BUCKLING AND RUPTURE FAILURES OF PIPELINES DUE TO LARGE GROUND DEFORMATIONS

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SUMMARY

In this paper an overview of the response of buried pipelines to large ground deformations in the past earthquakes and in particular in the 1971 San Fernando Earthquake is presented. Then a concise summary of the recent advances in the investigation of buckling and rupture failure of pipelines due to large ground deformation is given. It is shown that, in comparison to above ground structures, pipeline systems are particularly vulnerable to local differential movements of the ground.

INTRODUCTION

Seismic safety of utility systems have recently attracted the attention of researchers due to the great potential for destruction, damage and disruption of services [1-4]. It became quite apparent that seismic behavior of buried pipeline systems is quite different than that of above ground structures. For example, bridges and dams, for which horizontal inertial force is the most important factor, are mostly designed by the seismic coefficient method. However, in the seismic resistant design of buried pipelines, this method is not suitable because inertia loads are mainly resisted by the surrounding soil. Seismic damage to underground piping systems is caused primarily by relative ground movements and faulting, travelling seismic waves, liquefaction of sandy soil, or difference in stiffness of two horizontally adjacent soil layers.

Because modern cities depend heavily on utility systems for their day to day operation, earthquake threats to utility systems become increasingly important in proportion with the level of urbanization. Furthermore, as a result of population growth and environmental considerations, more and more structures for utilities and transportation systems are placed underground, and need to maintain service after an earthquake becomes more critical every day. Finally, since utilities are networks having sources, transmission lines, storage facilities and distribution systems within themselves, damage to single locations in a utility network often affects significant portions of the entire system.

During an earthquake, permanent differential movements of ground can be caused by faulting, soil liquefaction, slope instability and local compaction of the ground [5,6]. Buried pipelines can be damaged either by permanent movements of this type and/or by seismic ground waves. For instance surface faults, landslides and local compaction of the ground in the 1971 San Fernando earthquake caused the rupture and/or buckling failures in water, gas, and sewage lines [5-6] with high concentration of pipeline damage along the Sylmar segment of the San Fernando fault [7-8]. Similarly, the 1972 Managua earthquake caused surficial displacement along four prominent strike-slip faults through the downtown area of the city and nearly all water mains crossing the faults ruptured. Although relatively old and/or corroded pipelines have been damaged by wave propagation [9], seismic ground shaking alone generally cannot be expected to cause any major rupture and/or buckling failure in properly designed, manufactured and laid out welded steel pipelines [10-13]. This outcome is in complete agreement with the investigation of Youd [14]. After examining the 1971 San Fernando earthquake effects in detail, he concluded that strong and ductile steel pipelines withstood ground shaking but were unable to resist the large permanent ground deformations generated by faulting and ground failures.

Furthermore, it is important to recognize that permanent differential movements may be caused by any earthquake and that the movements can assume a variety of patterns depending on local soil conditions and the presence of faults. Therefore, the response of buried pipelines to permanent ground movement is an important part of lifeline earthquake engineering and its investigation is in line with the recommendations of a number of committees and individual researchers.

DAMAGES TO PIPELINES IN GROUND FAILURES

The type of severity of pipeline damage in earthquakes are directly related to the patterns of ground movements which can be due to faulting, soil liquefaction, landslides and compaction. Table 1 summarizes earthquake induced permanent ground movements [15]. Faults for example, may include strike-slip, reverse-slip and normal-slip components. Liquefaction disortions have been classified according to three types of failures; lateral spread, flow failure, and loss of bearing capacity [24,25]. Landslides can assume a variety of different forms, Many landslides caused by earthquakes are characterized by gradual changes in elevation punctuated by scarps with modest offsets ranging from several inches to one or two feet [15].

A survey of damage caused by the 1971 San Fernando Earthquake indicates that, in comparison to surface structures, pipeline systems are particularly vulnerable to local differential movement. The area of surface fault displacement caused by the earthquake was approximately one-half of one percent of the area affected by strong ground shaking [6,16]. Nevertheless, approximately 25 percent of all pipeline breaks in the area of strong ground shaking occurred at or near fault crossings [5,6]. In addition, the earthquake triggered over 1,000 landslides [15]. Block movements of soil along the northwest rim of the Upper Van Norman Reservoir and an extensive, tongue-like spreading of soil along the reservoir's eastern shore caused severe damage to water and gas transmission lines [17,18]. The surface faulting associated with the

Table 1

Summary of Earthquake-Induced Permanent Ground movements [15]

Form of Permanent Ground Movement	Specific Modes of Failure	Earthquakes During which Specific Failure Modes Caused Pipeline Damage
Faulting	Strike-slip	1906 San Francisco, 1931 Managua, 1940 Imperial Valley, 1968 Borrego Mountain, 1972 Managua
	Reverse-slip	1952 Kern County, 1971 San Fernando
	Normal-slip	1959 Hebgen Lake
Liquefaction	Lateral Spreads	1906 San Francisco 1964 Alaska, 1971 San Fernando
	Flow Failure	1957 San Francisco 1964 Alaska
	Bearing Capacity Loss	1906 San Francisco, 1952 Kern County, 1959 Hebgen Lake
Landslides	Rock Falls	1906 San Francisco, 1952 Kern County, 1959 Hebgen Lake, 1964 Alaska, 1971 San Fernando, 1972 Managua
	Relatively Shallow Slumping and Sliding of Soil	1906 San Francisco, 1952 Kern County, 1959 Hebgen Lake, 1964 Alaska, 1971 San Fernando, 1972 Managua
	Relatively Deep Rotational and Trans-lational Soil Movement	1952 Kern County, 1959 Hengen Lake 1964 Alasks
Seismic Compaction		1957 San Francisco 1958 Borrego Mountain

1971 San Fernando earthquake occurred mainly on a left lateral thrust fault, which has been designated by the U. S. Geological Survey (USGS) as the San Fernando fault zone which consists of four individual segments of the fault [5,7]. Among them, the Sylmar segment intercepted the largest part of the water and gas transmission and distribution systems.

Figures 1a and 1b represent a schematic view of the Sylmar segment of the San Fernando fault zone including damage to the water and gas mains [5,6]. Although the Sylmar segment was roughly 1.8 miles long in the east-west direction, the figures show only about one mile of the segment which was located in the City of Los Angeles along its eastern end. The ground displacements on the Sylmar segment occurred within a zone ranging from 150 to 350 ft. in width [7]. The broad boundaries of this zone are shown by the dashed lines in each figure. Note that most of the lateral movements and approximately half of the vertical displacements occurred within a zone 150 ft. wide along the southern edge of the fault

[5,7,16]. This zone is represented by the ruled area in each figure.

The ground north of the Sylmar segment was thrust upward and left laterally (to the west) along ruptures dipping 70° to the north [5,16]. The general sense of this displacement is indicated in Figure 2 [5,6], which represents an oblique view of the block movement. The maximum strike and reverse dip slip components of fault movement were 6.2 and 4.9 ft., respectively [16]. As shown in the figure, the strike-slip component of movement caused a net compression of the northeast-trending lines and a net extension of the northwest-trending lines.

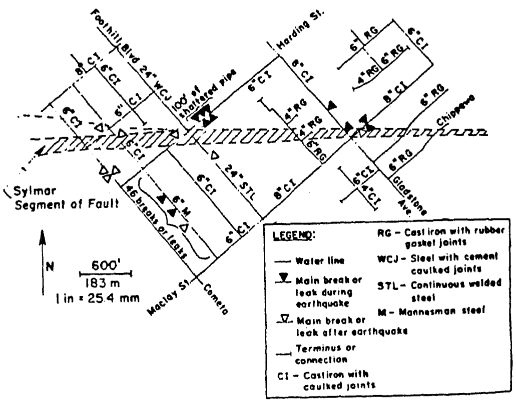

Figure 1a. Water main damage along the Sylmar segment of San Fernando fault zone [5]

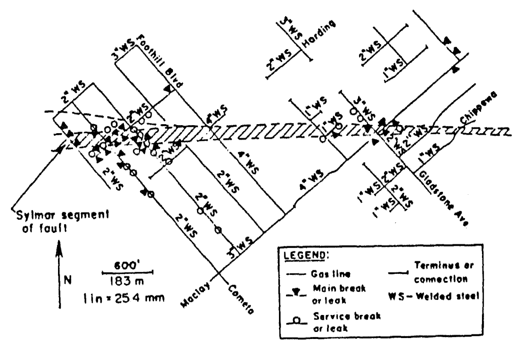

Figure 1b. Gas main damage along the Sylmar segment of San Fernando fault zone [5].

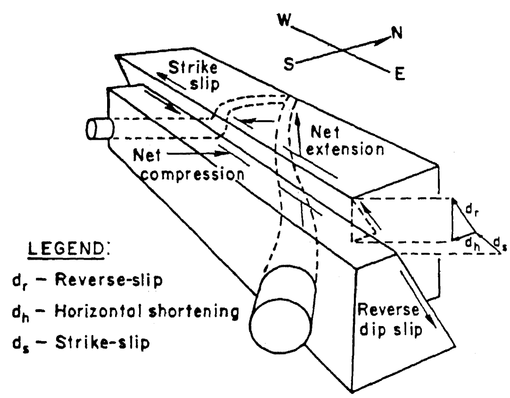

Figure 2. Block diagram of San Fernando fault zone [5].

Figure 3. Compression Forces Buckled 16 inch Steel Pipe and 10 inch T.

Most pipelines in the San Fernando area were buried primarily in alluvial sand and gravel at depths between 2.5 and 5.0 ft. The operating pressures for the gas and water distribution lines were approximately 60 to 150 psi, respectively. A detailed study of the damage to pipelines was reported in a number of references [6,16-18]. A brief reference will be made here regarding the damage to gas pipelines. As shown in Figure 1b, the gas distribution system in the area under consideration was composed of welded steel pipelines. Individual pipe lengths were approximately 40 ft. Service lines, typically 3/4 to 1 inch in diameter, connected to the distribution lines through welded service ties. Damage occurred at similar levels of intensity on both northwest and northwest-trending lines. Ruptures occurred mostly by buckling and twisting of the steel distribution lines, although in many locations, service ties were sheared at their connection with the mains. Damage was extensive in the western part of the fault segment where differential ground movements were largest. Severe damage was sustained by a 16 inch steel transmission line on Foothill and Glenoaks Boulevards[16,18]. There were 52 separate breaks in, approximately, a 6 mile length of this transmission line. In a number of sections it is observed that the 16 inch steel pipe buckled under compressive forces, as shown in Figure 3 [18]. Failures due to the buckling phenomenon were particularly dominant in transmission lines crossing the Sylmar segment of the fault.

BUCKLING OF BURIED PIPELINES

One of the damaging effects on seismic activity on buried pipelines is buckling. In a beam type of buckling, the pipe behaves basically as a beam and bends itself out of the ground. It is suggested that in regions of large ground deformations such as faulting, this type of buckling may even be desirable because breaking or severe fracturing can be avoided [19,20]. The second type of possible buckling is the shell type which is clearly evidenced by Figures 3-5 usually leads rupture as well as crushing or breaking of the pipe.

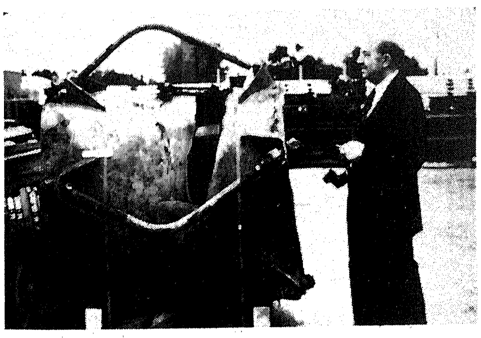

Figure 4. Buckling failure in a water main in San Fernando earthquake

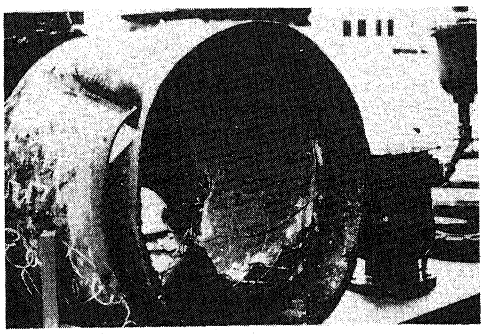

Figure 5. Rupture failures in a steel water main in San Fernando earthquake

Lee, Ariman and Chen [11,12] investigated the buckling of buried pipes under seismically induced axial strains. The pipe is modeled by an elastic [11] or elastic-plastic [12] cylindrical shell of finite length surrounded by soil which is represented by elastic uniform springs. Then an elastic quasi-static analysis was performed and the stability of a ductile iron pipe of L=40 ft (length), a=24 in (diameter) and h=0.51 in (thickness) was examined for different L/ma values (m=1,2,3,etc.). Figures 6 and 7 show the variation of Φ which is related to the axial buckling load as a function of L/ma and α , a non dimensional ratio of the stiffness of soil to that of the pipe. Both figures also give the case of no soil medium around the pipe (α =0). As long as all the points lie below the heavier dashed lines (no soil) or the solid lines (with soil) the pipe is stable. When the axial load P and hence Φ increases, all the points move upward and as soon as any point reaches one of the curves, the pipe is in neutral equilbrium and about to buckle. Both figures show that soil medium has important effect on the initial axial load by causing a large increase in P_{cr}. Furthermore, an increase in soil stiffness causes a decrease in wavelength of the critical-load mode and, consequently, causes an increase in P_{cr} .

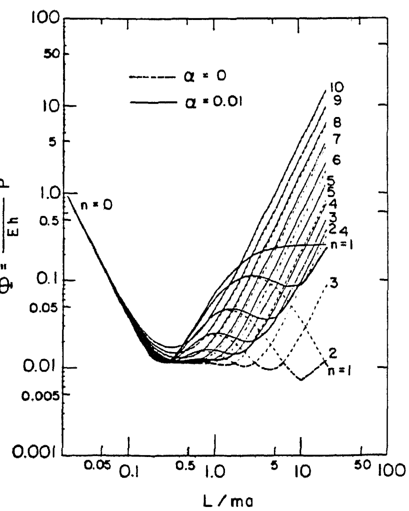

Figure 6. Buckling loads versus L/ma

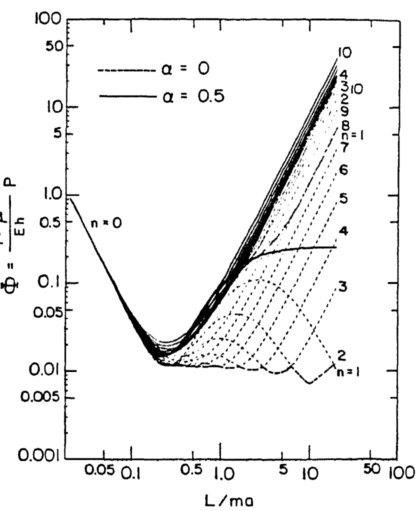

Figure 7. Buckling loads versus L/ma

In the second paper [12] a quasi-bifurcation theory of dynamic buckling and a simple flow theory of plasticity were employed to analyze the axisymmetric, elastic-plastic buckling behavior of buried pipelines subject to seismic excitation. Using the seismic records of the 1971 San Fernando earthquake, a series of numerical results have been obtained.

First, it was shown that, at strain rates prevalent in earthquakes, the dynamic buckling axial stress or strain of a buried pipe is only slightly higher than that of static buckling. Second, the results showed that the actual seismic excitation was not large enough to cause buckling. In fact the actual seismic displacement had to be amplified 100 times in order to cause buckling. As indicated by Kyriakides, Yun and Yew [20], these are very important results because they indicate that (1) buried pipelines, unless very close to the epicenter, would not buckle due to the strain caused by the seismic wave activity alone; and (2) a static analysis would be sufficient in the investigations of buckling of buried pipelines. The first result which is in complete agreement with that of Youd [18] clearly reiterates the importance of large gound deformations in the seismic safety of buried pipelines.

In addition to this ongoing research project, some studies on the behavior of oil pipelines subject to strike slip faulting and dealing with tension case exist [19,21]. Furthermore, in a recent paper [20] for a beam type buckling, the pipe was modeled as a heavy beam on an imperfect rigid foundation. The large displacement response of the beam under axial loading was found to be governed by a limit load which is sensitive to the type, amplitude and wavelength of the initial imperfection. An experimental procedure and results from two preliminary experiments for a shell mode of buckling were also presented. The pressure applied by the soil onto the buried pipe was seen to grow as the axially compressed pipe extended its perimeter. The test specimen buckled at values of stress very close to the material yield stress.

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