Use of geotechnical information for pipeline system analyses

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Abstract: Lifeline systems are distributed spatially over large areas, and can encounter a range of seismic and geotechnical hazards. Lifeline systems relying on pipelines include: water, sewer, drainage, natural gas, and liquid fuels. Tectonic and geotechnical hazard mapping is used for pipeline system analysis. When the evaluation focuses on single pipelines, more detailed geotechnical analysis may be required to determine site-specific ground displacement estimates due to wave propagation and lateral spreading and soil/pipe interaction.

Parameters that are considered in pipeline system evaluation include:

- Tectonic movement
- Ground motion
- Liquefaction
- Lateral spread
- Landslide
- Differential settlement
- Lurching

Pipeline damage due to these geotechnical hazards can be estimated by using damage algorithms for different categories of pipe and types of hazards. Pipeline damage algorithms have been developed using both empirical data and analytical techniques. Families of damage algorithms take into account:

- Pipe material
- Joint type and restraint
- Geometry (diameter/length)
- Condition (weakening from corrosion)

The pipelines can be assessed using a scenario-based (for systems) or probabilistic-based (for individual pipelines) ground motions.

Site-specific analyses can be used when evaluating specific pipelines when under consideration for mitigation. For these situations, the focus is on permanent ground movement, soil pipe interaction, and resulting pipe strains and/or joint displacements.

Introduction

Tectonic and geologic earthquake hazards affect pipelines. This paper describes the background for the use of this hazard information to evaluate the vulnerability of pipelines when subjected to earthquakes. The discussion is presented from the perspective of the author, a lifeline earthquake engineer (LEE).

System and pipeline segment analysis applications

Pipeline system analyses may be conducted for different purposes requiring differing levels of detail and geotechnical input. Planning evaluations often include entire systems requiring basic hazard mapping. Pipeline segment analyses are sometimes conducted to assess the vulnerability of a particular pipeline, or for the design of a new pipeline, and require detailed liquefaction/lateral spread numerical analyses.

Analyses can be conducted for scenario-based ground motions or probabilistic ground motions. Use of scenario-based ground motions is preferred when evaluating entire systems. The scenario earthquake ground motion levels may meet or exceed probabilistic ground motion levels for a portion of the system, but drop off to levels for portions of the system more distant from the earthquake source. An analysis using probabilistic ground motions would tend to over estimate system damage for a single event.

For analysis of specific facilities or pipeline segments, probabilistic ground motions are preferred as they take into account a weighted average of ground motion contributions from all potential source zones, better representing the actual earthquake risk.

Earthquake hazards

Tectonic and geologic earthquake hazards are included in the list below. The various hazards may or may not be incorporated in the evaluation of any given pipeline system or pipeline segment depending on the tectonic/geologic setting and the level of detail included in the analysis.

- Tectonic movement, including surface faulting and uplift/subsidence.
- Ground motion considering attenuation and site amplification.
- Liquefaction considering susceptibility, probability of occurrence/areal extent.
- Liquefaction-induced permanent ground deformation (PGD)/lateral spread.
- Landslide considering susceptibility/probability for a given ground motion.
- Differential settlement.
- Lurching.

The use of the parameters quantifying these hazards is described in the following sections. Providing the information in geographic information (GIS) format allows the LEE to quickly relate the hazards to the pipe parameters.

Tectonic Movement

Tectonic movement includes the movement of the tectonic plates, or segments of the plates along a fault. The resulting released energy produces ground motions/shaking. The LEE wants to know the ground motions that will be occur on the average at selected intervals (such as 72 years, 475 years, 2,500 years). These return periods can be converted to probabilities of exceedance in, for example, 50 years (which are 50%, 10%, and 2% respectively). Alternatively the LEE may want to know the ground motion expected from a selected earthquake on a specified fault, a deterministic scenario. The selected fault will have also an associated return period between events. These ground motions will be used to estimate pipeline performance using damage algorithms, and to estimate liquefaction probability.

If a selected fault's offset reaches the surface during an earthquake, it can damage any intersecting pipelines. If the fault location is well known, the LEE will want to know the probability of the fault moving, the expected movement/offset, and the direction of the offset. The LEE may decide to design the pipe to accommodate the movement. Strike/slip fault traces are more regular than normal fault traces (Yeats, et al, 1997). Therefore, it may be easier to identify fault locations to install special pipeline crossings on strike-slip faults. Such is the case for pipelines crossing the Hayward Fault, a strike-slip fault in the San Francisco Bay area in California. Crustal faults in the northwest such as the South Whidbey Island Fault and the Seattle Fault are normal or reverse faults. These faults are "located" in fault zones that may be 4 to 10 km wide. It is unrealistic to design a pipeline to accommodate a fault offset over the width of the fault zone. Further, in moderate earthquake events on these faults, the offset may never reach the surface. In larger events, the offset may reach the surface, but not at location where it was expected.

Tectonic movement may also result in localized uplift/subsidence of blocks of ground, such as occurred in the San Fernando Valley in the Northridge Earthquake. There can also be horizontal strain induced in the ground due to tectonic movement. Horizontal strain can damage pipelines. Uplift or subsidence can potentially render a gravity pipeline non-functional if the grade is changed. It is unrealistic to predict tectonic movement away from the fault trace, and it is therefore typically not considered in pipeline vulnerability analyses.

Ground Motion

Earthquake body waves (P and S waves) carrying energy away from the fault result in shaking/ground motion. As the waves move further away from the source zone, their amplitude is attenuated. There are various attenuation relationships that have been developed for different types of tectonic structures. The frequency content of the energy also changes. For example, for subduction earthquakes, longer period wave ground motion is expected to reach the inland population centers such as Vancouver and Seattle.

Once the earthquake waves reach the bedrock beneath the site, they propagate upwards through the soil column forming surface waves. At sites where the rock or firm soil extends to the surface, there will be little change in the frequency or amplitude of the earthquake waves by the time they reach the surface. Conversely, where there is deep soft soil, the ground motions can be amplified by as much as 1.5 to 2 times, particularly at low to moderate ground motions. At higher levels, the ground motion may be deamplified.

The LEE wants to know the ground shaking intensity, and frequency content of the earthquake energy. Current thinking is that pipeline damage from shaking is most closely correlated to peak ground velocity (PGV) that better represents longer period waves. Much of the damage data has been collected, and pipeline damage algorithms developed using peak ground acceleration or Modified Mercalli Intensity. With the ground motion intensity, the LEE can estimate the unit failure rates for various pipe materials. Also, the ground motion intensity is used to estimate liquefaction probability.

Liquefaction

Pipeline unit failure rates in liquefiable areas are in the order of 10 times higher than for similar pipe in competent soil. Therefore, it is important to have a clear understanding of the probability that liquefaction will occur, and what the affects will be.

Liquefaction susceptibility is a measure of the soils propensity to liquefy. A number of parameters contribute the liquefaction susceptibility such as: soil density (as measured by blow count), grain size distribution, depth/overburden, and presence of groundwater. The age of the deposit may influence its susceptibility.

With a known susceptibility, the probability of liquefaction can then be calculated for a given ground motion intensity and duration. The probability of liquefaction increases as ground motion increases, and as the duration increases. A subduction earthquake with a long duration will result in more extensive liquefaction than earthquakes with a shorter duration with the same ground motion intensities.

The LEE wants to know the probability that liquefaction will occur. Specifically, the LEE would like to know the areal extent of liquefaction expected for a given ground motion. We first used the concept of areal extent in an evaluation of the Everett, Washington water and sewer system (Ballantyne, 1991). The areal extent is the percentage of the area that will liquefy that will result in some surface expression. Much of the empirical pipeline damage data that has been gathered is categorized as being in or not in a liquefiable area. Being in a liquefiable area is implied if there was evidence of liquefaction on the surface such as sand boils or cracks from lateral spreading. If there was liquefaction at depth, with no evidence on the surface, the person gathering data would have assumed that liquefaction had not occurred. Estimates of the areal extent can vary dramatically. The estimate of the number of pipelines failures is directly proportional to the areal extent. Unfortunately, there is limited empirical data available to resolve this issue.

Lateral Spreading

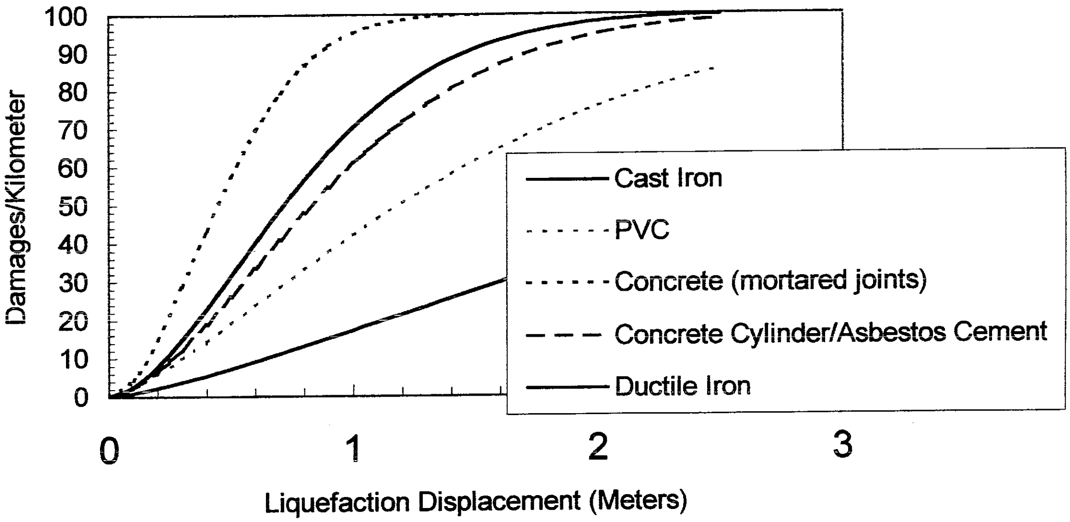
If liquefaction does occur, the LEE would like to know the net permanent ground deformation (PGD). For detailed analyses, the coefficient of friction between the soils and pipe is also required. Liquefaction by itself does not damage pressure pipelines. (Gravity sewer mains will float.) But when the soil liquefies, it is likely to move. It can consolidate, move laterally (lateral spread), displace vertically (such as occurs in sand boils), and even "slosh" within a basin. If the ground surface is flat, the liquefied soil may not move laterally. It can consolidate. With only a slight gradient as little as two percent, lateral spreading may be initiated. If lateral spreading does occur, the usual displacements would be in the order of 3 to 4 times the vertical displacements due to consolidation. Therefore, lateral spreading is more important than the vertical displacement.

A typical "shallow" pipeline installation with four feet of cover would often put the pipe in the non-liquefied layer, above the liquefiable layer. "Deep" pipe installations such as sewers are more likely to be directly in the liquefiable layer. In 1990, we first confronted the issue of estimating losses to pipelines in liquefiable soils, in a project for the City and County of San Francisco (Harding Lawson, 1991). After the Loma Prieta Earthquake, where there was significant liquefaction-related pipeline damage in the Marina District, San Francisco wanted to know what to expect if in the event of the recurrence of a 1906 San Andreas Fault event (1906 San Francisco Earthquake). They hired a team of consulting engineers including this author. The geotechnical team members were estimating PGD. It was clear that the "shallow" pipeline damage would occur at the ground cracks, but we would not know where or how many cracks there would be.

Ultimately, we decided to use PGD as a proxy for liquefaction-related pipeline damage. We considered using ground strain, but could not get estimates of strain from the geotechnical team members. Further, strain would not be evenly distributed along the pipe, so we could not have used it to directly analyze the pipeline's structural response. Once we decided on using PGD, we identified empirical data sources where pipeline damage rates and ground deformation information was available. To develop the damage algorithms, we used empirical damage data from San Fernando, 1971 for pipe damage in the fault zone (Eguchi, 1982), Noshiro, Japan, 1983 (Miyajima, 1989), San Francisco Marina District, 1989 (T. O'Rourke), and Santa Cruz, 1989, (Ballantyne). Typical damage algorithms for PGD are shown in Figure 1 (Heubach, 1996)

Both U.S. and Japanese researchers have pursued methods to estimate PGD. Youd and Perkins (1987) developed the Liquefaction Susceptibility Index (LSI) a measure of PGD. The LSI is a function of the earthquake shaking intensity and parameters used to calculate the liquefaction susceptibility. Bartlett and Youd subsequently developed the Multiple Linear Regression analysis (MLR) that also took into account the thickness of the liquefiable layer and the ground slope or proximity to a free face

Fig. 1. PGD Damage Algorithms



(Youd, 1999). The MLR has been widely used as an input to estimate pipeline damage. The MLR controlling parameter is grain size distribution, with lesser influence from slope/free face proximity, and liquefaction layer thickness. Unfortunately, for system-wide modeling studies, grain size distribution data is not normally readily available. Slope and proximity information can be developed using digital elevation data in geographical information systems. HAZUS, an earthquake loss-modeling program developed with FEMA funding in the United States, relies on the LSI.

Further evaluation by M. O'Rourke (1995) has concluded that for continuous pipe, PGD is less significant, but block size (pipe burial length) is critical. Significant longitudinal loading on the pipe cannot be developed in small blocks of soil. D. Honegger (1994) went on to develop estimates of soil block size using vector mapping of ground displacement developed by the Japanese for the 1964 Niigata Earthquake. For site-specific analyses, the MLR is not adequate. It only provides guidance on general expected displacements. Finite element analyses have been used to estimate PGDs and model the soil-pipe interaction using soil spring-slip relationships.

Landslide

The LEE is interested in the probability of landslide occurrence for a given ground motion. The landslide characteristics are important including:

- Width - can the pipeline span the landslide?
- Depth – will it pass above the buried pipeline?
- Displacement -if it is less than one to two meters, the pipeline could potentially accommodate the displacement.
- Coefficient of friction between the pipe and soil (for detailed studies).

Historically, documented damage from earthquake-induced landslides has caused less damage than liquefaction, particularly for water and sewer systems. This may be because flat areas have historically been developed before areas with steep terrain. Many of these areas are liquefiable. Generally, landslide hazard mapping has used geologic maps to categorize formations. Each category is then evaluated on is own characteristics, the topography/slope, presence of groundwater, and historic and geomorphologic evidence of landslides. In most cases, if a landslide occurs, it will cause the pipeline to fail.

Where cohesive soils exist, there is a possibility that landslides will creep rather than fail catastrophically, slowly displacing the buried pipeline. Segmented pipelines will simply pull apart, but continuous pipelines have some ability to ductily deform before they fail. In these cases site-specific analyses can be beneficial to estimate slide deformation rates.

Landslide incidents, including earthquake-induced landslides, can be influenced by rainfall. The expected earthquake-induced landslide rate can be seasonally dependent.

Differential Settlement

Poorly consolidated non-cohesive soils can consolidate when subjected to earthquake shaking. If the soils are below the groundwater table, the consolidation can lead to liquefaction. If the soils are above the groundwater table, settlement can occur. Differential settlement can result in pipeline failure. For regional planning studies, this type of failure would be expected to be included in the damage algorithms for damage to ground motion/shaking. For site-specific evaluations, this information is used for the design of flexible pipe connections that might be used at building foundation interfaces.

Lurching

Lurching is understood to mean localized ground cracking. It could result from the affects of strong ground motion on unstable blocks of soil where liquefaction does not take place. Lurching is difficult to predict. The LEE would include the affects of lurching in the pipeline damage algorithms for ground motion.

Alternate methods to estimate pipeline damage

Twenty-five years ago, Katayama (1975) introduced a pipeline damage algorithm relating PGA and pipeline repairs. It included a range of soil conditions from Niigata, 1964 (poor) to Fukui, 1948 (good). This “old” approach could accommodate the deficiencies of the current method that segregates ground motion and liquefaction pipeline damage. There are many pipeline failures that occur in a gray area where liquefaction is not clearly identified but may have occurred. Not until the early 1980’s did Eguchi develop separate damage algorithms for ground motion and liquefaction (Eguchi, 1982).

Researchers have not clearly segregated pipeline damage between ground motion and liquefaction affects for the Loma Prieta, Kobe and Northridge earthquakes. For example, for Kobe, Professor S. Takada showed the relationship of pipeline damage to fault proximity. For the Northridge Earthquake, T. O’Rourke (1998) showed the relationship between non-liquefaction induced ground strain and pipeline damage. In the Loma Prieta Earthquake, Pease (1997) showed the affects of transient movement of liquefied material in a basin, and the significant pipeline damage at the basin interface. These alternate methods may offer clearer insights into pipe damage from earthquakes.

Pipeline vulnerability

The earthquake hazard information discussed above can be combined with pipeline vulnerability information to estimate pipeline losses. The parameters that affect pipeline vulnerability include:

- Pipe material – brittle/ductile
- Joint type and restraint
- Geometry (diameter/length)
- Condition (weakening from corrosion)

Pipe earthquake vulnerability can be ranked as shown in Table 1 (Ballantyne, 1995):

System evaluation

The expected damage rate for each pipeline segment can then be estimated. The pipeline system, including the attributes of each pipeline, is laid over the tectonic and geotechnical hazard map layers using GIS. The GIS then identifies which hazard zones each pipeline segment is in, and calculates the expected unit failure rate from the damage algorithm for the pipe type (see Figure 1). The number of failures is then calculated by multiplying the failure rate times the pipe segment length.

The number of failures can be summed for the entire system, different hazard zones, different service areas, or other selected areas. The failure rates can also be shown graphically in on GIS using selected colors.

Depending on the owners needs, the system can further evaluated. This analysis can be performed using HAZUS, a loss estimation software product developed with funding from FEMA, or in greater detail using SAFENET, a proprietary software program developed by EQE. The pipeline damage states can be evaluated using a Monte Carlo analysis. The vulnerability of each pipe is represented by a probabilistic distribution of its expected failure. The system is evaluated by multiplying the probability of failure times a randomly generated number. The result is similar to the deterministic analysis previously described, but identifies the potential of low probability failures that may have catastrophic impacts on the system. The Monte Carlo analysis is run many times to get a distribution of damage state results.

Table 1
Relative Earthquake Vulnerability of Water Pipelines

Material Type/Diameter	AWWA Standard	Joint Type	Ruggedness	Bending	Joint Flexibility	Restraint	Total
Low Vulnerability							
Ductile Iron	C1xx Series	B&S, RG, R	5	5	4	4	18
Polyethylene	C906	Fused	4	5	5	5	19
Steel	C2xx Series	Arc Welded	5	5	4	5	19
Steel	None	Riveted	5	5	4	4	18
Steel	C2xx Series	B&S, RG, R	5	5	4	4	18
Low/Moderate Vulnerability							
Concrete Cylinder	C300, C303	B&S, R	3	4	4	3	14
Ductile Iron	C1XX Series	B&S, RG, UR	5	5	4	1	15
PVC	C900, C905	B&S, R	3	3	4	3	13
Steel	C2xx	B&S, RG, UR	5	5	4	1	15
Moderate Vulnerability							
AC > 8" D	C4xx Series	Coupled	2	4	5	1	12
Cast Iron > 8" D	None	B&S, RG	2	4	4	1	11
PVC	C900, C905	B&S, UR	3	3	4	1	11
Concrete Cylinder	C300, C303	B&S, UR	3	4	4	1	12
Moderate/High Vulnerability							
AC <=8" D	C4xx Series	Coupled	2	1	5	1	9
Cast Iron <= 8" D	None	B&S, RG	2	1	4	1	8
Steel	None	Gas Welded	3	3	1	2	9
High Vulnerability							
Cast Iron	None	B&S, Rigid	2	2	1	1	6

Includes ranking range from 1 – poor, to 5 – excellent.
B&S–Bell & Spigot, RG–Rubber Gasket, R–restrained, U-unrestrained

Using the results from each Monte Carlo analysis, the system can be evaluated using a hydraulic network analysis. The analysis first identifies which pipelines have failed, disconnects the system at those locations, and adds a hydraulic demand to represent leakage. The network analysis then proceeds, calculating the flows and pressures in each pipe and each node, respectively. The program has a special routine that removes sections of the system that have developed negative pressures in the model. This analysis is run for each of the system damage states estimated by the Monte Carlo analysis. The program output includes the damage index for each area of the system, and a serviceability index for selected nodes in the system. The serviceability index is an estimate of the flow that will be provided following an earthquake divided by the flow provided prior to the earthquake.

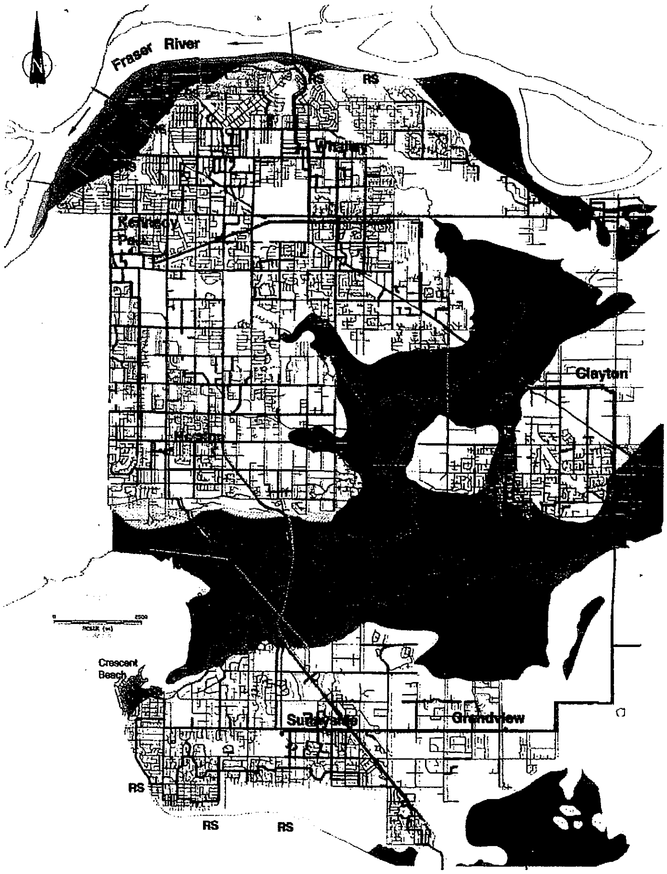
Pipelines that are the most vulnerable and represent the highest risk to the system if they fail can be quickly identified. Pipeline replacement alternatives can be tested to see which ones will most improve the system performance.

Examples

Two examples are presented. The first demonstrates the use of GIS to evaluate a pipeline system. The second shows a site specific analysis of large diameter yard piping that may be subjected to significant PGDs.

The City of Surrey retained the consulting team of KWL, EQE, and Golder to evaluate the seismic vulnerability of their water distribution system. Golder developed liquefaction/lateral spread hazard mapping for the city. EQE provided technical direction to KWL to estimate the pipeline damage from two levels of earthquakes. The most significant damage was found to be in the liquefiable areas of the city. A map showing the Surrey pipeline distribution system overlaid in the PGD for a 475-year event is shown in Figure 2.

Fig. 2. City of Surrey, B.C., Water Distribution System Overlaid on Liquefaction Induced PGD for 475-year Return Earthquake



The second example is for a site-specific analysis. A pump station with large diameter buried site piping is expected to be subjected to PGDs as large as 50 cm in a 475-year return earthquake (Fig. 3). The project geotechnical consultant used FLAC to develop the PGDs shown. The yard piping is concrete cylinder pipe with welded joints. It was analyzed to determine how much movement it could accommodate. The concrete cylinder pipe with welded joints results in a rigid system so it has limited capacity to accommodate PGD. Installation of flexible connections at the locations identified in Figure 3 was evaluated to mitigate its vulnerability along with a soil improvement alternative to limit PGD. Ultimately soil improvement was selected.

Design

The considerations used to evaluate existing pipe can be applied to design of new installations. We believe that most pipe types that are currently being installed can accommodate wave propagation.

Designing pipe to accommodate liquefaction and lateral spread is more of an issue. Use of low vulnerability pipe is recommended (see Table 1). Use of butt-welded steel pipe is preferred over welded steel bell and spigot pipe joints. Large diameter steel pipe can develop large bending stresses so great caution is recommended during design. The preferred design in liquefiable soils is to use a straight pipe with no bends or connections in the liquefiable zone and up to 500 meters on either side of the liquefiable zone. Unfortunately, straight pipe with no connections is unrealistic in distribution systems. It is also preferred to encase the pipe in a polyethylene wrap to minimize the coefficient of friction allowing the pipe to slide though the soil and distribute the induced strain.

Gravity sewers tend to float in liquefiable soils. Securing them in place with piles or auger pipe anchors may reduce their vulnerability. Stabilizing the soils along the entire pipe alignment is the most effective, but also very expensive.

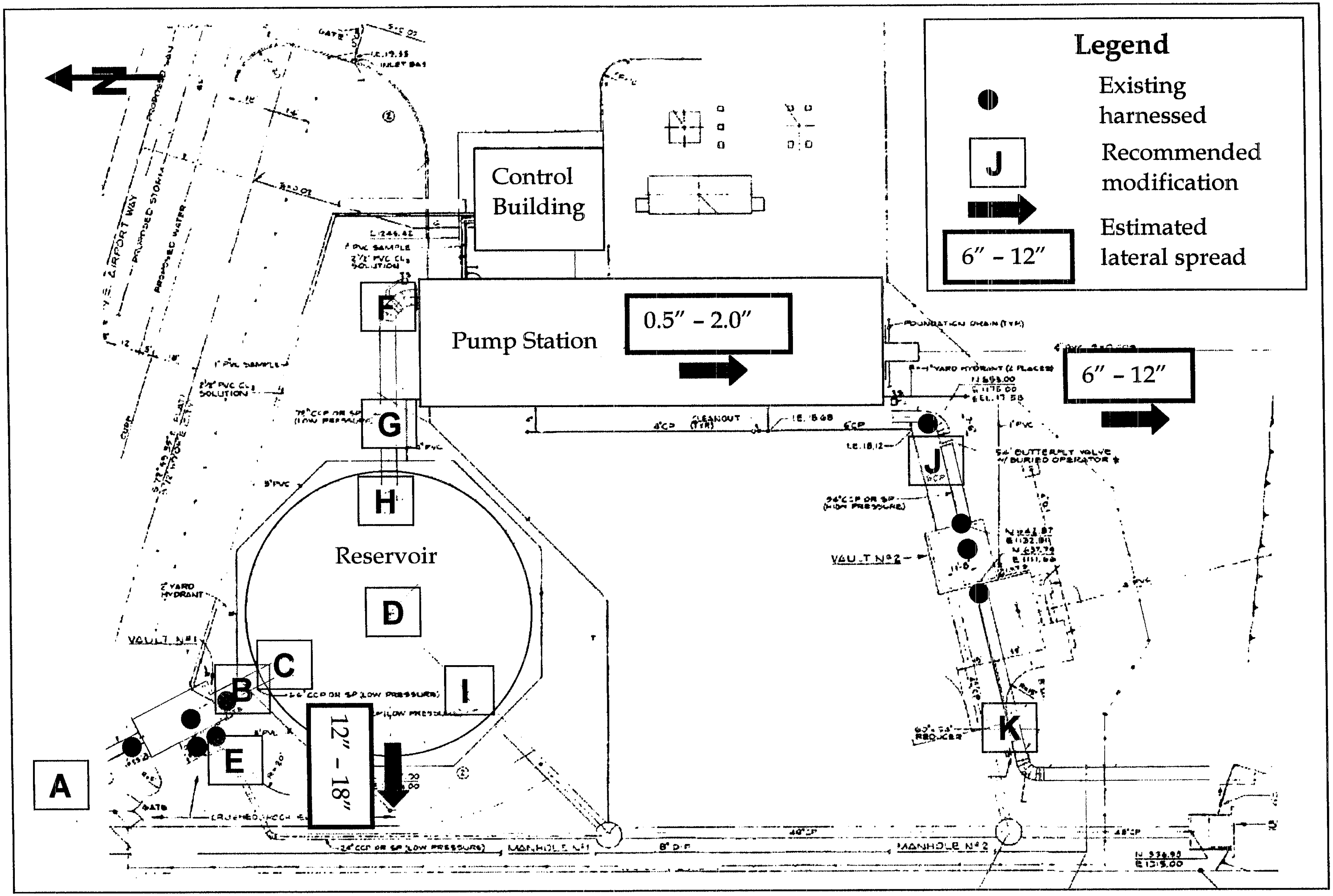
Conclusions

Ground motion and liquefaction/lateral spread (PGD) are the most significant geotechnical parameters affecting pipeline performance in earthquakes.

Damage estimates can be used for emergency response planning and developing mitigation programs. Unfortunately, loss estimation techniques rely on damage algorithms with significant levels of uncertainty.

Other earthquake hazards/failure mechanisms are included in empirical data and damage algorithms for ground motion and PGD.

Fig. 3. Pump station/large diameter buried site piping subject to PGDs.



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