziony, et al. [1985] estimate fault movements from a few to a few tens of centimeters on the main strand of the Newport-Inglewood fault.

6.3.4 Liquefaction

Figure 6-5 shows Lines 121 and 123 superimposed on a liquefaction susceptibility map prepared by Tinsley, et al. [1985]. The routing of the pipeline through Ballona Gap is within an area defined by Tinsley, et al. as having "moderate" susceptibility to liquefaction. The other sections of the pipeline are in areas rated as "low" or "very low", with the exception of a small "moderate" zone near the end of Line 123. This rating is based upon age and type of sedimentary

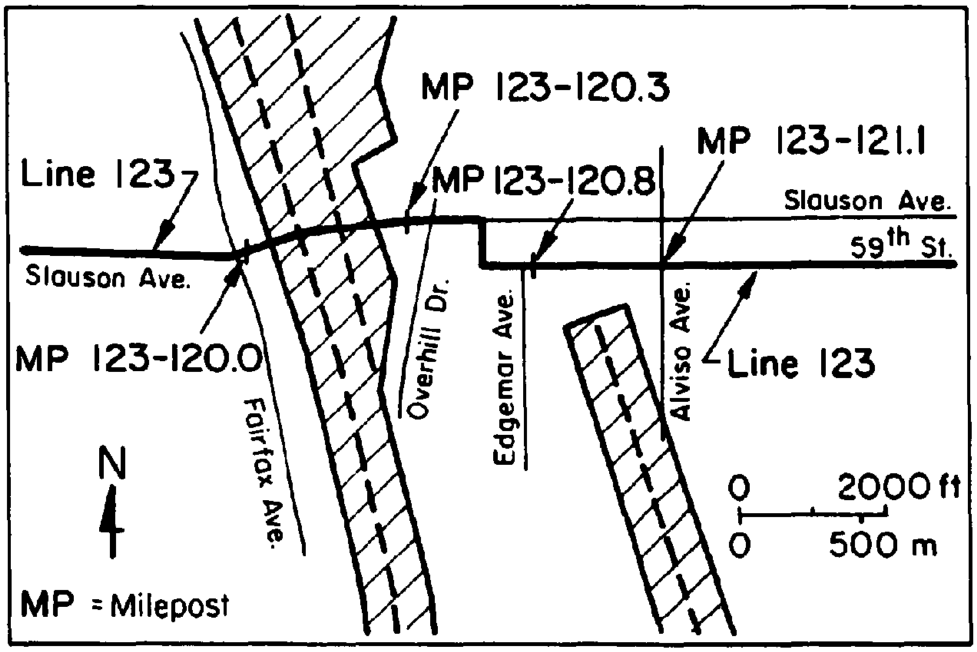


FIGURE 6-4. Line 123 Location Relative to Alquist-Priolo Zones for Newport-Inglewood Fault

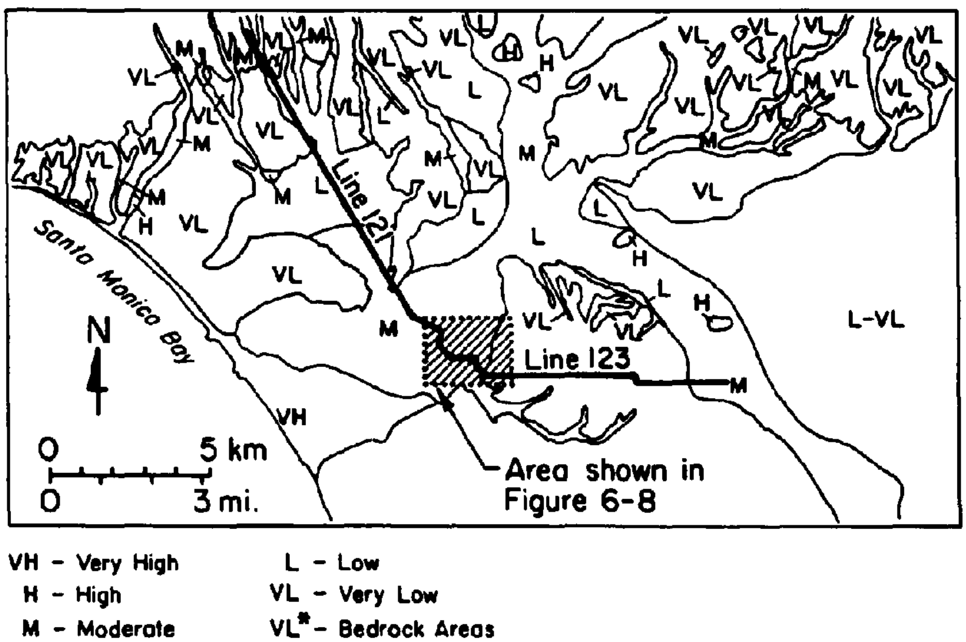


FIGURE 6-5. Line 121 and 123 Locations Relative to Liquefaction Susceptibility Map [adapted from Tinsley, et al., 1985]

deposit, penetration resistance, and depth to groundwater. A "moderate" rating is due to the presence of Late Holocene sediments and a depth to groundwater of between 3 and 10 m (10 and 30 ft). A "low" or "very low" rating indicates either groundwater levels lower than 10 m (30 ft) or Pleistocene or older sediments.

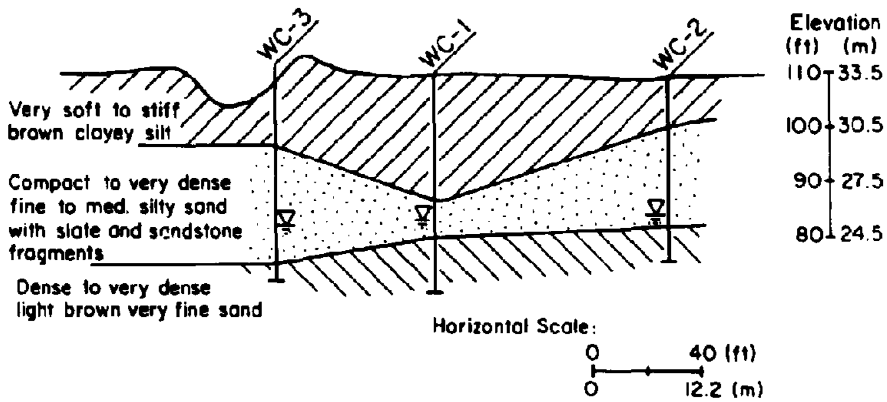
In an effort to provide a more comprehensive assessment of liquefaction and large ground movement potential, soil borings and air photos were collected for the pipeline in areas of moderate liquefaction susceptibility. The next two sections focus on the results of the soil profile and air photo interpretation.

6.4 INTERPRETATION OF SOIL BORINGS

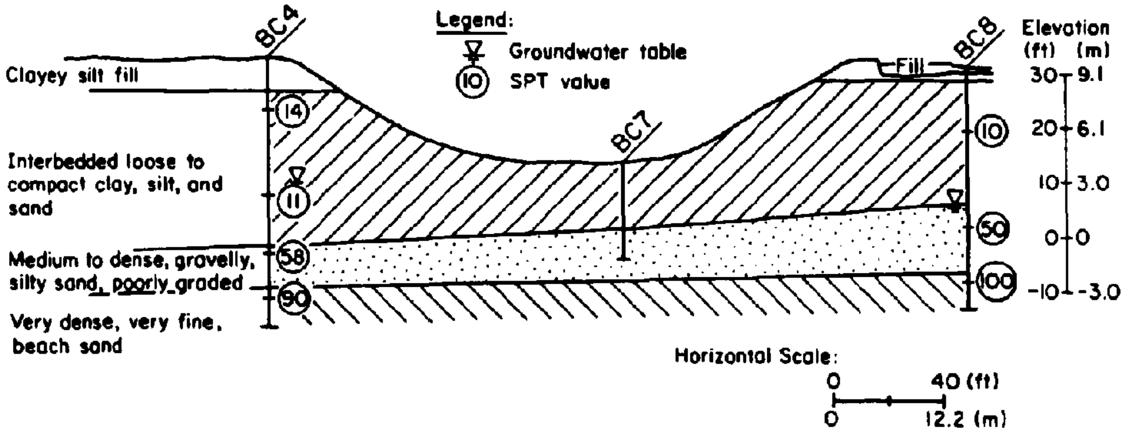
Based on geologic cross-sections provided by DWR [1961], two locations of possible high groundwater were identified in the Holocene alluvium of the Sawtelle Plain and Ballona Gap. Soil borings were collected from CalTrans that were completed in 1959 for the construction of the San Diego Freeway (I-405), which runs parallel to Sepulveda Blvd. in the area of interest. Over 250 borings with depths of 14 to 28 m (40 to 80 ft) were examined. Two areas of relatively high groundwater table were identified from the soil borings. These areas are shown in Figure 6-3, and include borings WC-1, 2, and 3, located in the Sawtelle Plain, and borings BC-4, 7, and 8, located in Ballona Gap.

Figure 6-6 shows simplified soil profiles representative of the soils encountered in the Sawtelle Plain and Ballona Gap. The borings used to draw the representative profile for Sawtelle Plain are located at the crossing of the San Diego Freeway and the Westwood Flood Control Channel near Palms Blvd. The soil profile in this area consists of an upper 3 to 4 m (10 to 12 ft) of clayey silt, with an underlying 4-m- (12-ft)-thick stiff clayey silt layer that contains slate and shale fragments. The bottom 5 m (15 ft) of the borings reveal a dense to very dense light brown very fine sand. Groundwater was encountered at depths of about 12 m (36 ft), with artesian pressures at a level of 8 to 9 m (25 to 27 ft) below the surface.

The borings used to draw the representative soil profile for Ballona Gap are located across Ballona Creek. The soil profile here consists of an upper 1- to 2-m (3- to 6-ft)-layer of compact clayey silt fill underlain by an 8- to 10-m-



a) Sawtelle Plain



b) Ballona Gap

FIGURE 6-6. Soil Profiles Along Pipeline Route at Sawtelle Plain and Ballona Gap

(24- to 30-ft)-layer of interbedded clay, silt, and fine sand combinations. Maps prepared by DWR [1961] indicate that this layer is most likely the Bellflower aquiclude. The groundwater table was encountered within this layer at depths of 6 to 8 m (18 to 24 ft) below the ground surface. Below the interbedded layer is a 2- to 3-m (6- to 9-ft)-layer of compact to dense, poorly graded, gravelly and silty sand. The bottom of borings BC-4 and BC-8 indicated a very dense layer of very fine poorly graded beach sand. Standard penetration tests (SPTs) [ASTM, 1991] were performed in the borings at this location. As shown in the soil profile, the uncorrected SPT values are 50 to 60 in the gravelly, silty sand and 90 to 100 in the underlying beach sand.

Another set of borings was obtained from Southern California Edison (SCE). Boring SCE-1, shown on Figure 6-3, is located near LaBrea and Slauson Aves. It was completed for SCE in 1969 during construction of a high voltage transmission line. The soil encountered was predominantly stiff to very stiff sandy clay and clayey sand. The boring extended to 8 m (25 ft) below the surface and no groundwater was encountered.

6.5 AERIAL PHOTO INTERPRETATION

Two sets of aerial photos were obtained and examined in relation to this project. The two sets were the: 1) 1928 C-300 series aerial photos of the Los Angeles Basin from the Fairchild Aerial Photo Collection held at Whittier College, Whittier, CA, and 2) 1938 U.S. Department of Agriculture aerial photos held by the National Archives-Center for Cartographic and Architectural Archives, Washington, D.C. These photos were used to evaluate the landforms and probable depositional environments along the route of Lines 121 and 123. The scales for the 1928 and 1938 photos are about 1:18,000 and 1:20,000, respectively.

The aerial photos were studied to identify landforms, soil types, vegetative patterns, variations in topography, and other features which would help in assessing the potential for liquefaction and associated large ground deformation. For example, aerial photo analysis of areas in the Sawtelle Plain disclosed a location along the pipeline route of potentially high water table, as evinced by surface drainage features and concentrations of vegetation. This area was very close to the location of the soil profile in Figure 6-6a, which shows soils that are fine grained in the upper portion of the profile, and dense to very dense granular material in the lower portion. Although the water table indicated by the borings was among the highest encountered in all the Caltrans borings evaluated in this study, it was still 8 to 9 m (26 to 30 ft) below ground surface.

Figure 6-7 presents a view from a 1938 aerial photograph of Line 123 in the area where it crosses Ballona Gap. Various physiographic features are labeled relative to the pipeline. A zone of special interest is identified in the southeast portion of the figure, which is shown in expanded form in Figure 6-8.

Figure 6-8 presents a 1938 aerial photograph of the area where Line 123 crosses Ballona Creek and enters through a small canyon at the bottom right of the photo into the Baldwin Hills. The location of this photo is shown in Figure 6-5. The alluvial valley of Ballona Gap, the western boundary of the Baldwin Hills, the alluvial fan underlying the pipeline, and the alluvial fan of Centinela Creek are labeled in the figure. The surficial boundaries of the alluvial fans have been outlined, based on stereographic interpretation of the photos. The locations of Caltrans soil borings, denoted as Locations A and B, are marked. Location A pertains to the soil profile illustrated in Figure 6-6b.

The toe areas of alluvial fans have been identified on the basis of experience during past earthquakes [e.g., Youd and Perkins, 1978] as areas where liquefaction-induced lateral spreads can occur. Movements at these locations are likely to be oriented in the downslope direction. Because the pipeline is constructed with two prominent bends in the area of the alluvial fan identified in Figure 6-8, any downslope soil movement will tend to concentrate pipe deformation at these locations.

Soil borings at Location B disclose about 3 to 5 m (10 to 16 ft) of fine grained overbank deposits underlain by 3 to 6 m (10 to 20 ft) of what appears to be alluvial fan deposits with rock fragments, debris, and some loose sand lenses. The water table indicated by the borings was between 6 and 9 m (20 to 30 ft) below ground surface, such that some loose sand lenses apparently were submerged.

An examination of aerial photos at other locations along the pipeline route in Ballona Gap and the Sawtelle Plain did not disclose features which were

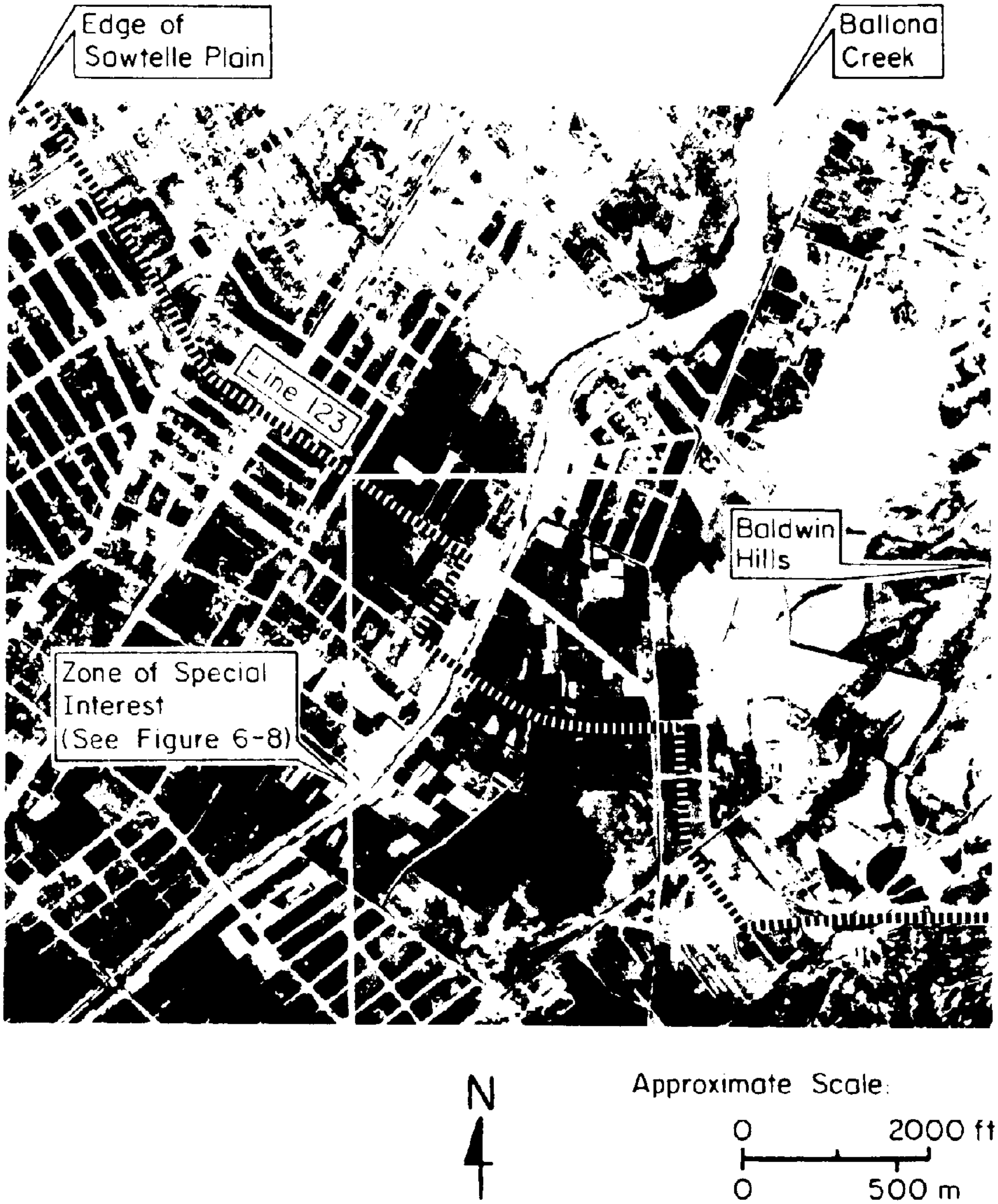


FIGURE 6-7. Aerial Photograph of Pipeline Route through Ballona Gap

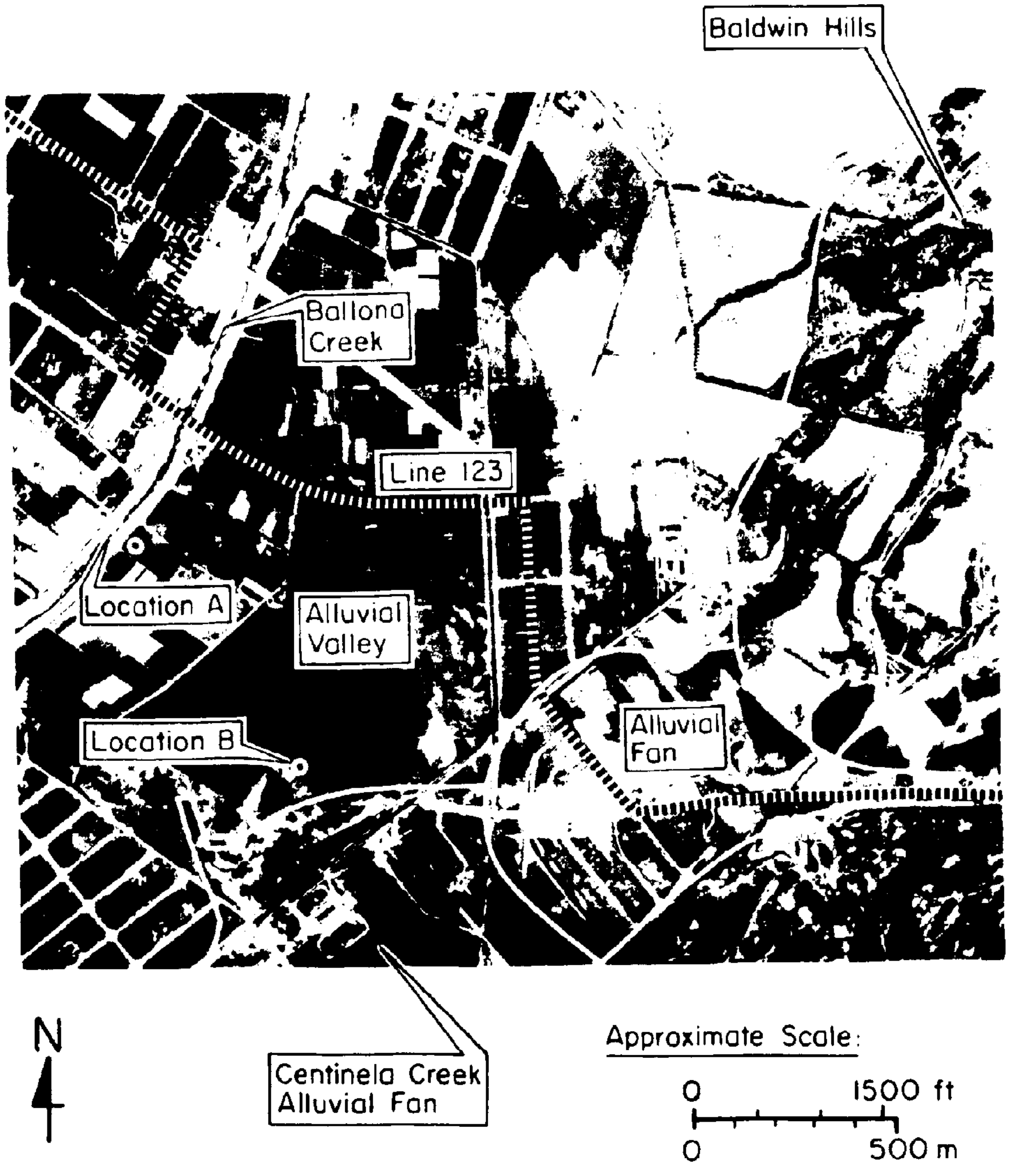


FIGURE 6-8. Aerial Photograph of Pipeline Route near Ballona Creek

conspicuous as locations of potentially large ground deformation in the event of soil liquefaction. General topographic and landform patterns nonetheless were easily recognized, and considerable detail in drainage patterns and surficial geologic formations could be perceived.

6.6 RELATIVE RISK OF PERMANENT GROUND DEFORMATION

On the basis of the assessments explained under the previous headings of this chapter, the relative risk associated with seismically-induced permanent ground deformation is summarized for Lines 121 and 123 in Table 6-II. In making an assessment of locations subject to permanent ground deformation, one must be mindful that the goal is to evaluate relative as opposed to absolute risk. The use of reconnaissance information, by nature, is not intended to provide site-specific data, but to promote systematic judgments about the general pattern of landforms, topography, soil deposits, and groundwater. The integration of this information improves one's understanding of geotechnical hazards and gives one a logical basis for discriminating locations where damaging ground movements are more probable than at other sites.

Two locations have been assigned a relatively high risk of permanent ground deformation associated with a future earthquake. One location extends from MP 123-116.90 to 123-118.22 and corresponds to those portions of line adjacent to and passing through the alluvial fan identified in Figure 6-8. The other location extends from MP 123-120.00 to 123-121.10 and corresponds to those portions of line adjacent to and passing through the Alquist-Priolo Zones for the Newport-Inglewood fault, as shown in Figure 6-4.

As mentioned previously, the toe areas of alluvial fans are known to be locations which are especially sensitive to permanent ground deformation in the event of liquefaction. Whether or not liquefaction will occur depends heavily on the depth of the water table, and it should be recognized that no soil borings have been acquired in the alluvial fan. Borings at Location B in Figure 6-8 indicate that there are some loose sand lenses below the water table, which is at a depth of 3 to 6 m (20 to 30 ft) below the ground surface. It is assumed that similar conditions exist in the alluvial fan in the vicinity of the pipeline route. Specific information could be obtained by means of borings located in this area to determine the depth of the water table and the presence or absence of loose granular deposits. It may be advantageous to collect such information to provide a better delineation of subsurface conditions which, if more favorable than estimated, will lead to a downgrading of the relative risk.

6.7 RECOMMENDATIONS

Lines 121 and 123 are composed mainly of pre-WWII oxy-acetylene welded pipe and, as such, qualify for a high priority of replacement if potentially subject to MM VIII seismic intensity, as explained in Section 5.6. Seismic intensities, estimated by Ziony, et al. [1985] for an earthquake with moment magnitude of 6.5 on the northern part of the Newport-Inglewood fault zone, are predominantly MM VII in the vicinity of Lines 121 and 123. It is possible, however, that intensities of MM VIII would be experienced on a local basis for such an earthquake, especially along Line 121, which crosses the fault.

An assessment of potential earthquake hazards did reveal two locations of relatively high risk regarding permanent ground deformation during an earthquake. It should be recognized that the portion of Line 123 adjacent to and passing through the alluvial fan shown in Figure 6-8 has been replaced with sections of X-42 and X-52 steel pipeline constructed according to modern electric arc welding procedures. Accordingly, the pipeline in this area should be characterized by strength and ductility consistent with pipelines most resistant to earthquake-induced ground movement. Furthermore, the introduction of higher strength steel piping in this area has resulted in hoop stresses under MAOP less than 30% SMYS. It is not likely, therefore, that extensive ductile rupture would occur even at the pipeline bends, where high strains could be concentrated by lateral spreading in a downslope direction.

The original 1930 pipeline is located from MP 123-120.00 to 121.10 in the Alquist-Priolo Zones of the Newport-Inglewood fault. Because this area could be subjected to a maximum right lateral strike slip a few tens of centimeters [Ziony, et al., 1985] to 2 m (6 ft) [Toppozada, et al., 1989] and is located within a heavily populated neighborhood, it would be prudent to place this section under special consideration. Additional investigations by qualified engineering geologists and seismologists would help clarify the potential for

TABLE 6-II. Relative Risk Assessment for Seismically-Induced Permanent Ground Deformation Affecting Lines 121 and 123

Line and Mile Post (MP)	Principal Ground Deformation Hazard	Relative Risk[a]	Pipeline Characteristics
Line 121 MP 121-106.50 to 121-110.46	Landslide	Low	650 and 750 mm (26 and 30 in.) 1930 oxy-acetylene welds
Line 121 MP 121-110.46 to 121-113.59 End	Liquefaction	Low	650 mm (26 in.) 1930 oxy-acetylene welds
Line 123 MP 123-113.59 to 123-114.85	Liquefaction	Low	650 mm (26 in.) 1930 oxy-acetylene welds
Line 123 MP 123-114.85 to 123-116.90	Liquefaction	Moderate	See Figure 6-1 and Table 6-I
Line 123 MP 123-116.90 to 123-118.22	Liquefaction	High	See Figure 6-1 and Table 6-I
Line 123 MP 123-118.22 to 123-120.00	Liquefaction	Low	See Figure 6-1 and Table 6-I
Line 123 MP 123-120.00 to 123-121.10	Surface Faulting	High	650 mm (26 in.) 1930 oxy-acetylene welds
Line 123 MP 123-121.10 to 123-122.17	Liquefaction	Low	650 mm (26 in.) 1930 oxy-acetylene welds
Line 123 MP 123-122.17 to 123-123.18 End	Liquefaction	Moderate	650 mm (26 in.) 1930 oxy-acetylene welds

[a]NOTE: Relative risk is expressed as low, moderate, and high in accordance with the following descriptions:

<u>Low</u>: Conditions along the pipeline route are unlikely to result in permanent ground deformation sufficient to cause pipeline damage.

<u>Moderate</u>: Conditions along the pipeline route indicate there is some possibility of ground deformation sufficient to cause pipeline damage. Data collected from reconnaissance sources suggest that portions of the pipeline route so labeled should not be given the same priority with respect to replacement considerations as other portions of the system assigned a high risk.

<u>High</u>: There are well-identified conditions along the pipeline route which are consistent with relatively large ground displacement, capable of pipeline damage.

concentrated ground deformation in this area. A probabilistic assessment of the potential for surface faulting relative to various time periods of remaining service life would allow for a more detailed assessment of risk. Alternatively, this portion of the line could be ranked as a high priority for replacement without pursuing additional investigations.

A detailed review of the repair record for Line 121 was performed, including an examination of leak repair records over 40 years old. There were no records of cracked oxy-acetylene girth welds. Only two leaks were reported at oxy-acetylene welds, both of which were attributed to corrosion activity. There were, however, records for 24 corrosion leak repairs in Line 123, which is relatively high. Some of these records indicate the absence of coating and presence of a pitted and rusted pipe surface.

Given the seismic hazards and condition of Line 123, it would be prudent to consider this pipeline as a high priority for replacement. Its location in a heavily populated area, repair history, fault crossing, and potential exposure to an intensity of MM VIII recommend it for replacement. The low incidence of repair on Line 121, its greater distance from the fault, and the apparent absence of moderate to high risk ground deformation hazards along its route (see Table 6-II) indicate that it represents a lower risk than Line 123 and need not be considered a high priority for replacement.

The seismic intensity assessments for Lines 121 and 123 are based on modeling reported by Ziony, et al. [1985]. It would be advantageous to perform additional assessments to cover variations in ground conditions and a range of potential earthquake magnitudes on the Newport-Inglewood fault in a future system-wide evaluation of the transmission and supply pipelines.

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 OVERVIEW

A study has been undertaken by Cornell University and EQE Engineering and Design to develop a methodology to replace or retain current and future steel pipelines within the Southern California Gas (SoCalGas) system. The pipeline system exists in an area of high seismic activity. Since 1933 there have been at least 11 major earthquakes of local magnitude 5.8 or larger, with epicenters inside the region of the gas delivery system. Earthquake effects need to be considered in the management of such a large, diverse pipeline network, but the risks associated with earthquakes also need to be evaluated in light of the many other factors affecting performance. Expenditures need to be managed prudently, and, at the same time, need to be allocated in such a way that the risks of damage and disruption are minimized throughout the system.

A feasibility study has been performed in which a general methodology was developed for evaluating the integrity of steel piping within the SoCalGas system and for setting priorities regarding the repair and replacement of such piping. Select aspects of the methodology were applied to a small portion of the supply line network to test the feasibility of assessing seismic risk for pre-World War II (pre-WWII) oxy-acetylene welded pipelines and judging the potential costs and benefits which accrue from the process.

Five research activities were pursued during the study, as follows:

- Existing methodologies were reviewed, with emphasis on the replacement procedures currently followed by SoCalGas.
- Economic and risk assessment models were refined to reflect more accurately the risks and benefits associated with different hazard mitigation and pipe replacement strategies.
- Improvements were recommended in existing replacement methodologies and applied to the SoCalCas system.
- Seismic hazard models were refined, with emphasis on the assessment of liquefaction prone areas, and applied to a select portion of the SoCalGas system.

economics of pipeline replacement. The first of these activities involves the Seismic Hazards Mapping Act which requires maps to be developed by the California State Geologist to identify seismic hazard zones. These maps will affect land use plans and may influence future pipeline replacement and construction requirements. The second activity involves the Pipeline Safety Act of 1992 which requires the U.S. Department of Transportation (DOT) to promulgate regulations requiring the periodic inspection of transmission lines in high-density population areas. During the course of this rulemaking, DOT will examine the issue of whether to require smart pig use. The extent to which replacement transmission facilities are required to be designed and constructed to accommodate smart pigs affects cost and therefore, the order of replacement priority assigned to various pipelines.

Environmental factors also are important for consideration in a steel pipeline replacement program, and these factors have been examined in the feasibility study. It will be advantageous to evaluate both environmental and regulatory activities as part of system planning input to the replacement methodology. Because of the change inherent in regulatory issues, it is advisable to promote close communication with regulatory affairs personnel.

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 $\geq$ 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 $\geq$ 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 7-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 7-1 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

TABLE 7-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

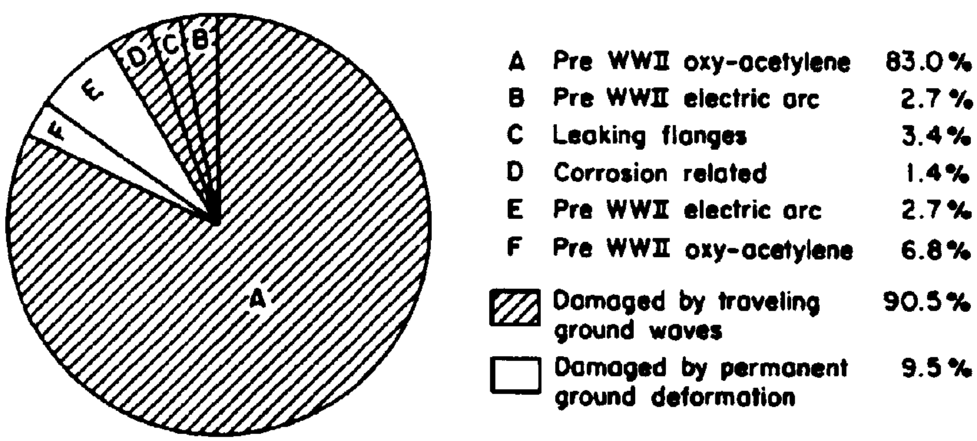


FIGURE 7-1. Pie Chart Showing Relative Proportions of Earthquake-Related Repairs Associated with Various Categories of Damage

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 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 1952 Kern County main 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.

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.

Refined risk assessment models also were developed to account better for the influence of pipe internal pressure and diameter. Risk is strongly influenced by the consequences of damage, and the consequences for transmission and supply lines will depend on the cratering potential of the pipe. The cratering potential, in turn, depends on the energy stored in the compressed gas. Should a rupture occur, either by longitudinal fracture propagation from a pipe wall defect or by a circumferential break at a girth weld, the sudden release of energy from the pressurized gas can cause cratering and substantial outflow of gas.

By relating the energy released per unit length of pipeline through pipe rupture with the internal pressure and diameter of the pipe, a model was developed on the basis of previous earthquake performance of transmission lines to evaluate the relative potential for cratering. The cratering potential is judged by means of a matrix relating pipe diameter and internal pressure with categories accounting for low to moderate, high, and very high cratering potential. The matrix provides for a rational and relatively quick assessment of the potential consequences of damage, should rupture occur in a buried transmission or supply line.

7.4 IMPROVEMENTS IN EXISTING PROGRAMS

The highest replacement priorities identified in this study pertain to pre-WWII oxy-acetylene welded and partially reconditioned oxy-acetylene welded pipelines.

It would be advantageous to rank the replacement of these pipelines according to their location with respect to human occupancy and congregation, as well as their susceptibility to damage and potential for harmful consequences. Accordingly, the ranking for replacement priority is as follows: 1) Class 4 locations and high consequence areas, 2) Class 3 locations and zones of seismically-induced permanent ground deformation or intensity of MM VIII or higher, and 3) Class 3 locations with very high and high cratering potential (see Figure 5-7).

Table 5-I provides a comparison between the replacement priorities from the VCA approach and this study. Whereas the VCA approach targeted all pre-WWII pipelines as potential replacement candidates, this study recommends focusing on pre-WWII oxy-acetylene welded pipelines. The VCA approach linked earthquake hazard with zones of potential surface faulting, landslides, and liquefaction. This study identifies earthquake hazards as all of the foregoing zones plus areas likely to experience MM VIII or higher. The VCA approach drew attention to pipelines with diameters equal to or larger than 400 mm (16 in.), whereas this study utilizes the very high and high cratering potential categories established in Section 5.4 to identify various combinations of nominal diameter and operating pressure as the primary candidates for replacement.

7.5 IMPROVED SEISMIC HAZARD MODELS

A general procedure for evaluating the relative risks from earthquake hazards to steel pipelines was developed. The procedure accounts for the influence of traveling ground waves, surface faulting, landslides, and soil liquefaction. The procedure utilizes information, acquired primarily through reconnaissance studies, on regional geology, groundwater conditions, aerial photos, and site-specific soil borings obtained principally through public agencies.

The research has taken advantage of the substantial case history data and new findings resulting from research sponsored by the National Center for Earthquake Engineering Research (NCEER) on soil liquefaction, large ground deformation, and effects on lifeline facilities. Specifically for the SoCalGas system, stereo pair aerial photos have been used to identify local geomorphological features which provide evidence for liquefaction potential and the likely patterns of ground deformation in the event of soil failure. This information has been used to ascertain whether or not, and with what pattern, ground deformation, such as lateral spread, might develop during a future earthquake. Aerial photo interpretation, in combination with geologic maps, groundwater studies, soil surveys, and select soil borings have been used to refine existing knowledge about the susceptibility of soil to liquefaction.

Two transmission pipelines, Lines 121 and 123, were selected for the feasibility study. Both lines were constructed in 1930, and therefore represent older, more vulnerable portions of the system which are joined with oxy-acetylene welds. Emphasis in this work has been placed on characterizing the geotechnical and earthquake hazards to these pipelines, especially the potential for surface faulting and large ground deformation caused by liquefaction.

The feasibility study for Lines 121 and 123 demonstrates a logical, consistent methodology for collecting and assessing existing geotechnical data for a refined and improved evaluation of seismic risk to transmission and supply lines. Of particular importance is the use of aerial photo stereo pairs to locate specific areas where there is potential for large ground deformation caused by soil liquefaction. The study revealed two locations of relatively high risk regarding permanent ground deformation during a future earthquake. At one location, Line 123 crosses an alluvial fan where evidence suggests that significant liquefaction-induced ground movement is possible. At the other location, Line 123 crosses the Newport-Inglewood fault zone. The conditions at these locations are described, and measures to clarify and reduce risk are discussed.

Given the seismic hazards and condition of Line 123, it would be prudent to consider this pipeline as a high priority for replacement. Its location in a heavily populated area, repair history, fault crossing, and potential exposure to an intensity of MM VIII recommend it for replacement. The low incidence of repair on Line 121, its greater distance from the fault, and the apparent absence of moderate to high risk ground deformation hazards along its route (see Table 6-II) indicate that it represents a lower risk than Line 123 and need not be considered a high priority for replacement.

7.6 OVERALL METHODOLOGY

A general replacement procedure is recommended in the form of the flow diagram in Figure 7-2. Although the flow chart has been developed so it is amenable to either transmission or distribution pipelines, its primary advantage is likely to be realized for the distribution supply line system.

The flow chart shows a three-step process in which a systems planning assessment is made, followed by a repair record cost assessment, with a risk assessment completing the evaluation. At each stage in the evaluation, a decision to replace or retain is made. If the pipeline is to be replaced at any of the three stages, the flow chart shows, by means of dashed lines, a return to specifying new pipeline characteristics and repeating the three tier decision process.

It is recommended that an economic assessment about the desirability of repair and retention versus replacement be made for steel pipelines. As discussed previously, the low leakage rate associated with the transmission system may obviate the need to make such an evaluation for pipe in the transmission network. It is not clear, however, if a similar conclusion can be drawn for the supply line system. It is recommended that the economically-based model (or derivative thereof), which has been developed in-house for distribution piping, be applied to the supply lines. Making an economic assessment based on repair records fits logically within a comprehensive procedure. By predicating part of the assessment on a review of the repair record, the procedure promotes a systematic collection and analysis of repair statistics which can have benefits in determining medium and long-term trends in performance.

As illustrated in Figure 7-2, risk assessment is performed in a three-step process, similar to the procedure followed in the VCA approach. Damage exposure represents the major hazards which need to be considered, including third party damage, corrosion, earthquake hazards, and natural hazards, such as flooding and landslides. Third party damage is defined as damage compromising pipe wall, welds, coating, connections, attachments, and associated devices which is the result of forces and deformations imposed on the pipe by external activity, such as construction, agricultural work, subsurface exploration, and abnormally heavy surface loads. The procedure developed in this study for evaluating the relative risks from earthquake hazards should be used in this part of the risk assessment process.

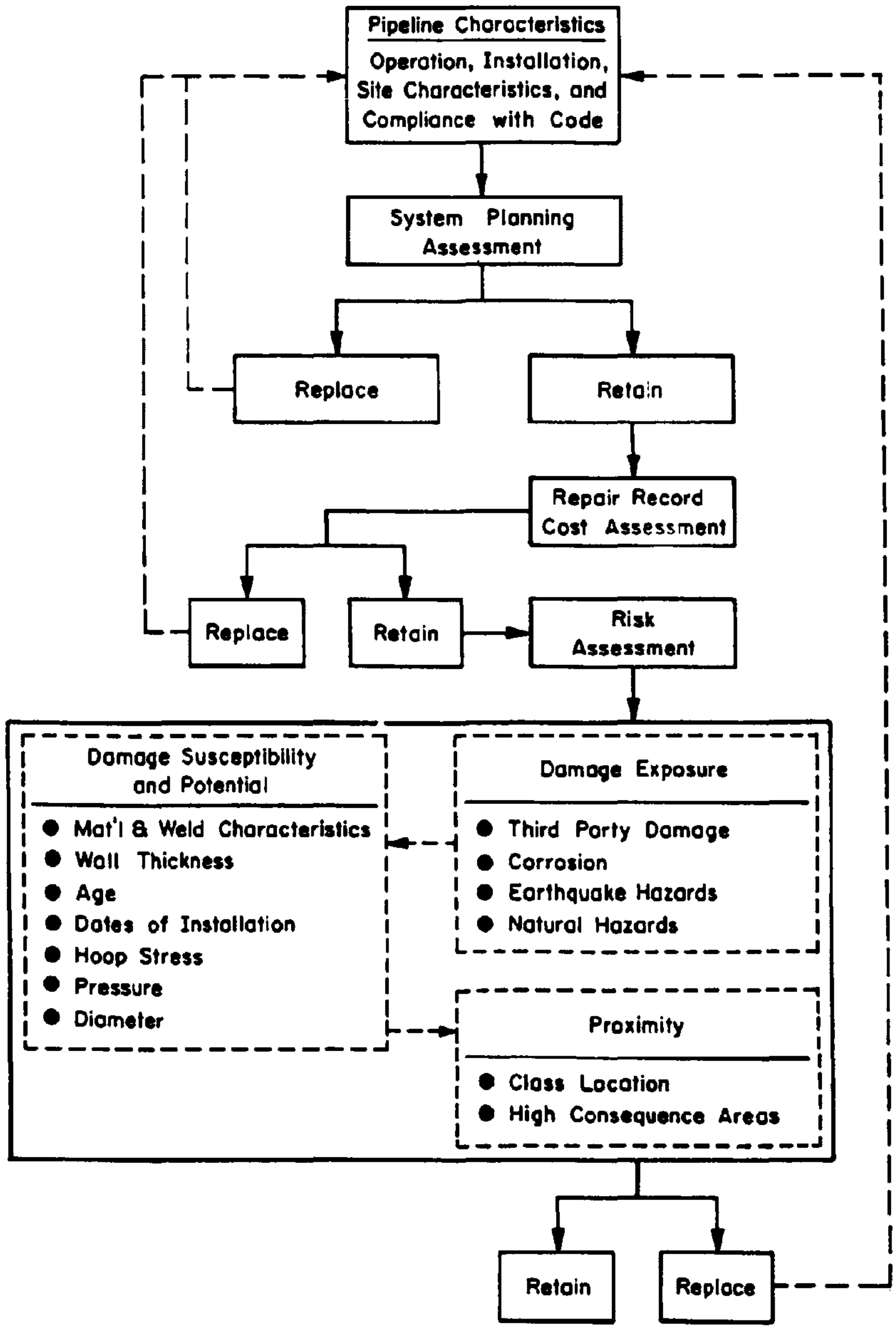


FIGURE 7-2. Flow Chart Showing General Replacement Procedure for Steel Pipelines

After potential hazards have been considered, an evaluation of vulnerability is made by weighing the factors which reduce pipeline capacity to sustain internal and external loads, as well as those which increase the potential for damage and/or injury in the area surrounding the pipeline. The refined models developed in this study for evaluating the susceptibility of pre-WWII pipelines with oxy-acetylene welds to earthquake damage and for judging the cratering potential of a buried steel pipeline should be used in this part of the risk assessment process.

The final evaluation in a systematic risk assessment involves consideration of how many people are exposed to injury in the event of pipeline damage. The highest relative risk associated with proximity is accorded to pipelines in Class 4 locations and high consequence areas.

7.7 RECOMMENDATIONS FOR IMPLEMENTATION

The procedure developed in this study for evaluating the relative risks of steel pipelines to earthquake hazards has been shown to provide a logical and systematic approach, which derives considerable benefit from the interpretation of aerial photos to delineate areas of potentially large ground deformation. It would be advantageous to apply this procedure to other portions of the pipeline system. A system-wide assessment of potential liquefaction, surface faulting, and landslide risks associated with transmission and distribution supply pipelines would result in a better process for establishing replacement priorities for both pre-and post-WWII steel pipelines. Moreover, this type of program would be responsive to regulatory trends. Current activities stimulated by both the 1990 Seismic Hazards Mapping Act and the California Seismic Safety Council are likely to promote a greater sensitivity to the risk of ground failure, and hence, encourage additional vigilance with regard to the consequences of this kind of earthquake-induced deformation.

It is recommended that a system-wide assessment of principal seismic hazards for transmission and distribution supply pipelines start with portions of the network where the potential is highest for large liquefaction-induced ground deformation. Considerable mapping already has been accomplished to delineate Alquist-Priolo Special Studies Zones, which serve as a reference for potential surface faulting. A similar exercise has not been performed for hazards associated with liquefaction-induced ground deformation, such that liquefaction hazards are often identified over broad areas which imply greater risk to system performance than is consistent with the actual hazard. If the methodology developed in this study is applied to the gas pipeline system, the next areas for study should include those with relatively shallow water tables and high susceptibility to liquefaction. Portions of the pipeline system in the Riverside and Irvine, CA areas may be regarded as good candidate locations.

As indicated in the general methodology, the use of pipeline repair statistics is encouraged for incorporating an economic evaluation in the decision process for pipe replacements. Repair statistics also can be used to augment risk assessment models. The review of factors influencing steel pipeline replacement undertaken in this study suggests that the most meaningful correlations involving incidence of damage are likely to be established relative to corrosion activity, age of pipe, and pipe wall thickness. For the supply system, it would be advantageous to collect and summarize data pertaining to these characteristics. Information should be acquired and systematically evaluated regarding location, frequency, and characteristics of corrosion; presence or absence and condition of protective coating; and supplemental information pertaining to cathodic protection, where available. The systematic and statistically correct acquisition and interpretation of information from repair records and field inspections is important for establishing both the relative risk and economic advantages of replacing or retaining various sections of pipe.

The mechanical properties of existing pipelines should be determined at select locations to provide information about quality of welds, wall thickness, strength and deformation characteristics, and brittle-to-ductile transition temperature of steel transmission and supply pipelines currently in service. These data can provide a better quantitative understanding of older pipelines in the system, and be used to augment the statistical trends from repair records with specific mechanical strength and condition information.

It is recommended that a program of select sampling and testing of both weld and pipe specimens be considered. The data collected would be used to establish a more accurate data base on quality of welds, wall thickness, stress-strain

properties of the steel, and brittle-to-ductile transition temperatures which would improve characterization of the system and enhance statistical risk assessment models employed for setting replacement priorities.

SECTION 8

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APPENDIX A

ENERGY EXPRESSION

In this appendix, an expression is derived for the work *performed* by an ideal gas which expands so rapidly that there is virtually no time for heat transfer. In classical thermodynamics, a reversible expansion of this kind is referred to as adiabatic. Adiabatic expansion is taken as being analogous to the rapid gas expansion that would occur if the girth weld of a high pressure pipeline was ruptured. It is important to recognize that adiabatic expansion is analogous to, but not the same as, gas expansion from a ruptured pipeline. Accordingly, the work or energy performed during adiabatic expansion must be regarded as an index for the actual energy released by pipeline rupture. It is assumed that this index can be used to scale the relative levels of energy that would be liberated by pipelines with different diameters containing natural gas at different pressures.

For adiabatic expansion, the pressure, P, and volume, V, are related to some initial state as:

$$PV^{\gamma} = P_1 V_1^{\gamma} \qquad \text{(A-1)}$$

in which P_1 and V_1 are the initial pressure and volume, respectively, and $\gamma = C_p/C_V$, which is the ratio of the specific heat at constant pressure and the specific heat at constant volume.

The work, W, performed during gas expansion is:

$$W = \int_{V_1}^{V_2} P dV \qquad \text{(A-2)}$$

Combining Eqns. A-1 and A-2, we obtain:

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