BURIED PIPELINE RESPONSE TO PERMANENT EARTHQUAKE GROUND MOVEMENTS

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SUMMARY

The principal causes of permanent ground movements during an earthquake include 1) faulting, 2) liquefaction, 3) landslides, 4) densification of cohesionless soils, and 5) tectonic uplift and subsidence. Much of the ground movements from landslides and liquefaction involve the same deformation patterns as surface faulting. There is little evidence during North American earthquakes of significant damage to butt-welded transmission pipelines constructed according to modern practices. Steel pipelines most susceptible to damage include those constructed before 1930 and pipelines where bends, elbows, and welded slip joints were located in areas of permanent ground movement. Pipeline system planning should be based on a broad, comprehensive survey of regional conditions, chiefly through reconnaisance.

INTRODUCTION

A pipeline system generally is built up over a large territory so that its exposure to permanent earthquake ground movements will be greater than that of a facility occupying a small area. Many water and natural gas transmission pipelines in California must cross active faults and liquefiable areas, whereas individual buildings can be sited away from these features. Permanent ground movements should be considered during the design of new pipelines and for risk assessment and retrofitting strategies in existing systems. Measures for mitigating the effects of earthquake displacements should begin with understanding the principal forms of permanent movement. Experience during previous earthquakes helps to identify conditions and facilities that are most susceptible to ground movement damage. Siting and maintenance plans can be developed to locate pipelines so their response to movement carries the lowest risk of damage.

CAUSES OF PERMANENT GROUND MOVEMENT

Permanent ground movements occur during and after many earthquakes. They result from irreversible deformations caused by shear failure and volume change, and develop concurrently with or subsequent to seismic shaking. Most buried pipelines tend to deform as the ground deforms so that dynamic amplifications need be considered only for above ground piping or where pipes tie into above ground structures. Because permanent movements frequently exceed the peak ground displacements from seismic waves, they may be taken to represent conditions of maximum distortion for buried pipelines and cables.

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Table 1. Principal Causes and Types of Permanent Ground Movement Associated with Earthquakes

Cause	Description
Faulting	Displacement of adjacent portions of the earth's crust. Movement concentrated in relatively narrow, fault zones. Principal types of fault movement include 1) strike, 2) reverse, and 3) normal slip.
Liquefaction	Displacement caused by transformation of saturated, cohesionless soils to liquefied state or condition of substantially reduced shear strength. Liquefaction-induced movements include 1) lateral spreading, 2) flow failure, 3) loss of bearing, 4) subsidence, and 5) buoyancy effects.
Landslides	Mass movement of the ground triggered by inertial forces from seismic shaking. Many displacement patterns are possible. Principal forms of movement include 1) rock falls, 2) relatively shallow slumping and sliding of soil, and 3) relatively deep translation and rotation of soil and rock.
Densification	Decrease in volume caused by seismic vibration of dry or partially saturated cohesionless soil.
Tectonic Uplift and Subsidence	Regional changes in dimension associated with tectonic activity. Generally spread out over large area.

Table 1 summarizes the pricipal causes of permanent ground movement associated with earthquakes. Each category of displacement is described briefly and specific types of movement within a given category are listed. It should be emphasized that different types of movement often are interrelated. For example, slumping of soil at the edge of an embankment may be related to both a landslide mechanism and the densification of loose fill by seismic shaking. In addition, landslides may be influenced by the liquefaction of underlying sand layers as well as by the interial forces caused by shaking.

The principal components of fault movement include strike, reverse, and normal slip. When reverse and normal faulting involve significant components of strike slip, the resulting movement is referred to as oblique slip. Reverse and normal faults tend to promote compression and tension, respectively, in underground pipelines. Strike slip may induce compression or tension, depending on the angle of intersection between the pipeline and fault. The angle of the pipeline-fault intersection is the most critical factor affecting the pipeline's performance. Newmark and Hall (Ref. 1) and Kennedy, Darrow, and Short (Ref. 2) have developed methods for analyzing continuous pipeline response to strike-slip and normal fault displacements. O'Rourke and Trautmann (Ref. 3) have developed analyses for jointed pipeline response to strike-slip movements.

Youd (Ref. 4) has identified three basic types of ground failure associated with liquefaciton: lateral spreading, flow failure, and loss of bearing. Uplift due to buoyancy and subsidence are also expressions of permanent movement. Lateral spreading involves the horizontal movement of competent surficial soils because of liquefaction of an underlying deposit. The earth pressures from competent soil makes lateral spreading especially destructive for buried pipelines. A flow failure involves the displacement of completely liquefied soil so that the pressures associated with this type of fluid movement are likely to be less than those from lateral spreading.

Buoyancy effects can be minimized by shallow pipeline burial, which also diminishes the earth pressures during lateral spreading. Conditions of buoyancy are likely to be most severe in areas that are nearly flat with a water table very near the ground surface. Small changes in relief, however, can result in lateral spreads, and it is difficult to pinpoint zones of potential spreading within a region generally susceptible to liquefaction. Under these conditions, pipeline performance might be evaluated in terms of its response to lateral spreading. Usually it will be advantageous to locate a pipeline along a constant contour of elevation. This practice not only minimizes grading and disturbance, but diminishes the chance of compressive strains from slope movement at oblique angles to the pipeline.

Landslides and lateral spreads involve many of the same deformation patterns associated with surface faulting. The most severe distortions generally are concentrated along the slide margins where movements tend to replicate strike-slip and normal faulting. At the bottom of landslides and lateral spreads, large compressive strains and reverse-slip displacements develop. For example, compressive thrusting of frozen soils occurred through a distance one-half kilometer from the bottom edge of the Potter Hill slides during the 1964 Alaska earthquake (Ref. 5). Of particular concern are river crossings where liquefaction leads to tensile strains at the upper margins of lateral spreads and compressive strains where the spreads converge at the river.

Evidence of densification exists for a variety of earthquakes and is particularly noteworthy near structures restrained against movement. Settlement of fills has caused distortion at bridges and cut-and-fill interfaces. Steinbrugge, et al. (Ref. 6) report that pipelines were separated and broken by settlements adjacent to their tie-ins with a pile supported sewage treatment plant during the 1957 San Francisco earthquake.

Tectonic uplift and subsidence generally occur over a long distance so that the strains imposed by this activity will be small. Subsidence adjacent to water bodies can flood sections of a pipeline and possibly lead to erosion and undermining.

PREVIOUS EARTHQUAKE EXPERIENCE

Table 2 summarizes various North American earthquakes for which significant pipeline and cable damage have been documented. In most instances, the pipeline damage can be attributed to permanent ground movements. For example, the locations of cast iron water main breaks after the 1906 San Francisco earthquake (Ref. 7) show a strong correlation with zones of lateral spreading mapped by Youd and Hoose (Ref. 8). Approximately 57 percent of all water main

Table 2. Summary of North American Earthquakes with Significant Reported Pipeline and Cable Damage

Earthquake	Magnitude and Maximum Intensity	Permanent Ground Movements	Observations of Pipeline and Cable Performance
1906 San Francisco	Magnitude = 8.3 Intensity = XI	Strike-slip faulting with max. offset of 6.4 m. Extensive slope stability problems. Lateral spreads and flow failures.	Water pipeline ruptured at nine locations along San Andreas fault. Extensive damage to water and gas pipelines from liquefaction-induced movements in San Francisco.
1929 Grand Banks	Magnitude = 7.2 Intensity not reported	Submarine landslides and flow failures.	Western Union and French communication cables broken as far as 500 km from epicenter.
1931 Managua	Not reported	One main zone of faulting. Landslides along steep natural slopes.	Principal water main for Managua ruptured at fault. Steel pipeline ruptured by landslide.
1933 Long Beach	Magnitude = 6.3 Intensity = VIII	Ground cracks with seeping water, sand boils, and local subsidence.	Over 500 pipeline breaks. Greatest concentration of pipeline failures near bays, rivers, and flood control channels.
1952 Kern County	Magnitude = 7.7 Intensity = X-XI	Reverse oblique surface faulting. Many landslides. Ground cracks in terraces along creek beds.	Oil pipeline ruptured along western extension of surface faulting. Gas transmission line deformed but not ruptured at fault crossing.
1958 Alaska	Magnitude = 8.0 Intensity not reported	Strike-slip faulting with max. offset of 6.5 m. Many submarine landslides. Lateral spreads and subsidence.	Submarine cables of the Alaska Communication System were severed at several locations.
1964 Alaska	Magnitude = 8.4 Intensity = XI-XII	Two reverse faults. Extensive landslides and submarine slope failures. Lateral spreads, flow failures, and subsidence.	Over 200 breaks in gas and 100 breaks in water pipelines in Anchorage. Three petroleum transmission lines undamaged except for one circumferential crack.
1971 San Fernando	Magnitude = 6.4 Intensity = XI	Reverse oblique surface faulting. Over 1000 landslides. Lateral spreads at Upper Van Norman Reservoir.	Over 2400 breaks in water, gas, and sewage pipelines. Majority of damage at faults and lateral spreads.
1972 Managua	Magnitude = 5.6 Intensity not reported	Four main surface faults with max. strike slip of 0.4 m. Landslides along steep natural slopes and granular embankments.	Extensive damage to water distribution system. Many pipelines ruptured at fault crossings. Electric cable deformed by landslide.

breaks occurred within three zones of lateral spreading, which involved about 10 percent of the area covered by the distribution system. During the 1971 San Fernando earthquake, the area of surface faulting accounted for approximately one-half of one percent of the area affected by strong ground shaking. Nevertheless, from 25 to 50 percent of all pipeline breaks in the area of strong ground shaking occurred at or near fault crossings.

During the 1929 Grand Banks and 1958 Alaska earthquakes, there was substantial damage to submarine cables from offshore landslides and flow failures. These earthquakes point out the vulnerability of submarine lifelines and suggest that analyses and data developed for mudslide problems in offshore oil production (Refs. 9) might be useful in earthquake engineering.

There is little evidence during North American earthquakes of significant damage to butt-welded transmission pipelines constructed according to modern practices. Continuous steel pipelines with quality welds have performed well, even when subjected to large differential ground movements. Liquefaction-induced landslides near the Upper Van Norman Reservoir during the 1971 San Fernando earthquake affected five oil and gas transmission lines (Ref. 10). The butt-welded steel pipelines were five years old at the time of the earthquake. Only one 170-mm-diameter pipeline failed in tension at a weld at the edge of the landslide area.

FACTORS AFFECTING PERFORMANCE

One of the most important factors affecting the earthquake performance of pipelines is the quality of the welds. Before and during the early 1930's, steel pipelines in California were often constructed under conditions of quality control less stringent than those imposed today. Experience during past earthquakes has shown that these pipelines may be susceptible to damage. After the 1933 Long Beach earthquake, over 50 breaks in high pressure gas pipelines were found at welded joints (Ref. 11). In every instance the breaks in large diameter lines were discovered at welds that lacked proper penetration or bond with the body of the pipe. During the 1952 Kern County earthquakes, gas pipelines failed at 11 welds in areas of the San Joaquin Valley east of Maricopa (Ref. 12). The pipelines had been installed during 1921 and 1926, and had both oxy-acetylene and electric arc welds.

Some of the most significant pipeline damage during the 1971 San Fernando earthquake was related to weld quality. Figure 1 shows a plan view of the San Fernando area, in which gas transmission pipelines and outlines of the Mission Wells and Sylmar segments of the San Fernando fault are shown. The approximate locations of pipeline damage and explosion craters are indicated. The craters were typically 3 to 5 m in diameter and were formed by the sudden release of gas at an internal pressure of 1.4 MN/m^2. Line 85 was initially constructed around 1930 with oxy-acetylene welds, but was rewelded in 1932 with electric arc techniques. Lines 1001 and 115 were constructed in 1926 and 1930, respectively, with oxy-acetylene welds.

A proper weld requires good fusion between the weld and pipe wall in the root and bevel areas, as illustrated in Figure 2. An improper weld may be caused by poor root penetration, undercutting and overlapping at the toe, and a lack of good fusion between the pipe and weld. During the repair of Line 115, toe undercutting was observed at several welded joints.

Experience has shown that pipelines with bends, elbows, and local eccentricities will concentrate deformation at these features, especially if ground movements develop compressive strains. Liquefaction-induced landslides during the 1971 San Fernando earthquake caused severe damage to a 1260-mm-diameter water pipeline at a combined bend and at eight welded slip joints (Ref. 10).

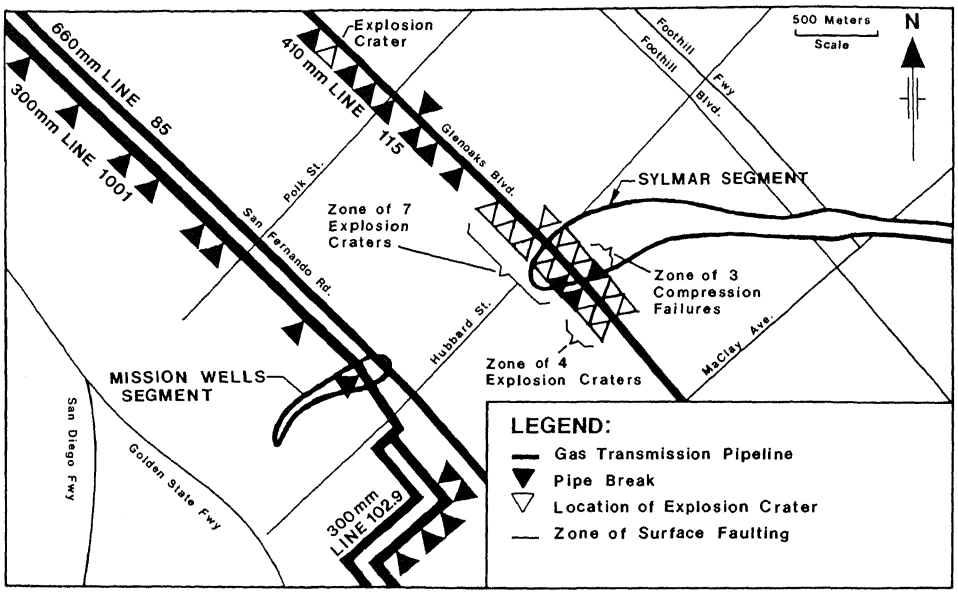

Figure 1. Plan View of Damage to Gas Transmission Pipelines (Ref. 13).

O'Rourke and Tawfik (Ref. 10) analyzed the axial thrust capacity of typical welded slip joints using shell membrane theory. The results of their analyses are shown in Figure 3, where the ratio of the load causing plastic deformation at the joint, P_y, to the maximum load carried by a straight, cylindrical section, P_o, is plotted as a function of the pipe's external diameter. Plots are shown for diameter-to-thickness ratios, D/t, of 100 and 200. There is a significant reduction in the axial load capacity as the diameter increases. For pipe diameters greater than 1000 mm, the axial load causing deformation at the slip joint is nearly an order of magnitude smaller than that causing plastic deformation in straight sections. For a given diameter, values of P_y/P_o are higher for

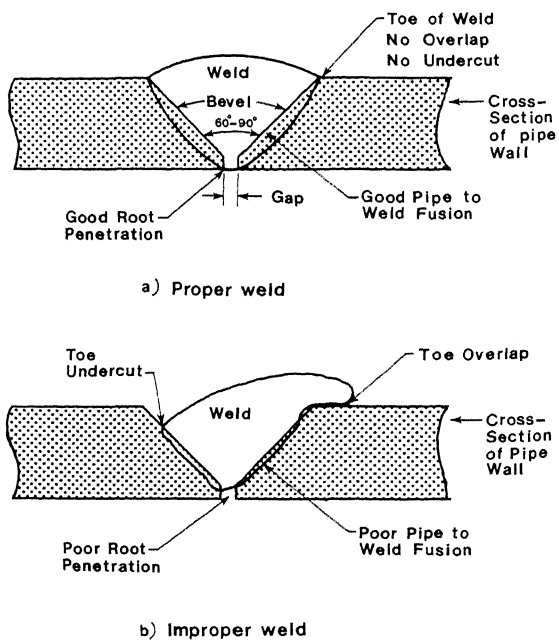

Figure 2. Cross-section of Weld.

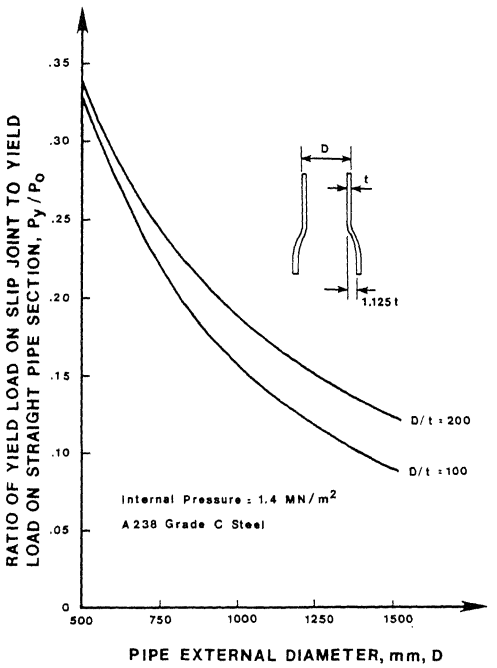

Figure 3. Ratio of Yield Loads as a Function of Pipe Diameter (Ref. 10).

D/t of 200 as opposed to 100 because the offset across the joint is smaller.

Butt-welded, steel pipelines can deform well into the inelastic range when subjected to tension. Pipelines of X-grade steel should be able to accomodate 2 to 5% tensile strain before rupture. In contrast, compressive strains can lead to local wrinkling. Studies have shown that, for D/t of 100, local wrinkling occurs at strains between 0.4 and 0.6% for straight sections of pipe (Ref. 2). Wrinkling is accompanied by high concentrations of strain as additional shortening of the pipeline takes place. Accordingly, ductile pipelines are especially vulnerable in areas of large compressive ground movements. Major pipelines will be oriented favorably at fault crossings when movements develop bending with moderate amounts of tension.

PLANNING FOR GROUND MOVEMENT HAZARDS

Transmission pipelines should be sited where possible to avoid ground failure and otherwise oriented and protected to minimize deformation from permanent ground movements. The geotechnical evaluation of a pipeline system should be made on the basis of a broad, comprehensive survey of regional conditions. This places a heavy emphasis on reconnaisance.

For example, settings particularly vulnerable to liquefaction include toe areas of alluvial fans and deltas, active flood plains, river channels, and saturated colluvial deposits. These landforms can be identified in the reconnaisance program. In some cases remote sensing techniques, such as color infrared photographs, can provide information on near surface moisture to help determine if groundwater conditions are suitable for liquefaction. Once a potential hazard has been identified, subsurface information can be obtained by borehole and trenching techniques. Of special importance are the geomorphic controls on ground movement during landslides, lateral spreads, and flow failures. The engineer should site the pipeline carefully with respect to local topographic and structural features to circumvent zones of maximum offset and avoid compressive ground movements. Steps can be taken to minimize the influence of differential displacement, including shallow burial, location along constant contours of elevation, and removal of bends, elbows, and belled joints from areas of potential movement.

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