within a city or town are limited to local regions where such potential hazards exist, avoidance of crossing active faults for water and sewer pipelines sometimes is possible or necessary and should be considered for economical and technical reasons.

Recently, the failure mechanisms of below-ground pipeline in a soil liquefaction environment induced by seismic shaking have been studied (Kuribayashi et al., 1985; Yeh and Wang, 1985). These studies are only preliminary and no design criteria have yet been developed for such conditions.

The effects of wave propagation from seismic ground shaking on buried straight pipelines located within uniform firm soil have been found to result in relatively minor damage as reported by Isoyama and Katayama (1981). The damage occurs mostly in regions where the soil and/or geological conditions change and at joints and junctions (Kubo and Isoyama, 1980). Since seismic shaking affects large areas, the design of buried pipelines to seismic shaking is unavoidable. A quantitative correlation between the incoherent ground motions and the pipeline responses would be necessary for an accurate design of buried lifelines.

DAMAGE LESSONS LEARNED FROM RECENT EARTHQUAKES

Introductory Remarks

The damage of buried lifelines after major earthquakes in the United States, Japan, China, and other parts of the world has been reported by many authors. It is not the purpose of this paper to repeat the same reports. Rather, it is intended to summarize the similar or different damage behavior from several known earthquakes so that some common conclusions can be drawn from these observations. This material is taken from Kubo and Isoyama (1980), Murphy (1973), Katayama (1979), Sun (1979), Ye (1980), Wang, Sun and Shen (1985), Okamoto (1986), and Lund (1977); however, other earthquake reports are also available.

Damage Experience from the San Fernando Earthquake

General Information

The United States has had several destructive earthquakes in its history. However, lifeline earthquake engineering did not receive much attention until the 1971 San Fernando earthquake when many lifelines (including water and sewer lifelines, oil and gas lifelines, transportation lifelines, and electrical lifelines) suffered heavy damage.
The San Fernando earthquake occurred at 6:01 a.m. on February 9, 1971, inflicting severe damage along the foothills on San Gabriel Mountains and along a narrow east-west band of faulting on the valley floor. The main shock of the San Fernando earthquake has been assigned the following values: Richter magnitude, 6.6; epicenter, 43°24.0' N, 118°23.7'W; focal depth, 13.0 km (8 miles).

Where the San Fernando fault reached the ground surface, lateral movements up to 3 feet apparently occurred. Vertical displacements of 3 feet were found, and ground shortening of almost 3 feet was noted across the fault zone.

Soil generally tends to be structurally poor throughout the San Fernando Valley particularly when the groundwater table is high. The soils underlying the basin consist of alluvium derived from the present bedrock. The alluvial deposits in the basin reach depths in excess of a thousand feet and range in consistency from soft to wet and highly compressible.

Damage Observations

The damage of water and sewerage pipelines ranged from numerous small service leaks to major trunk line breaks. Damage to water distribution and supply facilities involved pipes of every type and description, valves and fittings, large conduits, and tunnels. In some areas, distribution mains were damaged in as many as 8 to 10 locations per 100 feet of pipe. The water system had 363 breaks in mains and 513 leaks in service lines. There were 1,155 breaks in sewer lines.

All the cast iron water mains with cement-caulked joints that crossed faults in the area under consideration were damaged and the damage was most prominent along northeast tending lines where compressive ground deformations were largest and at points of differential settlement. In contrast to the lines with cement-caulked joints, cast iron mains with rubber-gasket joints showed little damage in the area under consideration.

Two aqueducts for water supply from the Woens River were damaged slightly: one had tunnel leakage and the other experienced impairment.

A survey of the damage of sewer lines, using video techniques, indicated that 126,000 linear feet of mainline needed to be reconstructed. Data on the extent of sewer pipe damage is given in Table 1. One can clearly see from this table that the flexible jointed pipe had the highest seismic resistance. Only 17 percent of the flexibly jointed pipeline needed to be reconstructed as compared to 36 percent for rigidly jointed pipes. Table 1 shows that larger diameter pipes seem to suffer more damage than the smaller diameter pipes.

The pertinent data on the water pipe system in San Fernando and its replacement after the earthquake are shown in Table 2. The water supply facilities were, in essence, severed from the distribution system by the multitude of breaks. The high replacement ratio for thin-walled riveted steel pipes may be attributed to the failures of the stove-pipe joints. For concrete-steel cylinder pipe, the replacement is for the failure of concrete or cement materials in the core or in the lining. The effect of pipe diameter for individual types of pipe is not conclusive. However, from an overall point of view, larger diameter pipes seem to suffer more damage than the smaller diameter pipes.

TABLE 1 Extent of Sewer Pipe Damage in Los Angeles

Pipe Size/ Joint Type	Pre-earthquake Length (linear ft)	Amount To Be Reconstructed Linear Feet	Percent (Individual)	Percent (All)
8-in. flexible	363,600	58,400	16.1	19.7
8-in. rigid	90,600	30,900	34.1	
8-in. encased	1,200	260	21.6	
10-in. flexible	23,800	4,000	16.8	17.2
10-in. rigid	5,300	1,000	18.9	
10-in. encased	270	40	14.8	
12-in. flexible	24,900	3,900	15.7	22.4
12-in. rigid	9,700	2,800	28.8	
12-in. encased	3,400	1,800	53.0	
15-in. flexible	13,900	3,500	25.2	30.0
15-in. rigid	3,500	1,800	51.5	
15-in. encased	3,600	1,000	27.8	
18-in. flexible	17,800	4,900	27.5	50.2
18-in. rigid	8,000	6,100	76.3	
18-in. encased	7,300	5,600	76.8	
All Flexible	444,000	74,700	16.8	21.8
All Rigid	117,100	42,600	36.4	
All Encased	15,700	8,700	55.4	

TABLE 2 Pertinent Data on Water Pipe in the San Fernando Water System

Pipe Type	Diameter (in.)	Total Pipe in System (linear ft)	Pipe Replaced Linear Ft	Percent (Individual)	Percent (All)
Cast iron	6	145,789	12,037	8.3	8.0
	8	48,620	2,265	4.6	
	10	18,619	2,705	14.5	
Thin-walled riveted	6	4,870	2,235	45.9	22.3
	8	7,530	720	9.6	
	10	6,779	1,320	19.5	
Concrete-steel cylinder (SSP 381)	18	5,493	1,200	22.0	22.0
Standard steel casting	6	25,115	856	3.4	3.4
All	6	157,774	15,128	8.6	9.5
	8	56,150	2,985	5.3	
	10	25,398	4,025	15.8	
	18	5,493	1,200	22.0	

Damage Assessment

Numerous variables could conceivably be related to the extent of pipe damage. These include the following:

1. Type of pipe
2. Buried depth of pipe
3. Proximity of other substructures
4. Type of soil
5. Location and direction with respect to fault zone and area of vertical uplift
6. Size of pipe
7. Type of joint
8. Encasement of pipe

The information available concerning all of these variables, however, is not extensive enough to permit conclusions to be drawn with respect to all eight items. In general, however, the information on pipeline damage along the San Fernando fault shows three significant features:

1. Pipelines with rubber-gasket joints performed substantially better than those with cement-caulked joints. In the area under study, there were no leaks on rubber-gasket mains during or immediately after the earthquake whereas there were several repairs at cement-caulked joints on lines in the immediate vicinity of those with rubber-gasket couplings.

2. Lines made of Mannesman steel were highly susceptible to internal corrosion and were more heavily damaged than lines composed of cast iron or other types of steel.

3. Damage to water mains continued to show up for several years after the earthquake, mainly in the form of rupture connections between mains and service lines.

Damage Experience from Earthquakes in China

General Information

In China, the severe 1975 Haicheng earthquake and the 1976 Tangshan earthquake caused heavy losses. Only the damage to water and sewer lifelines is discussed here.

The seismological data for the two earthquakes are as follows:

For the Haicheng earthquake--Beijing time of shock commencement, 7:36 p.m., Feb. 4, 1975; magnitude, M 7.3; epicenter, 40°39' N, 122°48' E, near Zhaojibao Village, Haicheng; focal depth, approximately 12 km.

For the Tangshan earthquake--Beijing time of shock commencement, 3:42 a.m., July 28, 1976; magnitude, M 7.8; epicenter, 30°24' N, 118°06' E in Tangshan; focal depth, 12-16 km.

Features of Seismic Damage to Pipe from the Haicheng Earthquake

The geological structure in Haicheng is mountainous land that is an upwarped district of paleometamorphic and eruptive rock. The soils at the site in Hiacheng City are divided into three classes:

I. Readily and moderately slackened solid rock,

II. Ordinary soil in steady state except I and III,

III. Saturated loose sand, silt and silty soil, alluvial soil and other impurities.

In the disaster region of the Haicheng earthquake, there were relatively integrated sewer systems in Yingkou City and Panshan Town. Only in Panshan Town were some sewers damaged. The seismic damage to water pipelines is summarized as follows:

1. Influence of Ground Conditions and Intensity--The various damage ratios of water supply pipelines in the disaster regions are listed in Table 3, and it can be seen that the soil of the site plays an important role in damaged pipes during an earthquake. Note that both the Dashiqiao and the Haicheng regions suffered 9° shock, but the ratio of the damaged pipes in Haicheng is much higher than that in Dashiqiao due to the unfavorable soil condition in Haicheng. Similarly, as liquefaction of sand occurred in Panshan, the damage ratio is also higher than that in Anshan even though both regions suffered the same intensity shock. If the ground condition is the same, the damage will be proportional to the intensities of the earthquake.

2. Influence of Pipe Material and Joints--The effects of pipe materials and joints, as measured by the damage ratios, on segmented pipeline are shown in Table 4. From this table, one can see that the ratio of steel pipes buried in the 9° intensity zone is higher, which is mainly due to the serious corrosion in its long-term burying. In Table 4, the relation of different joints and the seismic damaged ratios is listed, and it can be seen that the damage ratios of the flexible joint pipe were much smaller than those of rigid ones.

3. Influence of Pipeline Diameter--The seismic damage ratios for pipeline with different diameters from Haicheng earthquake are shown in Table 5 for a specific cast iron pipe with

asbestos cement gasket joint. One can see from this table that the larger the pipe diameters, the less the damage would be. Note that this situation is different from that observed from San Fernando earthquake. The difference may be attributed to the difference in local site conditions.

TABLE 3 Effect of Ground Condition and Intensity to Seismic Damage of Water Pipelines as Shown by the Haicheng Earthquake

Region	Intensity	Site Soil Type	Pipeline Diameter (mm)	Pipeline Length (km)	No. of Damaged Places	Average Ratio of Damaged Pipes/Km
Anshan City	7°	II	>100	537.40	3	0.006
Panshan Town	7°	III	>100	25.90	35	1.600
Yingkou City	8°	III	>50	158.50	372	2.350
Dashiqiao	9°	I,II	>75	26.10	26	1.000
Haicheng	9°	III	>50	21.35	216	10.000

TABLE 4 Seismic Damage Ratios (breaks/km) of Pipe of Different Materials from the Haicheng Earthquake

	Steel		Cast Iron		Asbestos		Prestressed Concrete
City, Intensity	Welded	Threaded	Lead Caulk	Asbestos Cement	Self-Stressed Cement*	Rubber Ring	Rubber Ring
Haicheng, 9°	-----	15.70	9.50	12.70	-----	9.0	-----
Yingkou, 9°	-----	2.10	0.89	0.94	5.0	2.0	-----
Yingkou City, 8°	0	11.40	0.85	1.28	4.5	1.5	0
Panshyan Town, 7°	-----	0.70	----	1.60	1.3	---	-----

*Self-stressed cement is a type of cement that expands when immersed in water and, thus, creates a prestressed action.

TABLE 5 Seismic Damage Ratios (breaks/km) of Asbestos-Cement Gasket Jointed Pipes in Yingkou City from the Haicheng Earthquake

Pipe Diameter (mm)	Ratio
75	3.03
100	2.65
150	0.60
200	0.68
250	0.48
300	0.43
350	0.39
400 to 700	0.30

Features of Seismic Damage to Pipe from the Tangshan Earthquake

Tangshan is located in the junction zone of the Hebei-Shandong downwarp and the Yanshan fault that has been historically known for earthquakes. The region is surrounded by different striking faults. The Tangshan fault rupture is located in the southeast of the Tangshan upwarp district, which is a principal shock belt in the earthquake. In the Tangshan region, soil conditions are again divided into three classes:

I. Dense silty clay

II. Dense sand of medium size

III. Fine silt and silty loam

Both water supply and sewer systems in Tangshan and its neighboring areas were damaged heavily from the Tangshan earthquake (Table 6).

For water supply systems, there were from about 2.0 to 10 breaks/km with an average damage ratio of 4 breaks/km in Tangshan and 0.2 to 1.2 breaks/km in Tianjing. Due to liquefaction effects, the damage ratios for Tanggu and Hangu were much higher. They ranged from 4 to 30 breaks/km. The influences of various parameters are discussed below:

1. Influence of Ground Condition at Site--The condition of site soil is an important factor in seismic damage to buried pipelines. In the Tianjing region, site soil is of Class III with a relatively high groundwater level, and the liquefaction movement of sand stratum is easily induced by an earthquake. In the regions with different intensities and site soils, the ratios of seismic damaged pipelines were different, as indicated in Table 6. One can see from this table that the damage ratio of pipe is higher when the ground condition is worse.

TABLE 6 Average Seismic Damage Ratios (breaks/km) of Pipelines under Different Conditions in the Tangshan Earthquake

Location	Seismic Intensity	Site Soil	Damage Ratio
Tianjin	7-8	III	0.18
Tang-gu	8	III*	4.18
Hangu	9	III†	10.00
Tangshan	10-11	II	4.00

*Site soil worse than that in Tianjin.
†Site soil worse than that in Tang-gu.

2. Influence of Joints--The types of seismic damage to joints were pulling out, loosening and leakage, shear break, and bell crack. Table 7 shows the seismic damage to pipes and joints for Tangshan and Tianjing Cities due to the Tangshan earthquake. This table shows that joint failures, pull-out failures, and fitting failures for pipes of all diameters occurred much more frequently than failures of the pipe itself.

3. Influence of Pipe Diameter--The statistics concerning the failure of different diameter pipe are shown in Table 7. One can see from this table that the failure of all types of pipe was in the same range with only a few exceptions.

TABLE 7 Seismic Damage of Pipes and Joints from the Tangshan Earthquake

City	Diameter (mm)	Damage Ratio (breaks/km) Length of Investigation (km)	Pipe (broken)	Joint (pulled out)	Fitting (damaged)	Total
Tangshan (all types)	600	6.77	----	1.89	----	1.89
	400	10.68	0.56	4.31	----	4.87
	300	19.42	0.41	4.22	----	4.63
	200	17.43	1.03	3.38	----	4.41
	100	12.61	1.35	3.88	----	5.23
	All	66.91	0.81	3.53		4.21
Tianjin (cast iron pipe)	600	1.85	----	1.63	----	1.62
	500	2.31	0.43	4.76	0.43	5.61
	200-250	12.28	1.22	1.87	----	3.10
	150-200	27.36	1.06	1.54	1.64	4.25
	75-100	35.51	2.56	1.58	0.42	4.55
	All	79.31	1.71	1.70	0.77	4.18
Average			1.11	2.86	0.82	4.05

4. Influence of Other Parameters--Geography and terrain, soil sliding, and tectonic ground fractures also influenced pipe damage in the Tangshan earthquake. The seismic influence of topography on the pipelines was mainly reflected by the evident sliding of slope and obvious downwarping difference between backfill and original soil where the ground fissure could be readily found in this shock. Also, all the pipelines that crossed the fault rupture zone suffered serious damages.

Damage Experience Learned from Earthquakes in Japan

General Information

Japan is located in one of the most highly seismic regions in the world and considerable damage data, including those for lifelines, are available. In this paper, most of the data refer to the Miyagi-Ken-Oki earthquake of June 12, 1978, but some available damage data from other earthquakes also are used.

The Miyagi-Ken-Oki earthquake data from the U.S. Geological Survey are: time, 08:14:27 GMT (17.14 local), June 12, 1978; magnitude, 7.4; epicenter, 38.2° N, 142.2° E, approximately 100 km from the city of Sendai; focal depth, 30 km.

The general geological setting of the Sendai area includes a tectonic line, and the alluvial plain is developing on the depression that occurred in the east of this line. The alluvial plain consists mostly of sand, silt, and gravels and partly of peat deposits.

Most of the damage resulting from the June 12, 1978, earthquake occurred within the Miyagi region, which consists of a broad central lowland bounded east and west by low mountains. The old part of Sendai City was built on the complex Sendai terrace, which consists largely of sand and gravel 5 to 7 meters thick overlying Neogeno bedrock. The sediment is soft and water-saturated. The June 12, 1978, Miyagi-Ken-Oki earthquake caused soils to liquefy at several sites on the coastal flood plain bordering the Bay of Sendai. Most sites of damage were on the coastal plain where the sediments were unconsolidated Holocene gravels, sands, silts, and clays, primarily deposited by rivers. Liquefaction occurred most commonly in channel deposits.

Damage Observations

Water supply facilities were damaged at 54 cities, towns, and villages in Miyagi Prefecture. A total of 232 breaks were reported to have occurred in the water distribution mains with diameters equal to or greater than 50 mm. The total damage to the distribution pipes with diameters equal to or greater than 75 mm is shown in Table 8. The steel pipe showed the least damage ratio of 0.014 breaks/km. Asbestos-cement pipe, which is considered to be the most vulnerable to earthquake ground motions, had 0.812 breaks/km. The ductile cast iron pipe showed good performance with a damage ration of 0.045 breaks/km. The average damage raio for all water pipes was 0.102 breaks/km. As to the pipe size, the smallest pipe, 75 mm diameter, had the highest damage ratio of 0.404 breaks/km.

TABLE 8 Damage to Water Distribution Pipe (by material and pipe diameter in Sendai from the Miyagi-ken-Oki Earthquake

Pipe Dia-Meter (mm)	Ductile Cast Iron L (km)	Brk	Steel L (km)	Brk	Asbestos Cement L (km)	Brk	Polyvinyl Chloride L (km)	Brk	Total L (km)	Brk	Breaks/km
75	18.4	3	1.1	1	7.0	32	114.4	21	140.9	57	0.404
100	183.6	15	1.7	0	29.1	5	207.2	22	421.6	43	0.102
150	205.0	4	1.4	0	7.0	0	-----	--	213.4	4	0.019
200	118.9	2	1.4	0	1.5	1	-----	--	121.8	3	0.025
250	39.9	3	0.7	0	1.3	0	-----	--	41.9	3	0.072
300	70.0	2	3.7	0	2.1	1	-----	--	75.8	4	0.053
350	2.0	0	0.1	0	---	--	-----	--	2.1	0	0
400	27.6	2	3.5	0	---	--	-----	--	31.1	2	0.064
450	1.7	0	0.1	0	---	--	-----	--	1.8	0	0
500	20.0	1	6.6	0	---	--	-----	--	26.6	1	0.038
550-1100	16.3	0	50.2	0	---	--	-----	--	66.5	0	0
Total	703.4	32	70.3	1	48.0	39	320.6	43	1148.5	117	0.102
Breaks/km	0.045		0.014		0.812		0.133		0.102		

There were three sewer systems in Miyagi Prefecture in 1978. At the outset of the earthquake on June 12, only two systems were operating to provide sewer drainage; the third was under construction.

Examination of damage reports showed that about 90 percent of the damage to the sewer system had occurred at junctions of buried piplines and manholes. The types of damages most commonly observed in these structures can be classified as follows:

- Longitudinal, circumferential and shear cracks on the pipe walls
- Breaks on the pipe couplings and the pipe body
- Cracks and breaks on the vertical walls of the manholes and the bottom connection boxes
- Crack, breaks and slippage of joints
- Pull-out of joint and rubber ring falling off

In addition, several other kinds of pipe and box-type culvert damage (e.g., subsidence, breakage, buckling) were caused by landslides and settlement of soil layers within the buried zones of the pipes/culverts. In general, it was determined that the damage to the sewer systems was small in comparison with total damage.

Damage Assessment

The Miyagi-Ken-Oki earthquake experience showed that both water and sewer pipeline damages are influenced heavily by the ground conditions, materials, and pipe sizes. The damage was generally slight in the central part of the city located on a geologically stable terrace. On the alluvial plain, the damage was caused possibly by liquefaction. In the areas where large-scale cut and fill altered the original ground profile, there was, as an inevitable consequence, inherent instability of the artificial slopes, insufficient densification of fills, and abrupt change in subsoil properties between cut and fill. These were the causes of local settlement and relative displacement over short horizontal distances, which broke or bent the buried water pipes. Asbestos-cement water pipe had the highest damage ratio.

For sewer systems, damage was caused by subsidence and settlement of soil layers. In general, the sewer systems were only slightly damaged in comparison with water and gas pipelines.

The damage characteristics of sewers for several earthquakes in Japan are summarized in Table 9 (Okamoto, 1986). As a general rule, the relationship between damage and earthquake intensity is shown in Table 10. For the ordinary push-on joint, joint construction is weaker than the pipe body. Sliding of joint starts at an intensity of IV while breaking of pipe body will start at Intensity V. Pipe damage is much more severe when liquefaction occurs.

Summary

Summaries of the types of seismic damage to buried segmented and jointed pipeline and its connected manhole are shown in Figures 1 and 2, respectively. Briefly they are as follows:

1. Damage to Pipeline as a Whole
    - Waving of center line (alignment problem)
    - Uplift
    - Settlement
    - Buckling
    - Soil deposit into pipeline

2. Damage to Pipe Body
    - Circumferential cracks
    - Longitudinal cracks
    - Breaking of joints
    - Rubber ring falling off
    - Mortar seal breaking away

TABLE 9 Summary of Damage to Sewer Systems from Several Earthquakes in Japan

Earthquake Damaged Place/ Intensity (JMA)	Pipeline Damage	Pumping Station/Treatment Plant Damage
Kanto (M=7.9), September 1, 1923 Tokoyo/ VI	A pipeline damaged near Yamanote and Shitamachi. Damage ratio = 250 breaks/ 180 km = 1.39 breaks/km. Damage to sewer is considered light compared to other buried pipelines.	A treatment plant suffered light damage without effect to its operation.
Niigata (M=7.9), June 16, 1964 Niigata City/ V	Damage mostly by liquefaction, uplift, collision of manhole and pipe, pull-out of joints, cracks; 70 percent of 35 km pipeline was misaligned.	Damage to sedimentation basin by liquefaction. Damage to pump canal (about 11 of 15 locations) by uplifting; 8 machines stopped (damage mostly in structure).
Tokachioki (M=7.9), May 16, 1968		
Hakodate City/ V	Because it was reclaimed land, damage was by liquefaction (uplift of pipe).	No sewer system.
Murorane City/ IV	Within a 5.5 km length, 750 m of pipe settled under soft ground.	Two places in a pumping station were slightly damaged.
Miyagi-Ken-Oki (M=7.4), June 12, 1978		
Sendai City/ V	630 m of 690 km of sewer lines had sight damage without stopping flow.	Nine of 11 places in main pumping station stopped functioning for lack of electricity.
Shiogama City/ V	700 m of 27 km pipeline suffered damage due to weak ground (reclaimed land).	One machine stopped; light damage to another.
Nihonkai-Chubu (M=7.7), May 26, 1983		
Akita City/ V	Pipeline damage by soil liquefaction within entire 286 km length; 1.7 km were reconstructed. Manhole damage in 93 places.	Damage by liquefaction (uplift of sand basin or detritus tank).
Noshiro City/ V	Pipeline damage from soil liquefaction within entire 60 km length; 8 km were reconstructed.	Treatment plant was under construction. No damage found in pumping station.

NOTE: Intensity from Japan Meteorological Agency.

TABLE 10 Relationship Between Damage and Intensity

Type of Damage	Intensity IV (~81 gal)	V (~250 gal)	VI (~450 gal)
Pipeline damage without liquefaction			
Joint	Sliding	Broken & pull-out	Pull-out
Pipe body	-----	Crack & broken	Severely broken
Pipeline alignment	-----	Misalignment & separation	Separation
Junction	-----	Broken & broken	Broken
Pipeline Damage with liquefaction			
Joint	Sliding	Broken & pull-out	Pull-out
Pipe body	-----	Crack/broken & severely broken	Serverely broken
Pipeline alignment	Misalignment	Misalignment & large separation	Large separation
Junction	-----	Broken	Broken
Uplift of pipeline	-----	Uplift	Uplift
Manhole damage without liquefaction			
Cup	Sliding	Broken	Broken
Inclined/vertical walls	Joint sliding	Crack & broken	Broken
Bottom wall/base plate	-----	Crack & broken	Broken
Invert	-----	Crack & broken	Broken
Soil settlement	-----	Slight to large	Large
Junction	-----	Broken & broken	Broken
Manhole damage with liquefaction			
Cup	Sliding	Broken	Broken
Inclined/vertical walls	Joint sliding	Crack & broken	Broken
Bottom wall/base plate	Crack	Broken	Broken
Invert	Crack	Broken	Broken
Soil settlement	Small	Large	Large
Junction	Broken	Broken	Broken
Uplift	-----	Uplift	Uplift

NOTE: Intensity from Japan Meteorological Agency.

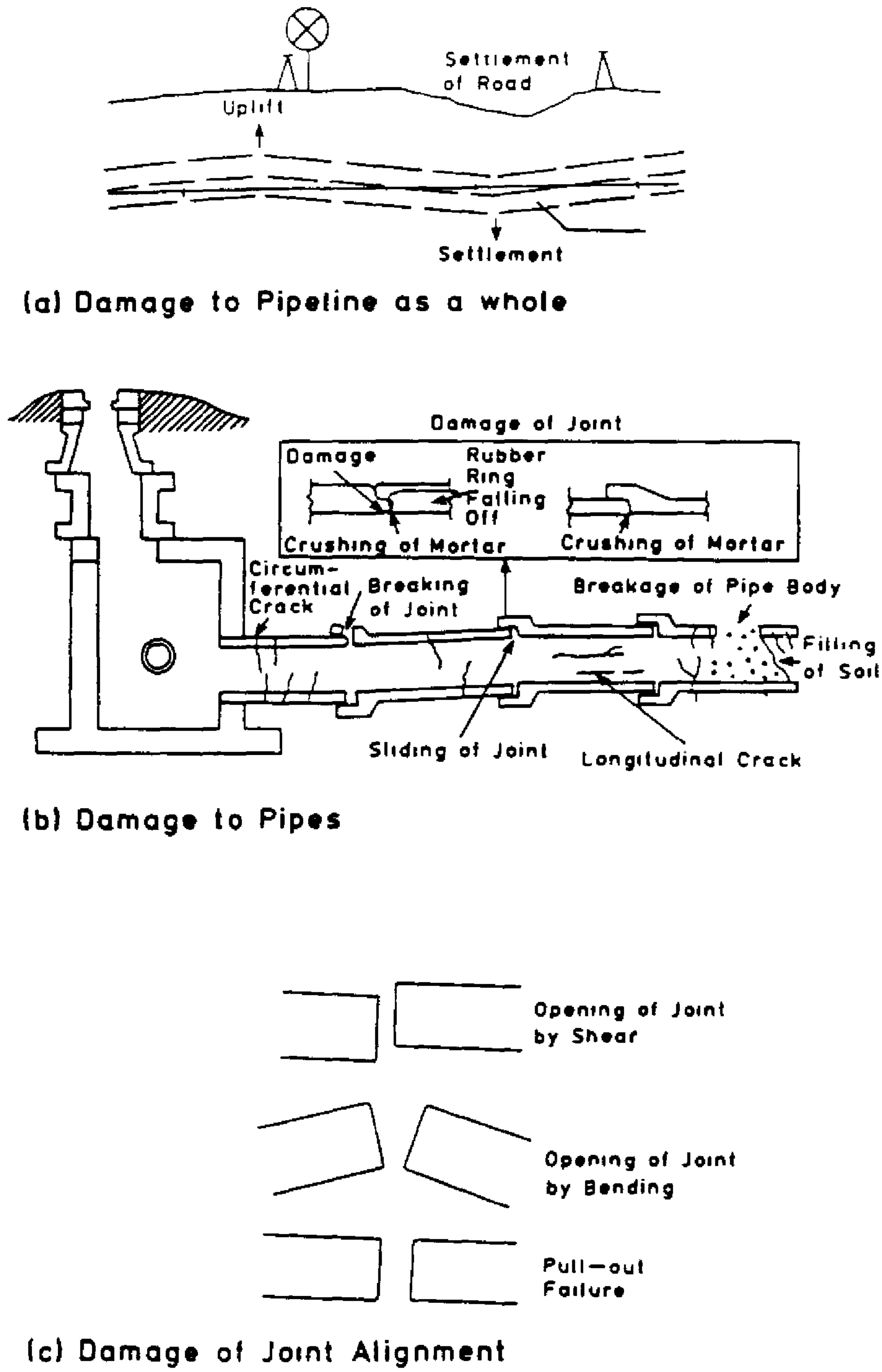

FIGURE 1 Seismic damage to segmented pipelines.

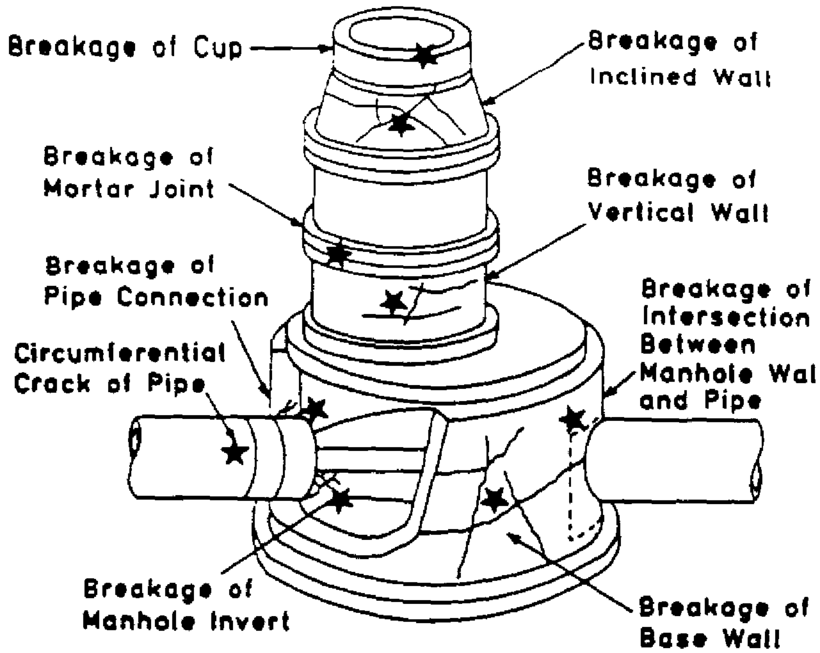

FIGURE 2 Seismic damage to manhole.

- Breaking of pipe body
- Soil deposit into pipe

3. Damage to Joint
   - Shear break
   - Bending opening
   - Pulling off
   - Loosening and leakage

4. Damage to Manhole
   - Breakage of top cup
   - Breakage of inclined wall, vertical wall and base wall
   - Breakage of mortar joint
   - Breakage of pipe connection
   - Breakage at intersection between manhole wall and pipe

Many factors affect the performance of pipelines. They include, but are not limited to, the following parameters:

1. Intensity of earthquake

2. Location with respect to fault zone

3. Tectonic ground fracture

4. Ground conditions with and without liquefaction potential

5. Ground conditions with and without landslide potential

6. Buried depth

7. Pipe materials

8. Joint construction

9. Pipe diameter

Not enough data are available to permit pipeline damage to be correlated with the above parameters; however, experience from earthquakes in the United States, Japan, and China permits the following general conclusions to be drawn:

1. Pipeline damage is proportional to earthquake intensity.

2. Rigid joints such as lead caulked joints fail more than flexible joints such as rubber gasket joints.

3. With ordinary push-on rubber gasket joints, the joint is weaker than the pipe body itself with respect to longitudinal ground motions.

4. Pipe fails more in weaker soil.

5. Liquefaction causes most damage to pipeline.

6. Smaller diameter pipes seem to have more failures (indicated by the statistics from China and Japan but not from San Fernando), but no firm conclusion about the effect of diameter can be drawn.

7. More failures occur at the connections between manhole or heavy structure and pipe.

8. Corrosion plays a major factor in failure of steel pipelines.

9. Damage to water and sewer pipelines may continue to appear for several years after an earthquake because cracks initiated due to an earthquake may not be or cannot be detected immediately after the earthquake.

SIMPLIFIED ANALYSIS AND DESIGN METHODOLOGY

Introductory Remarks

The analysis and design of buried pipelines for seismic ground shaking, which by their nature have both temporal and spatial variations, are much different than those of buildings. The design of buried pipelines for fault movement effects would require a nonlinear analysis involving both material and geometric nonlinearities. The behavior of pipeline under a soil liquefaction environment is still under study.

The presentation of a rigorous analysis including various types of seismic hazards to segmented or jointed pipelines is beyond the scope of this paper; however, to aid in the development of the action plan, a simplified analysis methodology for use concerning a seismic shaking environment is presented as an example. For other types of analyses, readers are referred to the author's earlier report (Wang, 1985).

Passive Design Considerations

Because there are no codified provisions for the design of buried pipelines to resist seismic loads in the United States, several passive design considerations have been used (Ford, 1975) by engineers to reduce seismic damage and minimize hazardous effects. Following are some common engineering practices and recommendations:

1. Redundancy should be built into the distribution system. Smaller pipes should be used in lieu of a single large pipe to minimize reduction in operation due to breakage of pipes.

2. Blow-off valves should be installed at a location where higher seismic activity is anticipated, such as along a fault line. By this technique, water is led to a nearby reservoir when the designed blow-off valve is triggered to open during a strong earthquake.

3. Ductile pipe materials such as steel, ductile iron, or PVC should be used to allow larger pipeline deformation.

4. For segmented pipelines, flexible joints such as rubber gasketed connections should be used to provide for relative joint movements. For anticipated large ground movement, extra long restraining sleeves or "bellow joints" should be used. When feasible, shorter segments that will experience less strain as a result of ground motion should be used. Also, relative joint displacements are less for shorter segments.

5. If feasible, consideration should be given to encase the pipeline in a larger tunnel in order to isolate the pipeline from the seismic ground motion or to lubricating the pipeline in order to increase the "slippage" between the pipe and the surrounding soil.

In summary, all these qualitative passive seismic design considerations may reduce damage to buried pipelines. Quantitative and comprehensive design guidelines are still urgently needed to ensure the safety of future designs. Action plans to prevent and/or mitigate the damages should be developed in the interim.

Simplified Analysis for Seismic Shaking Effects

Basically, the simplified analysis assumes no relative motion between the pipe and the ground. Thus, as upper bounds, one can take the seismic ground strains as the pipe strains and the seismic ground curvatures as the pipe curvatures. This is equivalent to assume that the pipe has no stiffness and, therefore, will follow the ground exactly.

For the analysis of and design of continuous pipelines, the upper bound of the axial strain of the pipe, $\varepsilon_{p,max}$, will be the maximum ground strain, ε_{max}, due to earthquake.

$$\varepsilon_{p,max} = \varepsilon_{max} = V_{max}/C_p \tag{1}$$

The upper bound for the maximum curvature of the pipeline, $\chi_{p,max}$, will be the maximum ground curvature, χ_{max}:

$$\chi_{p,max} = \chi_{max} = A_{max}/C_s^2 \tag{2}$$

where

V_{max} and A_{max} = the maximum ground velocity and the maximum ground acceleration during a seismic event at the site

C_p and C_s = the longitudinal (compressive) and transverse (shear) wave propagation velocities, respectively, of the controlling environments with respect to the pipeline

If a continuous piping system can meet both sets of upper bound criteria (strain and curvature), the pipeline will be adequate against earthquakes that produce ground velocities and accelerations less than the V_{max} and A_{max} used in the analysis.

From Eq. 1 and 2, it is noted that the strain is inversely proportional to the wave propagation velocity, whereas the curvature is inversely proportional to the square of the wave velocity. Numerically, the free-field strain may be in the order of 10^{-2} to 10^{-3} and the field curvature in the order of 10^{-5} to 10^{-6} ft^{-1} ($3.3 \cdot 10^{-5}$ to $3.3 \cdot 10^{-6}$ m^{-1}) for moderate to strong earthquakes. The ground strain has much higher magnitude than the ground curvature.

For segmented pipelines (Figure 3), the maximum relative joint displacements and the maximum joint rotations become important design parameters in addition to the pipe strains and curvatures. If it is assumed that the pipeline consists of rigid segments that have their midpoints move with the ground exactly, then the maximum relative motion/rotation between two points on the ground will be entirely taken up by the relative displacements and rotations of segments at the joints. Hence, the upper bounds of maximum joint displacement, $U_{p,max}$, and maximum joint rotation, $\theta_{p,max}$, shown in Figure 4, can be expressed as:

$$U_{p,max} = \varepsilon_{max} L \tag{3}$$

$$\theta_{p,max} = \chi_{max} L \tag{4}$$

where

L = the length of the pipe segment

ϵ_{max} and χ_{max} = the maximum free field ground strain and curvature defined in Eq. 1 and 2, respectively.

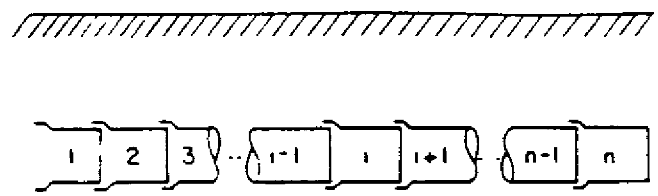

FIGURE 3 Schematic of a buried segmented pipeline.

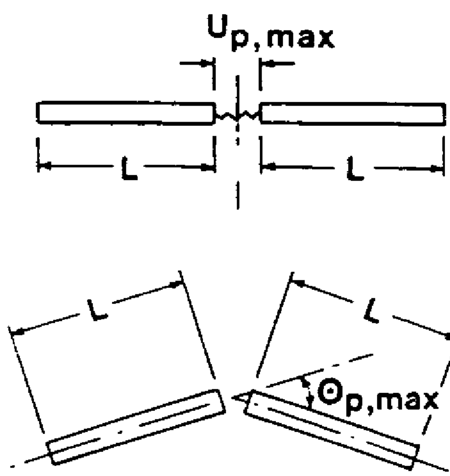

FIGURE 4 Maximum relative joint displacement/rotation of segmented pipeline.

If a buried segmented piping system can meet all four sets of upper bounds (pipe strain and curvature; joint displacement and rotation) specified in Eq. 1 through 4 for a design earthquake, the pipeline will be conservatively safe because in the real case, the pipe strain and relative joint displacement will jointly take up the imposed ground strain and both the pipe curvature and joint rotation will jointly take up the imposed ground curvature. Due to the difference in the order of the magnitude of free-field ground strains and ground curvatures, the relative joint displacements would be more critical than the relative joint rotations as far as the design of buried segmented pipeline is concerned. One must note that the above conclusions would be true only if one can accurately estimate the maximum ground velocity and acceleration in the region and the seismic wave propagation velocities at the site.

Active Design Procedures

Active design is the process of developing a set of physical parameters for a system capable of resisting the anticipated loads, called the design loads. In light of the fact that there is no seismic design code for buried pipelines in the United States, this paper outlines a preliminary active design procedure that may serve as a basis for future design code developments. Sequentially, the active design procedure involves three stages: site environment evaluations, engineering decision making, and design analysis.

Site Environment Evaluations

In order to satisfactorily design buried pipelines to resist the anticipated seismic ground shaking or fault displacements, the site environment must be evaluated so that the important site-dependent design parameters can be determined. The site-dependent parameters are the seismic risks of the region, wave propagation velocities at the site and/or magnitude of fault movement, and the soil resistant characteristics of the surrounding environment of the pipeline.

- Seismic Risks--In this paper, seismic risk is defined as the probability of exceeding a particular ground acceleration, velocity or displacement/fault movement in a given time period called the return period. Using seismic data in the region where the pipeline is to be designed, a family of curves of ground acceleration/fault movement vs. probability of exceedance for a number of return periods (e.g., 50 years, 100 years) can be determined.

- Propagation Velocity--Another site dependent parameter is the wave propagation velocity. The wave propagation velocity pertinent to buried pipelines is a function of the epicenter distance, focal depth, and geological and soil properties along the transmission path of the waves to the site.

  For important projects such as nuclear power plants, the effective apparent wave propagation velocities must be investigated carefully. However, for preliminary design, the wave propagation velocity resulting in pipeline curvature may be represented by the shear wave velocity, C_s, and the velocity resulting in axial strain may be represented by the pressure wave velocity, C_p, with respect to the pipeline at the site as follows:

  $$C_s = \sqrt{G/\rho} \quad \text{and} \quad C_p = \sqrt{3}C_s \tag{5}$$

  where G is the soil shear modulus and ρ is the soil mass density.

  Note that the effective wave propagation velocity is affected by the characteristics of soil of deeper layers; therefore, one should not use the shear modulus of the soil just near or surrounding the pipe. Engineering judgment must be exercised.

- Soil Resistant Characteristics--If the "quasi-static analysis" (Wang and Olabimtan, 1983) approach is used, the axial soil resistant characteristics are needed to study the soil-structure interaction effects. To study pipeline subjected to fault movement effects (Wang and Yeh, 1985), lateral soil resistant characteristics are also necessary. For important projects, these soil properties must be obtained experimentally from the site.

Engineering Decision Making

Engineering decisions for the seismic design of buried pipelines that should be made are: a determination of the "design earthquake" for the site and a choice of material and/or joint ductility or a combination of the two in order to resist the imposed ground strains/curvatures resulting in fault movement from the selected "design earthquake." Both aspects have great economic implications.

- Design Earthquake--The probability of failure of a system is directly related to the magnitude of the "design earthquake" used. It is obvious that the larger the earthquake used for design, the less the risk of failure of the system. In reality, there is no absolute earthquake-proof design without some risk. It is more costly to design the system to resist stronger "design earthquakes." No explicit criteria presently exists, from an economic point of view, for selecting a satisfactory "design earthquake." In most cases, it is a matter of engineering and administrative judgment.

- Pipe Materials and/or Joint Construction--Note that for the design of continuous pipelines to resist earthquakes, once the "design earthquake" is chosen, it is only necessary to select the proper material and check the thickness of the pipeline through one of the proposed analysis approaches discussed. However, for segmented pipelines, both pipe materials and joints share the resistance to the imposed groung excitations. The choice of pipe material and joint construction again involves both economic considerations and engineering judgment. Overall sizing of the pipeline will generally be controlled by hydraulic or other fluid flow considerations.

  Note that choosing more ductile materials and more flexible joints will increase the ability of buried pipelines to absorb higher imposed ground disturbances or fault movement due to earthquakes. Thus, the safety of the system will be increased by increasing ductility. From an economic point of view, the design should investigate the proper choice of material(s) and joint construction(s).

Design Analysis

After engineering decisions have been made to select a "design earthquake," pipe materials and joint constructions, with and without manholes, a set of physical parameters for the pipeline are thus established. The next step is the design analysis to determine the adequacy of the trial design. The design analysis includes a seismic design criteria analysis (Wang and Fung, 1980) coupled with a response analysis.

- Seismic Design Criteria Analysis--For a given material (e.g., cast iron, ductile iron, concrete, or steel pipes) and functional use (water, sewer, gas, and oil pipelines), a seismic design criteria analysis (Wang and Fung, 1980) is required to determine the reserve strength/ductility of buried pipes beyond normal nonseismic stress/strain conditions. This reserve strength/ductility is the capacity available in buried pipes to resist seismic loads.

  To evaluate the failure of buried pipelines consisting of materials with different tensile and compressive strengths (such as cast iron and concrete) under a bi-axial stress state, a modified Von Mises failure criterion has been proposed (Wang and Fung, 1980).

- Response Analysis in Design Process--For seismic ground shaking, the "simplified analysis" approach should be used as a first check since this approach is simple and conservative. It requires only inputs of maximum ground acceleration and velocity and seismic wave propagation velocities at the site. If the analysis results are below the seismic design criteria limits, the design is considered to be satisfactory.

  A more refined analysis may be required for technical or economic reasons. If so, the "quasi-static analysis" approach should be used since this approach will describe pipeline responses in more detailed and concise terms. However, the analysis requires more input such as joint and soil resistance characteristics, earthquake displacement-time functions, and some other physical piping parameters. For large fault movements, the suggested nonlinear analysis should be used (Wang and Yeh, 1985).

PRE-EARTHQUAKE PREPARATION MEASURES

Action Plans

In order to mitigate damage and facilitate the inspection, repair, and restoration of existing water and sewer pipelines under the confusing conditions during and after the earthquake, it is necessary to prepare action plans for emergency use. Following is a list of suggested action plan considerations:

1. Draw/map the pipeline system including pumping stations and manholes.

2. Identify regions of weak and liquefiable soils and slopes.

3. Identify weak points, abnormal points, and leaking points that have been discovered by the ordinary maintenance work.

4. Identify the points that need special attention and examination.

5. Establish an information exchange network about the earthquake and/or earthquake disaster.

6. Prepare portable pumps for emergency use.

Communication Between Related Organizations and the Public

In an earthquake emergency, it is necessary to exchange and communicate disaster information with related organizations and the public during the damage survey, repair, and restoration period. Such communications would involve:

1. Police--To exchange information on dangerous regions

2. Road Maintenance Office--To exchange information on unusual or damaged pavement subgrade and/or surface

3. Gas utilities--To exchange information on damage points of the gas and oil pipeline system

4. State, Regional, and Local Offices--To discuss policy on priority of repair and restoration

In order to carry out smoothly the damage survey and repair and restoration, it is also necessary to gather information from the public and to make announcements to the public that affect their well-being.

EMERGENCY DAMAGE SURVEY AND INSPECTION MEASURES

Introductory Remarks

The survey/inspection of damage of water and sewer pipeline requires special tools and is laborous. In order to carry out the survey/inspection efficiently, it is important to predict the types of possible damage caused by an earthquake. The characteristics of damage from past earthquake will help to identify the potential nature or scale of the damage and the potential distribution of the damage area when another earthquake occurs.

The emergency survey/inspection should include main line, distribution lines, and treatment and disposal plants.

One method of survey/inspection is by sight and the other is by instrument. It is also important to observe and record the road conditions, manhole conditions, and their surrounding environments.

Checklist for Emergency Survey/Inspection

The purpose of the emergency survey/inspection is to prevent the expansion of minor damage into a disaster. The main goal is to limit damage propagation to surrounding pipeline and facilities. Points to be considered are:

1. Whether there are unusual or abnormal signs in the operation in the pumping stations and/or disposal facilities

2. Whether there are unusual phenomena in manholes and the surrounding area of the pipeline

3. Whether there are leaks from water pipelines or from sewer manholes

4. Whether there are inflows of dangerous material (gas, oil, sandy soil, etc.) into the conduits or manholes

5. Whether there is damage to conduits, manholes, etc.

6. Whether there is any deterioration of pumping capability.

Emergency Repair and Restoration Measures

During and just after the earthquake, it is sometimes difficult to carry out all emergency measures because of insufficient manpower and material. Therefore, it is necessary to decide the priority of the regions or the tasks that need emergency attention, such as survey/inspection, repair and restoration.

When deciding whether or not to carry out an emergency repair and/or restoration measure, it is necessary to consider the possibility of the occurrence of induced disaster. Examples are the influence of the failure of roads and/or surrounding facilities on the water and sewer system.

For emergency repair and/or restoration measures, the structural damage and the functional damage as well as the influence of other facilities on pipeline should be investigated. The items to be considered are as follows:

1. The intensity and character of structural damage

2. The functional damage

3. The effects in users of such damage

4. The influences of the road conditions

5. The influences of other facilities and/or other systems

When it is decided that emergency repair and/or restoration should be carried out, the following measures should be considered according to the intensity or the effects of the damage.

1. Stop leakage from pipes/conduits using water proof band

2. Drain excess water or waste water using portable pumps

3. Set up temporary conduits or pipes

4. Dredge sand/soil in conduits/pipes and/or manholes

5. Repair gaps between manholes and roads

6. Fence the rupture places in roads

7. Set up signs warning of road settlement and/or ruptures

8. Set-up traffic control for the dangerous regions

Method of Damage Survey/Inspection

The selection of survey/inspection methods should be based on the following considerations:

1. The importance and type of structure

2. The investigation condition

3. The applicability of the observation method

Two types of survey/inspection method for buried pipelines are available: direct and indirect.

When possible, it is desirable to use the direct survey/inspection method in order to find out the exact location and intensity of the damage. The available direct survey/inspection methods can be implemented using actual observation by eye, lasers, radar, or remote controlled waterproof video cameras or rolling TV cameras with motors.

The indirect survey/inspection method is used when the direct method is not available for some reason or when it is difficult to assess the damage by the direct method. The principle of the indirect method is to observe the flow condition by using some type of instrument. Available indirect survey/inspection tools are smoke tests, added water tests, stopping water tests, flow rate tests, air pressure tests, water quality tests, relative leakage tests, and sewer infiltration by pumping water between manholes. In addition, when necessary, cleaning of the pipeline can serve as a survey/inspection method.