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ACTION PLAN FOR REDUCING THE EFFECTS OF SEISMIC HAZARDS TO SEGMENTED AND JOINTED PIPELINES

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Technical Report No. ODU LEE-03
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ISSUE PAPER*

Action Plan For Reducing the Effects of Seismic Hazards
to Segmented and Jointed Pipelines

By

Leon R. L. Wang
Professor and Chairman
Department of Civil Engineering
Old Dominion University
Norfolk, Virginia 23508
U.S.A.

and

Eiichi Kuribayashi
Professor and Chairman
Department of Civil Engineering and Regional Planning
Toayohashi University of Technology
Toayohashi 440
Japan

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I. INTRODUCTION

Recent experiences have shown that lifeline systems, which include water and sewer pipelines, oil and gas pipelines, electric power transmission lines, long span bridges, etc. have been damaged heavily by recent earthquakes, including the most recent 19 September 1985 Mexico Earthquake. At the present time, scientists, researchers and engineers in the United States, Japan, China, Mexico, and other countries are now actively engaged in research for adequate design of new lifeline systems and retrofitting of existing lifelines.

By their physical arrangements, most water and sewerage lifelines are below-ground, segmented or jointed pipelines. In some cases, water pipelines may be above-ground and continuous.

This paper deals mostly with buried segmented and jointed pipelines although continuous or above-ground pipelines will be mentioned briefly. In particular, this paper will describe the damage to water and sewer pipelines in recent earthquakes including those from the United States, Japan and China. This paper will also describe the available methods, criteria and techniques for pre-earthquake preparation, survey of damages, restoration and repair of damaged systems, design and construction of new pipelines as well as for retrofitting the existing ones. It will point out the on-going activities in the advancement of knowledge regarding the behavior of segmented pipelines during earthquakes, problems and issues needing attention and what should be done about them.

II. SCOPE

The object of this issue paper, in essence, is to provide a mini-action plan for reducing the effects of seismic hazards to segmented and jointed pipelines. The scope of this paper covers, but is not limited to, the following items.

- Damage lessons learned from recent earthquakes in U.S., Japan and China

- Assessment of Pipeline behavior and performance

- Assessment of available methods for survey and restoration of damaged water and sewer pipelines

- Assessment of available criteria, methods and techniques for design and construction of new seismic resistant lifelines

- Assessment of available methods of identifying and retrofitting vulnerable existing in-place systems

- Survey of on-going activities

- Identification of scientific and engineering information need

- Recommendations

III. BACKGROUND

In general, there are three causes of seismic hazards to below-ground lifelines, namely: a) soil straining induced by seismic ground shaking, b) ground movement/rupture along fault zones and c) soil liquefaction induced by ground shaking.

The major seismic hazards have been observed to come from large ground movement/rupture along fault or soil liquefaction zones. The preliminary responses/failures of below-ground continuous oil and gas lifelines due to ground rupture [1] and fault movements [2] have been studied. No specific study devoted to the analysis and design of segmented and jointed water or sewer pipelines for crossing an active fault has been found. Since the effects of fault movement to the transport of water and waste water 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 [3,4]. 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 of buried straight pipelines located within uniform firm soil have been found to result in relatively minor damage as reported by Isoyama and Katayama [5]. The damaged area is mostly at regions where the soil and/or geological conditions change and at joints and junctions [6]. Since seismic shaking affects a large area, 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.

IV. DAMAGE LESSONS LEARNED FROM RECENT EARTHQUAKES

IV.1 Introductory Remarks

The damage of buried lifelines in U.S., Japan, China and other parts of the world have been reported by many authors right after a major earthquake. It is not the purpose of this paper to repeat the same reports. Rather, it is intended to summarize the similiar or different damage behavior from several known earthquakes so that some common conclusions can be drawn from these observations. For the purpose of completeness, damages from each earthquakes will be described briefly. References 6 to 13 are selected for this purpose although many other earthquake reports are also available.

IV.2 Damage Experience Learned From San Fernando Earthquake in the United States

IV.2.1 General Information

The United States has had several destructive earthquakes in its history. However lifeline earthquake engineering has not received much attention until 1971 The San Fernando Earthquake when many lifelines including water and sewer lifelines, oil and gas lifelines, transportation lifelines and electrical lifelines suffered heavy damages. Using this data, this report assesses the damaged behavior of segmented and jointed pipelines.

The San Fernando Earthquake occurred at 6:01 AM on February 9, 1971 inflicting severe damage along the foot hills 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: $43^{o}24.0'$ N, $118^{o}23.7'$ W

Focal depth: 13.0 km (8 miles)

Where the San Fernando fault reached the ground surface, lateral movements up to 3 feet aparently 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 structually poor throughout the San Fernando Valley particularly when the ground water 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.

IV.2.2 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 1155 breaks in sewer lines.

All the cast iron water mains with cement-caulked joints that crossed the faults in the area under consideration were damaged and the damage was most prominent along northeast trending 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 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 20% of the flexibly jointed pipeline needed to be reconstructed, as compared to 42% for rigidly jointed pipes. Table 1 shows that larger diameter pipes seems 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 supply facilities were, in essence, severed from the distribution system by the multitude of breaks. As seen from Table 2 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 is not conslusive.

IV.2.3 Assessment of Damages

There are numerous variables which could conceivably be related to the extent of pipe damage. These include the following:

- Type of pipe.
- Buried depth of pipe.
- Proximity of other substructures.
- Type of soil.
- Location and direction with respect to fault zone and area of vertical uplift.
- Size of pipe.
- Type of joint.
- Encasement of pipe.

However, there is no sufficient information available concerning all of these variables to be able to develop conclusions 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 immediatley 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.

IV.3 Damage Experience Learned From Earthquakes in China

IV.3.1. General Information

In China, Haicheng Earthquake in 1975 and Tangshan Earthquake in 1976 were two severe earthquakes that caused heavy losses in recent years. This paper discussed only the damage of water and sewer lifelines.

The seismological data for the two earthquakes are as follows:

a) Haicheng Earthquake

Beijing time of commencement of the shock:

7:36 P.M., February 4th, 1975

Magnitude: M 7.3

Epicenter: $40^{\circ}39'$ N, $122^{\circ}48'$ E

Near Zhaojibao Village, Haicheng

Focal depth: Approx. 12 km

b) Tangshan Earthquake

Beijing time of commencement of the shock:

3:42 A.M., July 28th, 1976

Magnitude: M 7.8

Epicenter: $30^{o}24'$ N, $118^{o}06'$ E. In Tangshan

Focal depth: 12-16 km

IV.3.2 Features of Seismic Damage of Pipe From Haicheng Earthquake

The geological structure in Haicheng is mountainous land which is an upwarped district of paleometamorphic and eruptive rock.

The soils at the site in Hiacheng City are divided into three types (classes):

Type I. Readily and moderately slackened solid rock,

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

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

In the disaster region of the Haicheng Earthquake, there were relativley integrated sewer systems in Yingkou City and Panshan Town. Only in Panshan Town were some sewers damaged. Following are features of seismic damages to water pipelines.

a) Influence of Ground Conditions and Intensity

The various damage ratios of water supply pipelines in the disaster regions are listed in Table 3.

From Table 3, it can be seen that the soil of the site plays an important role in damaged pipes during an earthquake. Note that both Dashiqiao and Haicheng regions suffered 9^{o} 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, 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.

b) 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^{o} 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, from which it can be seen that the damage ratios of the flexible joint pipe were much smaller than those of rigid ones.

c) 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 observation is different from that observed from San Fernando Earthquake. The difference may be attributed to the difference in local site conditions.

IV.3.3 Features of Seismic Damage of Pipe From Tangshan Earthquake

Tangshan is located in the junction zone of Hebei-Shandong downwarp and the Yanshan fault which has been historically known for earthquakes. The region is surrounded by different striking faults. The Tangshan fault rupture is located in the south-east 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 types:

Type I. Dense silty clay

Type II. Dense sand of medium size

Type III. Fine silt and silty loan

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

For water supply systems, there are about 2.0 breaks/km to 10 breaks/km with average damage ratio of 4 breaks/km in Tangshan and 0.2 breaks/km to 1.2 breaks/km in Tianjing.

Due to liquefaction effect, the damage ratios for Tanggu and Hangu were much higher. It ranged from 4 breaks/km to 30 breaks/km. The influences of various parameters are discussed below:

a) Influence of Ground Condition at Site:

The condition of site soil is an inportant factor in seismic damage of buried pipelines. In the Tianjing region, site soil is of class III with higher ground water level, and the liquefaction movement of sand stratum is easliy 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.

b) Influence of Joints:

The types of seismic damaged joints are as follow:

- Pulling out;
- Loosening and leakage;
- Shear break;
- Bell crack.

Table 7 shows the seismic damage of pipes and joints for Tangshan and Tianjing Cities due to Tangshan Earthquake. This table shows that the failures of joint, pull-out failures and fittings for pipes of all diameters were much higher than the failures of the pipe itself.

Among these pipelines, the self-stressed concrete steel cylinder pipeline with rubber flexible joints appeared to be shock-resistance in this earthquake. (Note that the self-cement expands when immersing in water and thus pushes the cylinder. Acting each other, the steel cylinder will be pre-tensioned and the self-stressed concrete core will be prestressed.) The conventional prestressed concrete pipeline joined by socket with rubber ring appeared to be satisfactorily shock-resistance. The serious seismic damages to cast iron pipelines were evidently affected by corrosion.

c) Influence of Pipe Diameter:

The statistics of failures of pipes with different diameters is also shown in Table 7. One can see from this table that smaller diameter pipes seem to fail more than that of 500 - 600 mm diameter pipes. However, the failures of 75 mm - 400 mm pipes were in the same range.

d) Influence of Other Parameters:

From the Tangshan Earthquake, the influence of geography and terrain, soil sliding and the tectonic ground fractures on pipe damages were also noted.

The seismic influence of topography on the pipelines was mainly reflected by the evident sliding of slope and obvious downwarping difference between back fill and original soil where the ground fissure could be readily found in this shock. Also, all the pipelines which crossed the fault rupture zone suffered serious damages.

IV.4 Damage Experience Learned From Earthquakes in Japan

IV.4.1 General Information

Japan is located in one of the most highly-seismic regions in the world. It has much damage data, including lifelines. In this paper, most data are referred to the Miyagi-Ken-Oki Earthquake of June 12, 1978. To supplement the analysis, some available damage data from other earthquakes, will also be used.

The Miyagi-Ken-Oki earthquake data from U.S. Geplogical Survey (USGS) source are:

Time: 08:14:27 GMT (17.14 local), June 12, 1978

Magnitude: 7.4

Epicenter: 38.2° N, 142.2° E, approximate 100 km from 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 which occurred in the east of this line. The alluvial plain consists most 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 consisted 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 consisted 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.

IV.4.2 Damage Observations

Water supply facilities were damaged at 54 cities, towns and villages in Miyagi Prefecture. Total 232 breaks were reported to have occurred in the water distribution mains with diamters 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. Among many kinds of water pipes as shown in Table 8, the steel pipe showed the least damage ratio of 0.014 breaks/km. Abestos cement pipe which is considered to be the most vulnerable against earhquake ground motions had 0.912 breaks/km. The ductile cast-iron pipes showed good performance with damage ratio of 0.045 breaks/km. The average damage ratio for all water pipes is 0.102 breaks/km. As to the pipe size, the smallest pipes 75 mm diameter had the highest damage ratio of 0.404 breaks/km.

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

Based upon the examination of damages the reports showed that about 90% of the damages to the sewer system had occurred at junctions of buried pipelines and manholes. The types of damages most commonly observed in these structures can be classified in the following items:

- 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 pipe and box-type culvert damages such as subsidence, breakage and buckling, etc. 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 on the sewer systems was small in comparison with total damages.

IV.4.3 Assessment of Damages

The Miyagi-Ken-Oki Earthquake experience showed both water and sewer pipelines 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 features were 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, damages were 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, as compiled in Ref. 12, for several earthquakes in Japan are summarized in Table 9. As a general rule, the relationship between damages and earthquake intensities 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 sever when liquefaction occurs.

IV.5 Summary

The best 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 listed below:

a) Pipeline as a whole

- Waving of center line (alignment problem)
- Uplift
- Settlement
- Buckling
- Soil deposit into pipeline

b) Pipe Body

- Circumferential cracks
- Longitudinal cracks
- Breaking of joints
- Rubber ring falling off
- Mortar seal breaking away
- Breaking of pipe body
- Soil deposit into pipe

c) Joint

- Shear break
- Bending opening
- Pulling off
- Loosening and leakage

d) 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:

- Intensity of earthquake
- Location with respect to fault zone
- Tectonic ground fracture
- Ground conditions with and without liquefaction potential
- Ground conditions with and without landslide potentials
- Buried depth
- Pipe materials
- Joint construction
- Pipe diameter

There are not enough data to correlate the pipeline damage to above parameters. However, with the experiences learned from earthquakes from the United States, Japan and China, the following general conclusions can be made.

1. Pipeline damage is proportional to earthquake intensity.
2. Rigid joints such as lead caulked joints failed 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 failed more in weaker soil.
5. Liquefaction will cause most damage to pipeline.
6. Smaller diameter pipes seem to have more failures as shown from the statistics in China and Japan, but not San Fernando. Therefore, the effect of diameter is inconclusive.
7. More failures occurred at the connection 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 the earthquake because of the initiation of cracks due to an earthquake may have not been or can not be detected immediatley after the earthquake.

V. SIMPLIFIED ANALYSIS AND DESIGN METHODOLOGY

V.1 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 from those of buildings. The design of buried pipelines for fault movement effects would require a non-linear analysis involving both material and geometric non-linearities. The behavior of pipeline under a soil liquefaction environment is still under study.

The presentations 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 the development of the action plan, a simplified analysis methodology under seismic shaking environment will be presented as an example. For other types of analysis, readers are referred to the author's report [14].

Presently, there are no codified provisions for the design of buried pipelines to resist seismic loads in the United States. Passive design considerations will be presented to mitigate hazards to buried pipelines.

V.2 Passive Design Considerations

In the absence of seismic design codes for buried pipelines, several passive design considerations have been used [15] 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. More 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 stronger earthquake.

3. Ductile pipe materials such as steel or 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 which will experience less strain imposed by the 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 lubricate 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 the damage of 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 mean time.

V.3 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 sismic 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 continous pipelines, the upper bound of the axial strain of the pipe, $\varepsilon_{p,max}$, will be the maximum ground strain, ε_{max}, due to the 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} is the maximum ground velocity and A_{max} is the maximum gound acceleration during a seismic event at the site; C_p and C_s are the longitudinal (compressive) and transverse (shear) wave propagation velocities, respectively, of the controlling environments with respect to the pipeline.

If a continous 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 Eqs. (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 velsocity. Numerically, the free field strain may be in the order of 10^{-2} to 10^{-3} and the free field curvature in the order of 10^{-5} to 10^{-6} ft^{-1}(3.3×10^{-5} to $3.3 \times 10^{-6} m^{-1}$) for moderate to strong earthquakes. The ground strain has much higher magnitude than the ground curvature.

For segmented pipelines (Fig. 3), the maximum relative joint displacements and the maximum joint rotations become important design parameters in addition to the pipe strains and curvatures. If we assume that the pipeline consists of rigid segments which 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 Fig.4 can be expressed as:

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

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

where L is the length of the pipe segment; ε_{max} and χ_{max} are the maximum free field ground strain and curvature defined in Eqs. (1) and (2), respectively.

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) to Eq. (4) for a design earthquake, the pipeline will be conservativiely 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 only be true if one can accurately estimate the maximum ground velocity and acceleration in the region and the seismic wave propagation velocities at the site.

V.4 Active Design Procedures

Active design is a process to develop a set of physical parameters of 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 which may serve as a basis for future design code developments. Sequentially, the active design procedure involves three stages, namely: (a) Site Environment Evaluations, (b) Engineering Decision Making and (c) Design Analysis.

V.4.1 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, etc.) 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 as well as the geological and soil properties along the transmission path of the waves to the site.

For importnat 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:

$$C_S = \sqrt{\frac{G}{\rho}} \quad \text{and} \quad C_P = \sqrt{3}C_S \tag{5}$$

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

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

. Soil Resistant Characteristics: If the "Quasi-static Analysis" [16] approach is used, the axial soil resistant characteristics are needed to study the soil-structure interaction effects. To study pipeline subjected to fault movement effect [17], lateral soil resistant characteristics are also necessary. For importnat projects, these soil properties must be obtained experimentally from the site.

V.4.2 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 the 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 the 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". At the present time, there is no explicit criteria, from an economical point of view, to select a satisfactory "Design Earthquake". In most cases, it is a matter of engineering and administrative judgement.

. 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 judgement. 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).

V.4.3 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 will be the design analysis to determine the adequacy of the trial design. the design analysis includes a seismic design criteria analysis [18] coupled with one of response analyses.

. 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 [18] is required to determine the reserve strength/ductility of buried pipes beyond normal non-seismic 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 criteria has been proposed [18].

. 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 output pipeline responses in more detailed and concise terms. However, the analysis requires more input such as joint and soil reistance characteristics, earthquake displacement-time function as well as some other physical piping parameters.

For large fault movement, the suggested nonlinear analysis shoud be used [17].

VI. PRE-EARTHQUAKE PREPARATION MEASURES

VI.1 Action Plans

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

1. Drawing/mapping-up the pipeline system including pumping stations and manholes.
2. Identifying regions of weak and liquefiable soils and slopes.
3. Identifying weak points, abnormal points and leaking points which were discovered by the ordinary maintenance work.
4. Identifying the points that need special attention and examination.
5. Establishing an information exchange network about the earthquake and/or earthquake disaster.
6. Preparing portable pumps for emergency use.

VI.2 Communication Between Related Organizations and Public

Under an earthquake emergency, it is necessary to exchange and communicate the disaster information with related organizations and the public during the damage survey, repair and restoration. The example of such communications are as follow:

- Police - To exchange information on dangerous regions
- Road Maintenance Office - To exchange information on unusual or damaged pavement subgrade and/or surface
- Gas utilities - To exchange information on damage points of the gas and oil pipeline system
- State, Region and Local Office - To discuss policy on priority of repair and restoration

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

VII. EMERGENCY DAMAGE SURVEY AND INSPECTION MEASURES

VII.1 Introductory Remarks

The survey and inspection of damage of water and sewer pipeline need special tools and are laborous. In order to carry out the servey and inspection efficiently, it is important to predict the types of possible damage caused by an earthquake. The features of damage learned from past earthquakes would help us to know the nature or scale of the damage and estimate the distribution of the damage area when the earthquake occurs.

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

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

VII.2 Check Points of Emergency Survey/Inspection

The purpose of the emergency survey/inspection is to prevent the expansion from a minor damage to a disaster. The main effort is to limit the effect of the damaged propagation to the surrounding facilities and the pipeline itself. Check points for emergency survey/inspection are suggested as follows:

1. Whether there are unusaul or abnormal sign of operations 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 are damages of conduits, manholes, etc.

6. Whether there is any deterioration of pumping capability.

VII.3 Emergency Repair and Restoration Measures

During and just after the earthquake, it is difficult sometimes to carry out all emergency measures because of insufficient man power and material. Therefore, it is necessary to decide the priority of the regions or the tasks that need emergency measures, 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 influences of the failures 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 influences 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 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

VII.4 Method of Damage Survey and Inspection

The selection of the survey/inspection method will be based on the following consideration:

. The importance and type of structure

. The investigation condition

. The applicability of the observation method

The survey/inspection method for buried pipelines can be classified into two types, namely: direct and indirect methods.

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 direct method is to examine the damage point by eye or by remote control camera. The available direct survey/inspection methods are listed below:

. Actual observation by eye

. Laser

. Radar

. Robotic inspection by a video, special water-proof camera, or rolling TV camera with a motor

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. The available indirect survey/inspection methods are listed below:

- Smoke test
- Added Water test
- Stopping Water test
- Flow-rate test
- Air Pressure test
- Water Quality test
- Relative Leakage test
- Infiltration in sewers by pumping water between manholes

In addition, when necessary the cleaning of the pipeline can serve as survey/inspection of damage.

VIII. COMPLETE REPAIR AND RESTORATION

VIII.1 Introductory Remarks

The purpose of complete repaired restoration is to rebuild water and sewer system to its original form.

The decision on a complete repair and restoration of a damaged system rests on the following considerations.

- The intensity and character of damage to pipes.
- The intensity and character of damage to manholes.
- The intensity and character of damage to inlets.
- Comparison of fuctional operations before and after the earthquake.
- The expected life and plan of usage of the facility.
- The expected life of the structures.
- Soil properties, ground water level and buried depth.
- Construction environment.
- Special characteristics of the stricken area.
- The effect on users.
- The effect on roads.
- The effect on surrounding facilities.
- Restoration method and its application.

VIII.2 Methods of Restoration and/or Repair

The repair/restoration works for water and sewer pipelines can be classified into three catagories, namely:

- Repair/Restoration to its original strength
- Repair of cracks to stop leakage

- Restoration of pipeline axis alignment.

The methods of repair/restoration for above three catagories are given separately below:

1. Methods of Repair/Restoration to Its Original Strength

   . Replacement of pipes

   . Reuse of old pipes

   . Adding concrete around pipe

   . Injection of epoxy

   . Welding of steel plate

   . Caulking

   . Encasement of pipe

2. Methods of Repair for Leakage

   . Caulking

   . Super joint glue

   . Sealing

   . Grouting chemically

   . Rubber band on outside surface of pipe

   . Rubber band on inside surface of pipe

   . Water stopping flexible joint

   . Replacement at bottom of pipe by special frame

   . Injection of epoxy

   . Encasement of pipe

   . Steel plate connection

3. Methods of Correcting Misalignment of Pipeline

   . Injection of epoxy

   . Grouting with cement

   . Replacement with new pipe

- Leveling techniques

IX. ISSUES ON RETROFITTING

Since a seismic design code for buried pipelines is not available at this time, existing pipelines, either sewer or water pipelines, are probably not designed for seismic resistance. Retrofitting of existing lines for seismic resistance is definitely one of the desires that the owner of the utility may wish to consider. However, retrofitting of existing water or sewer pipelines is a very expansive, if not impossible task. The difficulty lies in the facts that (1) most water and sewer lines are buried under congested streets and (2) so many lines are in need of retrofitting. The opening of a street for repair at an isolated location is very difficult and expensive, the opening of all street for retrofitting of all existing lines is out of question.

Other important facts are that (1) so many uncertianities, such as exact soil properties, seismic intensities, etc. are involved in a retrofitting project and (2) no effective retrofitting method has been yet developed. Therefore, retrofitting of all existing buried pipelines is not recommended by most experts in the lifeline earthquake engineering field.

What can one do at the present time to upgrade the existing system during routine maintenance or disaster repair works. Following items are to be considered.

- Replace current brittle pipe with more ductile pipe
- Replace current rigid joints with more flexible and/or restrained joints
- Replace current pipes that have been weakened by corrosion
- Repair cracks with strong epoxy

For an important project such as a nuclear power plant, retrofitting, repair and/or replacement of pipelines may be necessary. the methods are as follows:

- Add drainage around existing pipes at regions of possible soil liquefaction
- Injection of chemical (or epoxy) or cement into soil liquefaction region
- Drive piles at junction between pipeline and interconnected structures
- Densify soils surrounding the pipeline
- Add anchorage to pipeline.

X. SCIENTIFIC AND ENGINEERING INFORMATION NEEDS AND RECOMMENDATIONS

For the mitigation and/or prevention of an earthquake disaster, repair and/or restoration of earthquake damage as well as the development of an aseismic code for segmented and jointed pipelines, much scientific and engineering information are needed as list below:

. Understanding of Earthquake Damage Behavior

. Pre-earthquake Preparation

. Repair and Restoration Strategy During and After an Earthquake

. Development of Aseismic Design Code for New Systems

. Further Research

X.1. Understanding of Earthquake Damage Behavior

Session IV of this paper had given damage lessons learned from recent earthquakes in the United States, Japan and China. Some types of damage to be expected are now known. However, the influence of many parameters are known only qualititativley, such as soil resistance characteristics, joint resistance characteristics, etc. Detailed or quantitative information regarding these parameters will be needed. The effects of other geological parameters, ground strain variations, liquefaction potential, etc. are still relatively unknown. Therefore monitoring of pipeline damage should be continued. When possible, seismometers, strain and displacement gages should be implemented.

X.2 Pre-earthquake Preparation

In session VI, Pre-earthquake preparations and measures have been discussed. For this task, complete inventory and maps of pipeline systems should be prepared for emergency use. It is necessary to identify the most vulnerable regions for quick reference. It is also necessary to set-up communication networks in advance. Parametric studies of analytical response behavior will be helpful in identifying weak areas. In this respect, session V along with its reference should be reviewed.

X.3 Repair and Restoration Strategy During and After Earthquake

For efficiently repairing and/or restoring buried pipelines during and after the earthquake, effective repair and restoration strategies must be developed. The emergency survey and inspection measures have been presented in session VII. One must now then to assess various methods and their applicability to variuos conditions so that such methods can be implemented in the strategic plans. Session VIII discussed various methods of repair and restoration of buried lifelines and their related structures or facilities.

The strategic plan would be to identify the method, procedure and priority for repair and/or restoration under different intensities of an earthquake disaster. The manpower and materials or parts needed for the repair/

restoration should be estimated. The organization of the repair/restoration team and an inventory of material/parts should be prepared accordingly.

XI. ON-GOING AND RECOMMENDED FUTURE RESEARCH ACTIVITIES

As indicated earlier, a seismic code for buried pipeline has not been developed and there still are many uncertainties at this time. Research and development work is being diligently pursued in many countries, including the United States and Japan, by many researchers and engineers. The major topics of current and recommended research investigations are summarized below.

XI.1 Ground Motion Measurement

Seismic behavior of buried linear structures, such as pipes and tunnels, is strongly influenced by the relative displacement of the surrounding soil. This concept has been implemented in the design considerations for buried pipelines, but observation data on soil strain have been limited and fragmentary. Recently, several strong motion network arrays to study ground motion characteristics have been established around the world, particularly in Japan, United States and Taiwan.

Using the strong motion data recorded from the dense network arrays, the ground displacement/strains can be calculated. As a result, the correlation of ground strains with local seismological, geological and geotechnical conditions can be studied.

For the correlation between ground motion characteristics (ground displacement/strains) and the buried pipeline seismic behavior, the Institute of Industrial Science, University of Tokyo has implemented two L-shape buried pipelines at its Chiba Site Experimentation Station. Preliminary results have been obtained from several actual earthquake records. The field observation of buried pipeline reponse to actual earthquakes is a long term project.

Similar projects are being proposed by several investigators. Once the correlation between ground motion characteristics and the pipe responses in terms of local site conditions has been confirmed, the design of buried pipelines for seismic resistance would be more effective.

XI.2 Pipeline Under Soil Liquefaction Environment

There has been heavy damage to buried pipelines under soil liquefaction environment, particularly at the junction of heavy structures and pipelines, as observed and reported in Japan and in China. Although both analytical and experimental studies on the behavior of buried pipelines under soil liquefaction environment have been initiated, results obtained are only preliminary and limited.

The importance of the uplift and soil movement upon pipelines during liquefaction have been recognized. Analytical correlation and prediction of pipeline responses are of interest. Most of all, methods to mitigate damages and improve site environments are under development. Some of the on-going Japanese research activities on buried pipeline responses under soil liquefaction environment are listed below:

- Experimental study of buried pipeline including manhole by shaking table tests;

- Experimental study of improved measures for buried pipelines including manholes under soil liquefaction environment;

- Dynamic response study of buried pipelines including manholes under soil liquefaction environment.

To complement and/or supplement the Japanese investigation, similar research with common objectives but different scope and approach should be initiated and implemented under the U.S. - Japan Cooperative Research Program immediately. This task from the U.S. side may be done by one or more academic and/or research institutions. A budget of $300 K is estimated.

XI.3 Dynamic Soil Resistant Characteristics

The seismic response of buried pipelines is greatly influenced by the dynamic soil resistant characteristics. Without accurate information, the analytical prediction of the dynamic response behavior would not be accurate. Using inaccurate results, the design of buried lifelines will not be satisfactory. Therefore, the complete understanding of the dynamic soil resistant characteristics is necessary for development of a seismic design code for buried pipelines.

Under a seismic shaking environment, the dynamic axial soil resistant characteristics is most important. Under soil liquefaction environment, the dynamic lateral soil resistant characteristics is also important, because both uplift and lateral motion would become dominant under a liquefaction condition.

For a buried pipeline under large fault movement, the static axial and lateral soil resistant characteristics would be of interest. Because Japan has much new and sophisticated equipment, such as shaking tables with multiple degrees of freedom, reaction walls, etc, this task would probably be carried out by Japanese investigators, or under a US-Japan Joint Research Program using Japanese equipment. This task may be accomplished in two years with a budget of $200 K.

XI.4 Joint Resistant Characteristics

For segmented and jointed pipelines, joint resistant characteristics play a major role in the seismic resistance of pipelines. Currently, the conventional joints and seals have not been studied thoroughly for performance during an earthquake.

Futhermore, in order to allow larger displacement and to absorb more energy during seismic shaking, liquefaction and fault movement, new types of flexible-restrained joints should be developed. It is recommended that such development work will be carried out in the near future. The industries of pipe joints should be encouraged to cooperate in this task by contributing their pipe-joint specimens. The budget is about $150 K without including equipment and specimen costs.

XI.5 Development of Tentative Manual of Practice

While research is being carried out and/or proposed toward the development of a comprehensive seismic design code for buried segmented and jointed pipeline for future applications, it is necessary, in the mean time, to develop a tentative manual of practice for immediate application using current state of knowledge however. This manual should be refined continuously as new information or new knowledge is known.

The development of such manual of practice would be best done by a group of academic researchers and practicing engineers in the field. Currently, the Water and Sewerage Committee of the ASCE Technical Council on Lifeline Earthquake Engineering (TCLEE) which consists both academic researchers and practicing engineers, has initiated a proposal to undertake the task. It is recommended that funds be sought to sponsor the project. A budget of $150 K - 200 K is estimated.

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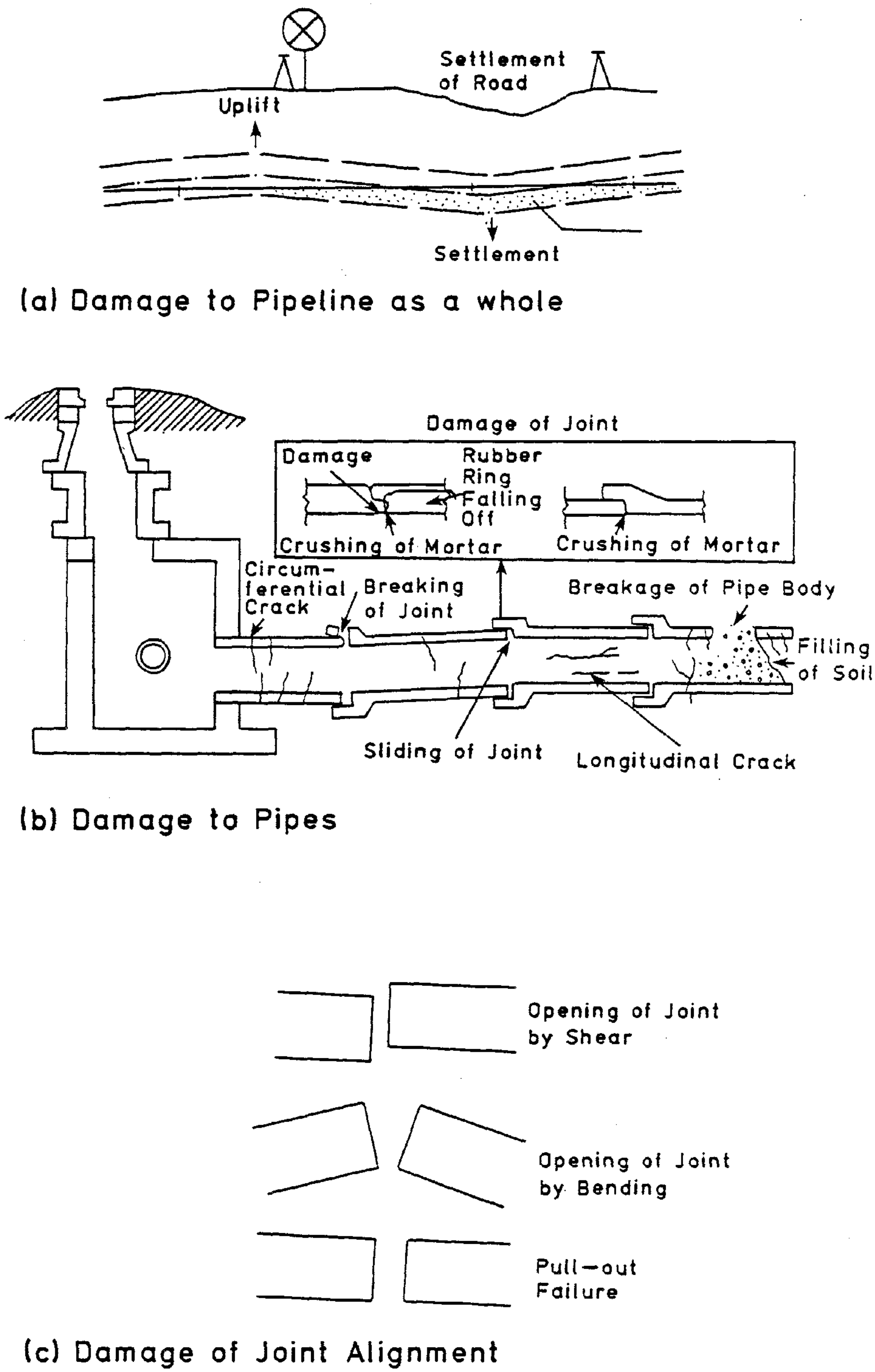

Figure 1 Seismic Damage to Segmented Pipelines

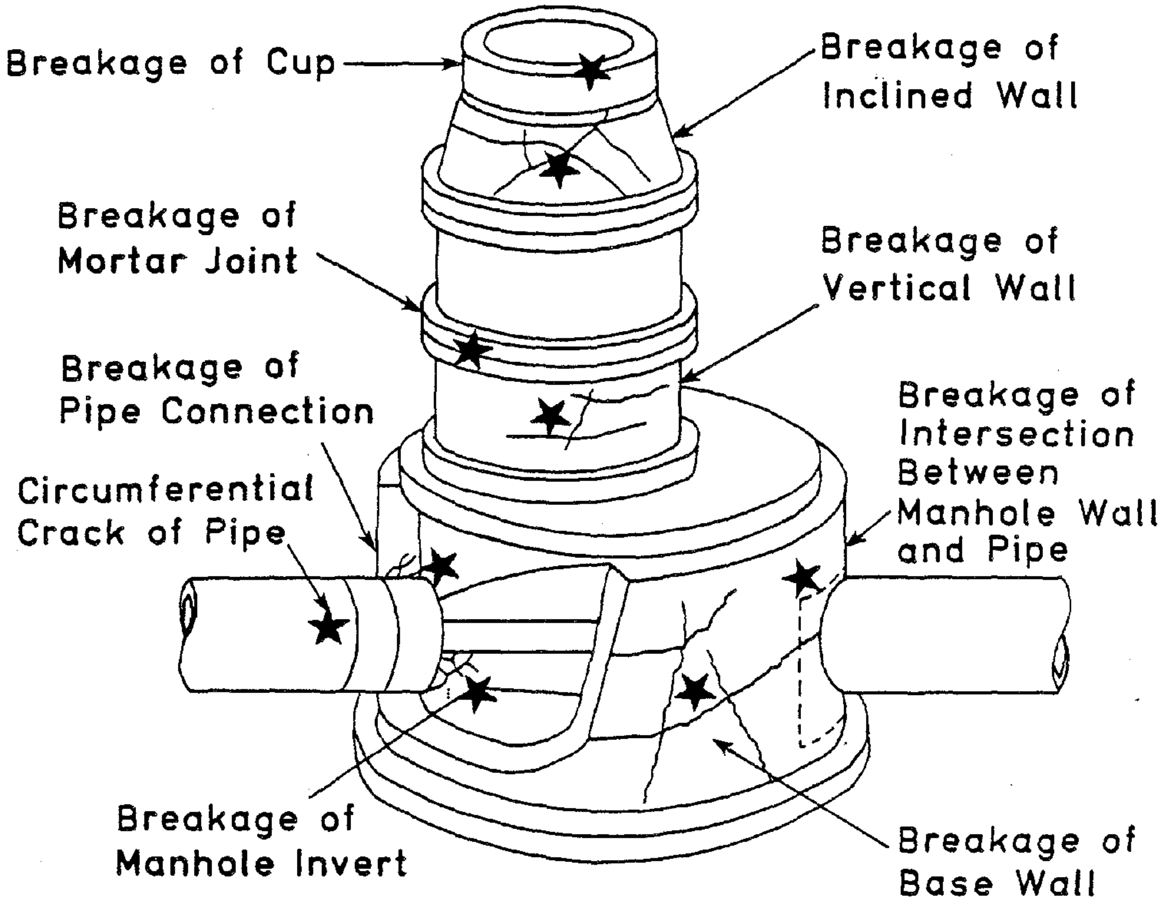

Figure 2 Seismic Damage to Manhole

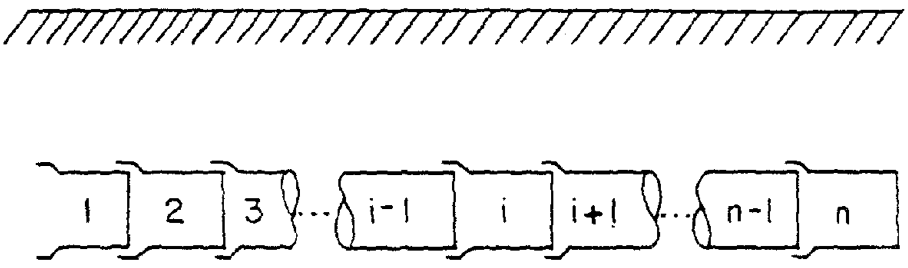

Figure 3. Schematic of a Buried Segmented Pipeline.

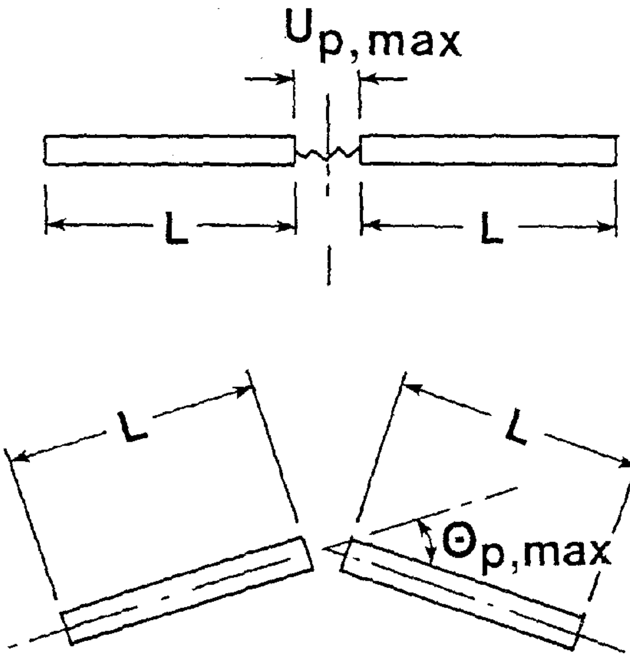

Figure 4. Maximum Relative Joint Displacement/Rotation of Segmented Pipeline.

Table 1 Extent of sewer pipe damage in Los Angeles

Pipe size and type of joint	Length of existing Pre-earthquake	Length to be recostructed	percent to be reconstructed	
	Lineal feet	Lineal feet	%	Ave
8-in. flexible	363,600	58,400	16.1	
8-in. rigid	90,600	30,900	34.1	23.9
8-in. encased	1,200	260	21.6	
10-in. flexible	23,800	4,000	16.8	
10-in. rigid	5,300	1,000	18.9	16.8
10-in. encased	270	40	14.8	
12-in. flexible	24,900	3,900	15.7	
12-in. rigid	9,700	2,800	28.8	32.5
12-in. encased	3,400	1,800	53.0	
15-in. flexible	13,900	3,500	25.2	
15-in. rigid	3,500	1,800	51.5	34.8
15-in. encased	3,600	1,000	27.8	
18-in. flexible	17,800	4,900	27.5	
18-in. rigid	8,000	6,100	76.3	60.2
18-in. encased	7,300	5,600	76.8	
Average flexible joint			20.3	
Rigid joint			41.9	
encased joint			38.8	

Table 2 Pertient data on water pipe in San Fernando water system

Type of pipe	Diameter	Total linear feet of pipe in system	Linear feet of pipe replaced	Percent of pipe replaced	
	Inches			%	Ave
Cast iron	4	10,450	....	-	
	6	145,789	12,037	8.3	
	8	48,620	2,265	4.6	9.1
	10	18,619	2,705	14.5	
	14	4,431	....	-	
Thin-walled riveted	6	4,870	2,235	45.9	
	8	7,530	720	9.6	
	10	6,779	1,320	19.5	25.0
	12	....	1,460	-	
	14	....	4,555	-	
Concrete-steel cylinder(SSP 381)	18	5,493	1,200	22.0	22.0
Standard steel .... casing	2 to 4	17,790	....	-	
	6	25,115	856	3.4	3.4
	8	8,260	....		
	10	2,600	....		
Average	6"			19.2	
	8"			7.1	
	10"			17.0	

Table 3 Effect of Ground Condition and Intensity to Seismic Damage of Water Pipelines As Shown by Haicheng Earthquake

Region	Intensity	Site Soil Type	Diameter of pipeline (mm)	Length of pipeline (km)	Number of damage places	Average ratios of the damaged pipes/km	Notes
Anshan City	7°	II	≥100	537.40	3	0.006	
Panshan Town	7°	III	≥100	25.90	35	1.60	
Yingkou City	8°	III	≥ 50	158.50	372	2.35	
Dashiqiao	9°	I,II	≥ 75	26.10	26	1.00	
Haicheng	9°	III	≥ 50	21.35	216	10.00	

Table 4 Seismic Damage Ratios (Breaks/km) of Pipe of Different Materials from Haicheng Earthquake

Material of Pipe		Steel		Cast Iron		Asbestos		Prestressed concrete
Kind of joint		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 Haicheng Earthquake

Diameter (mm)	75	100	150	200	250	300	350	400--700
The ratio	3.03	2.65	0.60	0.68	0.48	0.43	0.39	0.30

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

Location	Seismic intensity	Site Soil	Damage Ratio	Note
Tianjin	7--8	III	0.18	
Tang-gu	8	III	4.18	The site soil worse than that in Tianjin
Hangu	9	III	10.00	The site soil worse than that in Tang-gu
Tangshan	10--11	II	4.00	

Table 7 Seismic Damage of Pipes and Joints
Tangshan Earthquake

Diameter (mm)	The length of investigation (km)	Damage Ratio (breaks/km)			Total
		Pipe (Broken)	Joint (Pulled out)	Fitting (Damaged)	
a) Tangshan City					
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
Total	66.91	0.81	3.53	-	4.21
b) Tianjin City (Cast Iron Pipes)					
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
Total	79.31	1.71	1.70	0.77	4.18
Average		1.11	2.86	0.82	4.05

Table 8 Damage to Water Distribution Pipe in Sendai
Mixagi-ken-Oki Earthquake

Diameter of Pipe (mm)	Materiale of Pipe								Total		Breaks/km
	Ductile Cast Iron		Steel		Asbestos Cement		Polyvinyl Chloride				
	Length (km)	Breaks	Length (km)	Breaks	Length (km)	Breaks	Length (km)	Breaks	Length (km)	Breaks	
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		

Table 9 Summary of Damages to Sewer Systems from several Earthquakes in Japan.

Earthquake	Damaged Place	Intensity (JMA)	Damage to Sewer System: Pipeline	Damage to Sewer System: Pumping Station/Treatment Plant
Kanto Earthquake M=7.9 September 1, 1923	Tokyo	VI	A pipeline damaged near Yamanote and Shitamachi. Damage ration =250Breaks/180km =1.39Breaks/km, Damage to sewer is considered light as compared to other buried pipelines.	A treatment plant suffered light damage without effect to its operation.
Niigata Earthquake M=7.9 June 16,1964	Niigata City	V	Damage mostly by liquefaction, uplift, collision of manhole and pipe, pull-out of joint, cracks, 70% of 35km pipeline were mis-aligned.	Damage to sedimentation basin by liquefaction. Damage to pump cannal @ 11 out 15 locations by uplifting. 8 machines stopped. (damage most in structure)
Tokachioki Earthquake M=7.9 May 16,1968	Hakodate City	V	Because it was a reclaimed land, damage was by liquefaction (uplift of pipe)	No sewer system.
	Murorane City	IV	Within a length of 5.5km, 750m of pipe were settled under soft ground.	2 places of a pumping station had a slight damage.
Miyagi-Ken-Oki Earthquake M=7.4 June 12,1978	Sendai City	V	630m out of 690km sewer lines had slight damage without stopping flows.	9 out of 11 places of the main pumping station were stopped function because of out of electricity.
	Shiogama City	V	700m out of 27km pipeline suffered damage due to weak ground. (reclaimed land)	Machine stopped light damage to other.
Nihonkai-Chubu Earthquake M=7.7 May 26,1983	Akita City	V	Pipeline damage by soil liquefaction within entire length of 286km, 1.7km pipeline was reconstruction. Damage of manhole 93 places.	Damage by liquefaction. (uplift of sand basin or detritus tank)
	Noshiro City	V	Pipeline damage by soil liquefaction within entire length of about 60km. Reconstruction about 8km.	Treatment plant was under construction during the earthquake. No damage found in pumping station.

Table 10 Relationship Between Damage and Intensity

Type of Damage	Intensity of Japan Meteordogical Agency			
	IV (~81gal)	V (~250gal)		VI (~450gal)
a) Pipeline Damage without Liquefaction				
Joint	Sliding	Broken	Pull out	Pull out
Pipe Body	-	Crack/Broken	Broken	Severly broken
Pipeline Alignment	-	Misalignment	Separation	Separation
Junction	-	Broken	Broken	Broken
b) Pipeline Damage with Liquefaction				
Joint	Sliding	Broken	Pull out	Pull out
Pipe Body	-	Crack/Broken	Severly broken	Severly broken
Pipeline Alignment	Misalignment	Misalignment	Large separation	Large separation
Junction	-	Broken	Broken	Broken
Uplift of pipeline	-	-	Uplift	Uplift
c) Manhole Damage without Liquefaction				
Cup	Sliding		Broken	Broken
Inclined and Vertical Walls	Joint sliding	Crack	Broken	Broken
Bottom Wall and Base Plate	-	Crack	Broken	Broken
Invert	-	Crack	Broken	Broken
Soil Settlement	-	Slight settlement	Large settlement	Large settlement
Junction	-	Broken	Broken	Broken
d) Manhole Damage with Liquefaction				
Cup	Sliding	Broken	Broken	Broken
Inclined and Vertical Walls	Joint Sliding	Crack/Broken	Broken	Broken
Bottom Wall and Base Plate	Crack	Broken	Broken	Broken
Invert	Crack	Broken	Broken	Broken
Soil Settlement	Small settlement	Large settlement	Large settlement	Large settlement
[illegible]	Broken	Broken	Broken	Broken

APPENDIX

LIST OF TECHNICAL REPORTS ON LIFELINE EARTHQUAKE ENGINEERING

No. 1 Leon Ru-Liang Wang, "Design Considerations for Buried Pipelines Under Various Seismic Environments," June 1985.

No. 2 Leon Ru-Liang Wang, Shao-ping Sun and Shijie Shen, "Seismic Damage Behavior of Buried Lifeline Systems During Severe Earthquakes in U.S., China and other countries," December 1985.

No. 3 Leon Ru-Liang Wang and Eiichi Kuribayashi, "Action Plan for Reducing the Effects of Seismic Hazards to Segmented and Jointed Pipelines," October 1986.