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16. Abstract (Limit: 200 words)

State-of-the-art information is presented on the behavior and design of buried water/sewer lifelines subjected to earthquakes. Pipeline failure mechanisms observed from the 1971 San Fernando Earthquake, the 1964 Alaska Earthquake, and various earthquakes in Japan are considered in a tabular format. Eight current design practices and considerations are outlined and grouped into three general classifications: Reducing the earthquake hazard by placing the pipelines, if possible, away from active faults, steep hillsides and poor soil sites; designing a flexible pipeline system by selecting ductile pipeline material and/or flexible joints; and providing "fail safe" systems at locations where damage is anticipated. Design criterion/code provisions and analysis procedures are discussed. From a review of pipeline damage some general conclusions are made.

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Earthquakes	Water pipelines	

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STATE OF THE ART OF BURIED LIFELINE EARTHQUAKE ENGINEERING

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Abstract

This paper presents state of the art information on the behavior and design of buried water/sewer lifelines subjected to earthquakes. Specifically, a survey of pipeline damage due to past earthquakes as well as current design practices, analysis procedures, and code provisions are presented.

Introduction

Recent studies (2,6,12,14,15,19,20,24) have shown that buried water/sewer pipelines have been damaged heavily by earthquakes. Because of the importance of lifelines vis-a-vis the health and safety of the populace, lifeline earthquake engineering is now beginning to draw the attention of the engineering profession (7). In regards to buried water and sewer pipelines, present design guidelines do not consider seismic loads, not even through the use of a statically equivalent static load. More research is needed for the development of future design codes.

Observed Pipeline Damage

There are essentially two reasons for obtaining a record of pipeline damage due to earthquakes. First of all, by reviewing past damage records and noting the typical modes of failure, designers are better able to mitigate the effects of an earthquake. In developing analytical models for pipeline behavior, the more information that is available on how pipelines have failed, the more effective will be the check of the analytical model developed. Also, through investigation of past damage records, it may be possible to establish statistical relationships between various failure mechanisms and parameters such as the type and size of pipe, soil conditions, joint details, etc. Furthermore, some unnecessary analyses which deal with the modes of failure not likely to occur can be eliminated.

Pipeline damage to mains, joints and branches can be attributed to either direct or indriect earthquake effects. The direct earthquake

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damaging forces are:

. Seismic shaking and vibration
. Fault displacement
. Tectonic uplift-subsidence

The indirect damaging forces refer to mass ground movements triggered by the earthquake such as:

. Landslides
. Soil Liquefaction
. Compaction of Sediment

The modes of failure of pipeline due to tectonic uplift-subsidence, landslide or liquefaction are catastrophic and covered a large area. Usually, such failures are accompanied by breakages of mains, branches, connections and joints of the entire or a large portion of the pipeline system in the failure area.

Failure from seismic shaking may result from large dynamic tension that can cause a pull-out at joints, compression that can cause crushing and/or buckling, shear that can cause cracks or breakages of connections, bending that can cause fractures, etc.

Specific Observations

Most of the existing literature concerning buried pipeline damage due to earthquakes, gives a qualitative rather than quantitive description of the damages. This is due to the fact that a complete quantitative survey of buried pipeline damages is rather difficult and expensive.

It should also be noted that only the most recent severe earthquakes have been subjected to intensive investigations. Among them, best documented is the San Fernando Earthquake (1971) which has been discussed by many investigators (6,12,14,15,19). The others are the Alaska Earthquake (1964) which has been reported on by Richardson (24), the Managua Earthquake (1972) by Cajina (3) and Katayama et al (14) and several earthquakes in Japan by Katayama et al (14) and Okamoto (20). The observations of failure mechanisms from these earthquakes are summarized in the following tables.

Table 1 shows the qualitative failure mechanisms observed from the 1971 San Fernando Earthquake. The observations show that most damage in the San Fernando Valley area was due to seismic shaking. Furthermore, it was observed that pipelines with rigid joints failed more than those with flexible joints. The major failure mechanisms were crushing and flexural failure of pipe sections and pull-out and shear at joints.

Table 2 shows the failure mechanisms observed from 1964 Alaskaian Earthquake. It was observed that buried pipelines were destroyed completely in slide areas; differential settlement due to earthquake shaking caused breakages of mains and service lines while direct seismic shaking forces crushed and sheared pipes, broke bells and pulled joints apart.

Table 3 lists the failure mechanisms from several earthquakes which have occurred since 1920 in Japan with Richter magnitude greater than seven. The damage was caused mostly by direct seismic shaking except for the Niigata Earthquake (1964) in which liquefaction occurred and caused most of the failures. The types of failure observed during these Japanese earthquakes were similar to those during the San Fernando and Alaska Earthquakes. Although not a report on pipeline damage per se, Sakurai et al. (25) present the observed dynamic stresses induced by the Matsushiro earthquakes (1965). The observed stress in the underground pipes was discussed in connection with the observed deformation and wave character of the ground. The paper indicates the relative displacement between the pipe and the soil is small.

A complete table of the available buried pipeline quantitative damages can be found in the authors report (27).

Parameters Affecting Damage

Unfortunately, the available pipeline damage data is not sufficient to completely correlate various types of pipeline damage with all of the pipe and soil parameters. However, attempts have been made to correlate similar pipeline damage to geological (13) and other conditions (10,14).

After reviewing damage data from the 1964 Alaska earthquake, the 1971 San Fernando earthquake and the Mechering, Western Australia earthquake of Oct. 14, 1968, Kachadoorian (13) concluded that the geologic environment under the buried pipeline influenced the intensity and frequency of the pipeline damages. Qualitatively, the damages occurred least in bedrock, moderately in coarse-grained soil and the most frequently in fine-grained soils such as clay or silt.

With damage data from the 1923 Kanto earthquake near Tokyo, Katayama et al (14) correlated the pipeline damage to ground condition and pipe size. The authors (14) quantified the ground conditions in two ways, one based on the dynamic response frequency and the other on physical composition of the surface layers. They concluded that most damage occurred in soil with response frequency between 3.5 - 4.5 Hz (soft alluvial type). As to the effect of pipe size, the paper indicated that smaller pipes are more liable to break. Using maximum accelerations in several earthquakes including the San Fernando earthquake, the authors (14) concluded that the damage (No. of failures/km) seemed to be linearly proportional to the max. acceleration (in gal) on log-log paper.

Note that the above correlation is probably the most recent and rigorous attempt to quantify buried pipeline failure phenomenon due to earthquakes. However, the conclusions must be viewed as tentative since all parameters have not been taken into account.

For example, using 1971 San Fernando earthquake data (19), the extent of water/sewer pipeline damages is given in Table 4. The percent of damage vs pipe diameter for data including all joint conditions is shown in Fig. 1. From this figure, one can not conclude what is the effect of pipe size for water pipes in the range of 15cm (6 in) to 46cm (18 in). Secondly, from the sewer pipeline information, there seems to

Table 1

Pipeline Failure Mechanisms Observed From 1971 San Fernando Earthquake
Magnitude 6.6 Richter Scale, Duration of strong shaking: 12 seconds

Location/Conditions	Pipeline Information	Failure Mode
Sylmar/Sunland Area . About 10 km south of Epicenter . Native soil: Alluvium . Backfill soil: Native or Sand . Backfill Depth: Pipe Dia. 30 cm or less: 76 cm Pipe Dia. 30 cm up: 90 cm Area experienced strong horizontal and vertical ground motion	Cast Iron Water Mains . Dia: 15cm-120 cm . Age: 1-40 years	. Both pipes and joints were damaged . Pipe Failures by (1) circumferential cracks and (2) shattering . Joint Failures by both tension and compression in order of* (1) Cement caulked (rigid) joints, (2) Lead caulked (semi-(rigid) joints and (3) Rubber-gasket (Flexible) joints
	Steel Water Mains . Dia: 15cm-120cm . Age: 1-55 years	. Both pipes and joints were damaged . Pipe failures by (1) small holes and (2) blow-out by combination of corrosion, internal pressure and earthquake . Joint failures by both tension and compression in order of* (1) welded (rigid) joints, (2) Riveted (semi-rigid) joints and (3) rubber-gasket (Flexible) joints
Kagel Canyon Area . About 10 km west of Epicenter . Native and Backfill Soil: Canyon: Silt, Sand and boulders Hillside: poorly cemented Sandstone and conglomerate . Backfill Depth: 76cm-90cm Area subjected to extensive vertical and lateral vibrations	Cast Iron Water Mains . Dia: 10cm-15cm . Age: 18-20 years	. Both pipes and joints were damaged . Pipe broken by shear . Joint failures equally distributed between shear failure and failure due to pull-out

Table 1 (Cont.)

Pipeline Failure Mechanisms Observed From 1971 San Fernando Earthquake

Location/Conditions	Pipeline Information	Failure Mode
City of San Fernando . About 25 km southwest of Epicenter . Native and Backfill Soils: Alluvial Sediments . Backfill Depth: 76cm-150cm Area had risen 4 feet or more (tectonic uplift)	Cast Iron Water Mains . Dia: 10cm-35cm . Age: 10-40 years	. Joint failures in order of* (1) splitting of bells, (2) stripped threads and (3) cracks at service taps
	Thin Wall Steel Water Mains . Dia: 46 cm	. Joint failures in order of* (1) pull-out (2) loosening, (3) crushing and (4) broken service connections
	Cement/Steel Cylinder . Dia: 46 cm . Age: 6 years	. Joint failures in order of* (1) pulled apart, (2) misalignments and (3) crushing
Entire San Fernando Valley Area; Including . Sylmar Knollwood & part of City of San Fernando . 15-20 km from Epicenter . Native and Backfill Soils: Alluvial . Backfill Depth: 1.50 M - 18.3 M	Clay Sewer Mains . Dia: 20cm-53cm . Age: 25+ years	. Both pipes and joints were damaged . Pipe failures by (1) crushing and (2) shear cracks . Joint failures by (1) crushing and (2) pull out * order of decreasing damage frequency

Table 2

Pipeline Failure Mechanisms Observed From 1964 Alaska Earthquake
Magnitude 8.3-8.6 Richter Scale, Duration 3-4 Minutes

Location/Conditions	Pipeline Information	Failure Mode
Anchorage Area . About 120 Km northwest of Epicenter . Native and backfill soils: outwashed sand, gravel, some glacial till and clay . Backfill depth: At least 3 m	Cast Iron Water Mains and Intake . Dia: 10cm-76cm . Age: 2 years	. Extensive failure of pipe sections and at joint due to landslides
	Steel Water Mains . Dia: 50 cm . Age: 2 years	

Table 2 (Cont.)

Pipeline Failure Mechanisms Observed From 1964 Alaska Earthquake

Location/Conditions	Pipeline Information	Failure Modes
	Wood-stare Water Mains . Dia: 25cm-60cm	. Failure mostly caused by landslides and some failures caused by compression of pipe section
	Asbestos/Cement Distribution . Dia: 10cm-50cm	Entire system failed by landslides or crashing
	Concrete Sewer Mains . Dia: 25cm-75cm	. Both pipes and joints were damaged . Pipes cracked and leaked . Joints offset and broken
	Corrugated Metal Sewer Mains . Dia: 76cm-100cm	

Table 3

Pipeline Failure Mechanisms Observed From Earthquakes in Japan

Earthquake Information	Pipeline Information	Failure Mode
Kanto Earthquake (1923) . M = 8.16	Cast Iron Distribution . Dia: 110 cm	. pipe broken into sections . joints and bends were broken
Fukui Earthquake (1948) M = 7.2	Cast Iron Water Mains	. Distribution mains were damaged mainly in North-South direction . Damage every 12.5 m . Straight pipe damaged at flanges . Curved pipe damaged at bends
Tokachi Earthquake (1952) M = 8.1	Cast Iron Water Mains	. Heavy damage . Breaking of pipes . Destruction of branching pipe section at joints

Table 3 (Cont.)

Pipeline Failure Mechanisms Observed From Earthquakes in Japan

Earthquake Information	Pipeline Information	Failure Mode
Niigata Earthquake (1964) M = 7.5 Liquefaction was observed and most failure occurred in liquefied area	Cast Iron Water Mains . Dia: 10cm-30cm	. 68% of the distribution lines were damaged. The failure mechanism in order of decreasing importance are (1) pull-out of joints, (2) breaking of caulking, (3) pull out of joints between caulking and lead pipes (4) breaking of control valves and pipes . socket joints were damaged more extensively than mechanical joints
	Asbestos/Cement Water Mains Dia: 10cm-15cm	. Pipe diameter 15 cm; joint pull out most common failure . Pipe diameter 10 cm or less, breaking of pipes most common failure
Tokachioki Earthquake M = 7.9 . Seismic shaking	Cast Iron Water Mains Asbestos/Cement Water Mains	. Mains broken and joints separated . Some joints loosen
	Cast Iron Gas Steel Gas Pipe	. Breakages in pipe and at screw joints . Joint loosening

Table 4

Extent of Water/Sewer Pipeline Damages
Observed From 1971 San Fernando Earthquake

Type		Diameter (cm)	% Damage	
			(1)	(2)
Water Mains	Cast Iron	15.2		8.3
		20.3		4.7
		25.4		14.5
	Thin Walled Riveted Steel	15.2		45.9
		20.3		9.6
		25.4		19.5
	Conc./Steel Cylinder	45.7		21.8

Table 4 (Cont.)

Extent of Water/Sewer Pipeline Damages
Observed From 1971 San Fernando Earthquake

Type		Diameter (cm)	% Damage	
			(1)	(2)
	Steel Casing	15.2		3.4
Sewer Mains	Flex. Joint	15.2	16.1	25.4
	Rigid		34.1	
	Encased		26.1	
Clay	Flex.	25.4	16.8	16.8
	Rigid		18.9	
	Encased		14.8	
	Flex.	30.5	15.7	32.5
	Rigid		28.8	
	Encased		53.0	
	Flex.	38.1	25.2	34.8
	Rigid		51.5	
	Encased		27.8	
	Flex.	45.7	27.5	60.0
	Rigid		76.3	
	Encased		76.3	

(1) % damage by joint classification
(2) % damage including all joint conditions

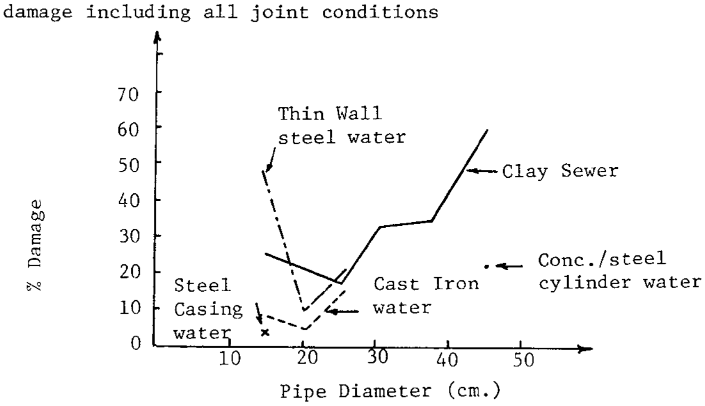

Fig. 1 % Damage vs Pipe Diameter
1971 San Fernando Earthquake

be a definite trend that larger pipes are more liable to fail, which contradicts Katayama's observation from the Kanto earthquake. One possible explanation is that the damage data in the two investigations are different. The number of joint loosenings was used in Kanto earthquake investigation while the number of breaks was used in San Fernando earthquake.

Finally, Fig. 2 shows a relationship between the number of breaks in service lines and the number of breaks in the mains for the water distribution system in San Fernando valley area due to the 1971

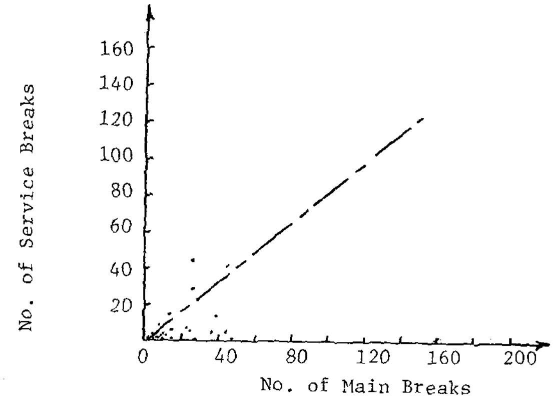

Fig. 2 Relation Between Service and Main Breaks
1971 San Fernando Earthquake

San Fernando earthquake (19). It appears that the damages in main lines is proportional to the damages in service lines as one might expect.

Current Design Practice

The structural design of most buried water and sewer pipes is based on static analysis. However, occasionally passive physical designs (17) are used to avoid damage due to seismic effects. The following is a list of common practices and considerations:

1) The pipeline should be located as far from fault lines as possible. At least, pipeline should not be parallel to the fault line. Thus, the location of fault lines is an important task as far as the planning of underground pipeline is concerned. For locations where the pipeline must cross an active fault, locating the pipeline at an oblique angle to the fault tends to reduce the shear on the pipeline (8).

2) Pipeline construction on steep hillsides should be avoided when feasible.

3) Provide redundancy in the distribution system. That is, more lines of smaller pipes should be used in lieu of a single larger line to avoid the complete destruction of a single line.

4) Installation of blow-off valves (Fig. 3) near the fault line where higher seismic activity is anticipated should be considered. In this system, water is lead to a nearby reservoir after the blow-off valve fails during an earthquake.

5) Select more ductile pipe material such as steel, ductile iron, copper or plastic, etc. to allow for larger deformations.

6) Flexible joints using rubber gaskets and ball-socket-type joints should be considered in areas of potentially strong seismic activity. Extra long restrained sleeves could be provided for sliding pipe connections.

7) Consideration should be given encasing the pipeline in a large tunnel (see Fig. 4) in order to isolate the pipeline from seismic motion.

8) For locations where main pipeline cross active faults, consider providing flexible expansion/contraction joints as suggested by Ford (4,8) and Okamoto (20). The schematics of these flexible joints are shown in Fig. 5. Basically, the pipeline is designed to allow large seismic movements. For example, the so-called "Bellow joint" is capable of bending 15^{o} whereas the simple mechanical joint can only be designed to bend 2^{o}. Fig. 6 shows the pipe deformation followed through the fault displacement.

Design Criterion/Code Provisions

Okmoto (20) suggested the seismic coefficients of 0.1g to 0.3g for the designs of buried pipelines in Japan. The coefficients depend upon soil conditions, the softer the soil the larger the seismic coefficient.

In the U.S., no formal provision has been set by code organizations. Ref. 19 suggested that a 0.5g earthquake force should be used to design all pumping and power plants located with 20KM (12 miles) of any major fault.

As to an overall design approach, Duke and Moran (7) and Whitman et al (28) have suggested the use of a reliability/damage level approach to the design of lifeline systems to resist various intensities of ground motion.

Analysis Procedures

A survey of most of the recently published literature in the areas of earthquake engineering and structural dynamics indicated that there is no single complete analytical model which is capable of predicting the behavior of an underground lifeline system under the attack of an earthquake. Standard text books (18,20,29) have not covered the subject. There are, however, quite a few articles which, after making simplifying assumptions, provide models for analyzing the underground pipelines for particular types of earthquake damage.

In a recent paper, Newmark and Hall (17) present a method which can be used to analyze and design buried pipelines for large fault displacement. In this paper, the ductility (plasticity) of the material is used to allow for the large deformation. Using three possible grades of steel (X70.X65.X60), they concluded that all three types of steel can survive a 3 Meters (10 ft) fault motion, with deformation extending over a length of less than 50 Meters (160 ft) on each side of the fault.

Based on a plane strain formulation, Parmelee and Ludtke (22)

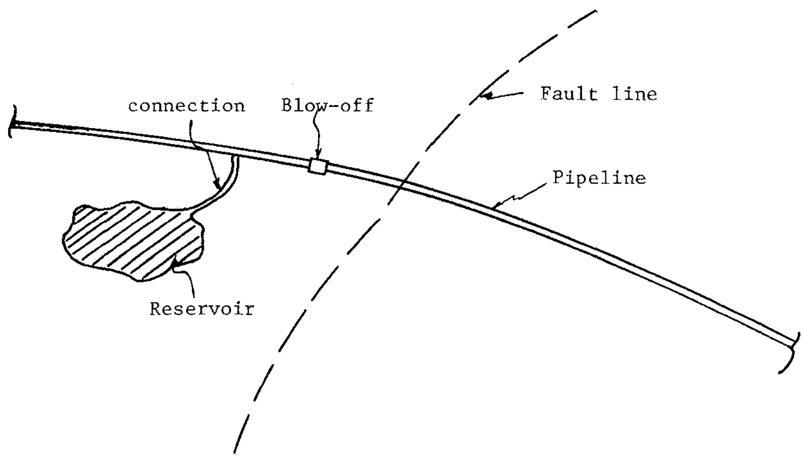

Fig. 3 Scheme For Pipeline Crossing a Fault Line

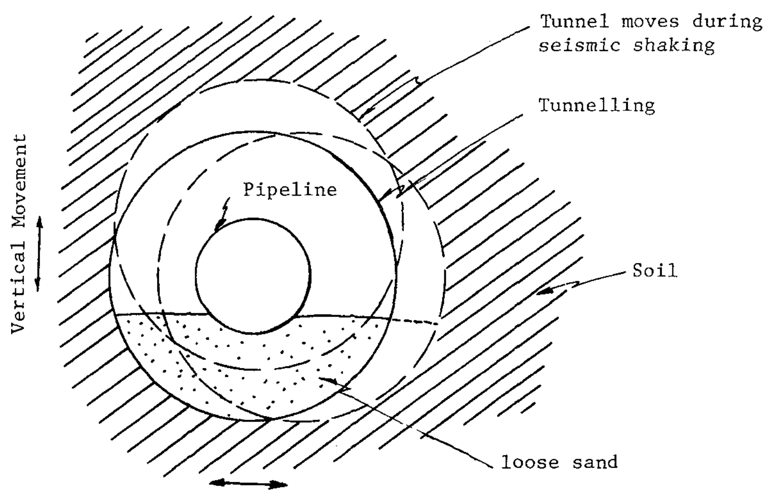

Fig. 4 Encasement of a Pipeline in a Large Tunnel

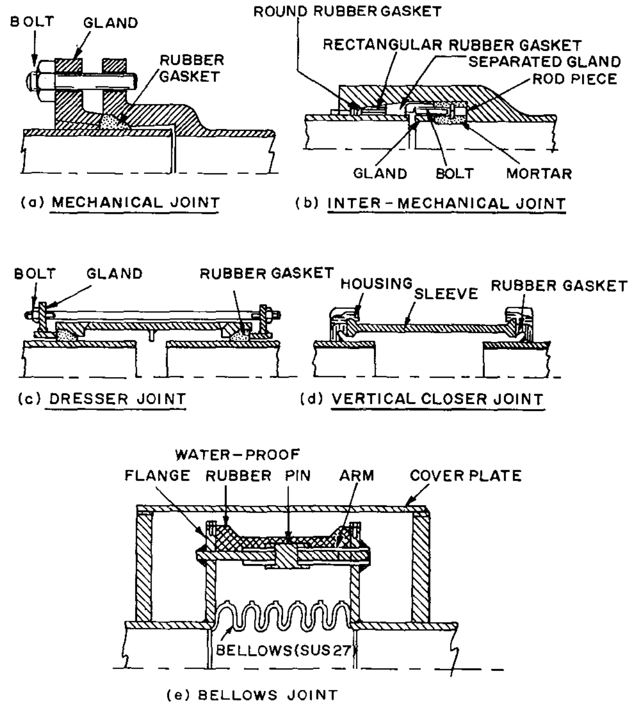

FIG. 5 FLEXIBLE JOINT DETAILS

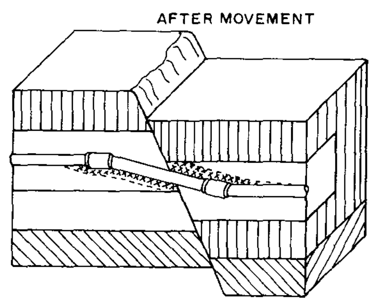

FIG.6 FLEXIBLE JOINT ARRANGEMENT FOR LARGE FAULT DISPLACEMENT

presented a methodology for defining the soil stiffness, mass and damping ratios for a soil-buried pipe system.

Treating the soil supports as elastic springs, above ground pipelines (1) and underground structures (11,20,26) have been studied. In a recent paper, Luscher et al (16) discussed briefly the design of the below-ground portion of the Trans-Alaska pipeline.

As to failure behavior, both Cheney (5) and Forrestal and Hermann (9) present solutions for the buckling of underground tubes. In related fields, the behavior of tunnels (21) and imbedded cylindrical shells (23) has been studied experimentally as well as analytically. Azar (2) presented a static stress analysis for a simply suspended pipe.

Conclusions

State of the art information on the behavior and design of underground water/sewer pipelines subjected to earthquake was presented. From a review of observed pipeline damage, the following general conclusions may be drawn;

1) Pipelines with flexible joints experience less damage during an earthquake than pipelines with rigid joints.
2) Pipelines in soft soil experience more damage during an earthquake than pipelines in firm soil.
3) The relative motion between the pipeline and the surrounding soil during seismic excitation is small.
4) There are conflicting reports as to the effect of pipe size vis-a-vis earthquake damage.

There are a few analytical models which may be used to analyze a buried pipeline for particular types of earthquake damage or for specific types of earthquake excitation. However, there is no complete model for all types of pipeline behavior. Also standard codes of practice do not present design procedures for buried pipelines with seismic loads.

However, various design practices are presently being used to mitigate the effects of earthquakes. These practices may be grouped into three general classifications:

1) reducing the earthquake hazard by placing the pipelines, if possible, away from active faults, steep hillsides and poor soil sites.
2) designing a flexible pipeline system by selecting ductile pipeline material and/or flexible joints.
3) providing "fail safe" systems at locations where damage is anticipated.

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