CHANGING NEEDS FOR HAZARD INFORMATION FOR PIPELINE LOSS ESTIMATION

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ABSTRACT

Continued development of pipeline loss estimation methods requires different types of permanent ground deformation, PGD, hazard information This paper briefly summarizes methods for pipe loss models used over the past 20 years considering wave passage and liquefaction susceptibility Current trends in loss modeling are explored such as.

- PGD net displacement for segmented pipelines (Harding Lawson, 1991)
- Soil block dimension influence on vulnerability (M O'Rourke, 1992)
- Methodology to define areal extent of PGD

The need for PGD information associated with non-lateral spread and non-tectonic related ground movement is explored as evidenced by an estimated 1500 pipeline failures in the Northridge earthquake with almost no liquefaction and no surficial fault expression

INTRODUCTION

Continued development of pipeline earthquake loss estimation methodologies is important, loss estimation is a useful tool in assessing the risk of pipeline system failure in earthquakes, developing earthquake mitigation programs, and developing emergency response programs

This paper briefly reviews pipeline earthquake loss estimating methods used over the past 20 years It then presents a proposal for a methodology for earthquake pipeline loss estimation associated with liquefaction induced lateral spreading. Finally, the proposed methodology is discussed, and the future direction of pipeline earthquake loss modeling is posed

One of the objectives of having such a methodology available is for use in regional loss studies With that in mind, it is important to minimize the required number of parameters required to achieve a meaningful result The methodology proposed herein tries to limit the number of those variables

This proposed methodology has been developed working with the Fragility Task Committee of the American Society of Civil Engineers Technical Council on Lifeline Earthquake Engineering The objective of the committee is to establish a methodology for earthquake loss modeling of lifelines Once an approach is established, it will provide a format for acquisition of earthquake damage data from future earthquakes The methodology is designed to upgrade its components as new information is developed Comments on the methodology from participants of this workshop are welcome.

OVERVIEW OF PIPELINE LOSS ESTIMATION

This section discusses the development of pipeline earthquake loss estimation as well as methods used to estimate PGD in support of pipeline loss estimation Empirically based water pipeline damage algorithms reviewed in this paper were initiated in Japan and refined in both the United States and Japan as described below

Katayama

A pipeline earthquake loss estimation methodology was introduced by Professor Katayama in the mid-1970s He developed pipeline damage algorithms relating pipe failures and earthquake peak ground acceleration His damage algorithm included an envelope of loss estimates depending on the soil response characteristics, including liquefaction (Katayama, 1975)

Eguchi

Pipeline damage from wave passage, fault rupture, and liquefaction was segregated by Eguchi in the early 1980s He gathered empirical damage data from over 20 earthquakes worldwide, but was able to develop the most significant relationships based on damage data from the 1971 Sylmar Earthquake (Eguchi, 1982) For that earthquake, he related earthquake intensity to cast iron pipeline failures from wave passage for a range of Modified Mercalli Intensities He then related damage rates for other pipe materials to cast iron for one intensity, establishing a family of damage algorithms For that same earthquake, he also developed pipeline damage rates for liquefaction conditions for a family of pipe materials, but did not relate them to permanent ground deformation from liquefaction Finally, he developed damage rates based on proximity-to/displacement-of the fault offset.

Ballantyne

In the late 1980s, Ballantyne segregated pipeline damage into pipeline breaks and pipeline leaks (Ballantyne, 1990) This information became valuable for use in deterministic post-earthquake water system hydraulic modeling As part of the same study, the question of areal extent of liquefaction along a pipeline corridor or in a microzone had a very significant effect on loss estimation results It became clear to this author in that study that permanent ground deformation pipeline damage would often control the overall system performance, and that pipeline unit damage rates for liquefaction/permanent ground deformation were an order of magnitude greater than for wave passage

Youd, Perkins, and Bartlett; LSI and MLR

In 1987, Youd and Perkins published the Liquefaction Severity Index, LSI, approach to estimate the maximum permanent ground deformation at a given site for a particular earthquake scenario Initially, this information was not applied as a pipeline damage estimation tool (Youd, 1987). More recently, Bartlett and Youd have refined the LSI method with the Multiple Linear Regression analysis method, MLR, for estimating maximum permanent ground deformation from liquefaction related lateral spreading (Bartlett, 1992)

M. O'Rourke

In 1992, M O'Rourke identified the significance of lateral spread block geometry on the extent of continuous (welded steel) pipeline vulnerability (O'Rourke, 1992) A major problem related to this approach was being able to estimate the block size/ground breakup pattern

San Francisco Liquefaction Study

Following the 1989 Loma Prieta Earthquake, the City and County of San Francisco selected a project team to estimate utility losses that might occur in liquefiable soil areas around the periphery of the city for a magnitude 8 3 San Andreas Earthquake (Harding Lawson, 1992). The project team developed damage algorithms relating pipeline damage to permanent ground deformation using empirical damage data from the 1971 Sylmar Earthquake, the 1989 Loma Prieta Earthquake (including the San Francisco Marina District and the City of Santa Cruz data), and the 1983 Nihonkai Chubu, Japan Earthquake It was found to be very difficult to find damage data that included a record of permanent ground deformation

The San Francisco project team geotechnical engineers used Tohata's (1990) method to estimate the extent of lateral permanent ground deformation. The assumption was made that the entire soft soil area would liquefy considering the soil properties, large peak ground accelerations, and long duration. This permanent ground deformation displacement and areal extent information was then passed along to the earthquake lifeline pipeline project team members for use in estimating pipeline damage

Further Loss Studies

The San Francisco project had an extensive geologic data set available, and a significant budget for analysis. Pipeline earthquake loss estimation projects for the Greater Vancouver Regional District in Vancouver, British Columbia (Kennedy/Jenks Consultants, 1993), and the Portland Bureau of Environmental Services, Portland Oregon, (Dames & Moore, 1994) made pipeline loss estimates using the LSI to estimate permanent ground deformation. In both cases the project team geotechnical engineers were asked to make estimates on the areal extent of liquefaction and a mean permanent ground deformation In this author's opinion there was a significant level of uncertainty associated with those estimates because of the lack of available methods The areal extent of liquefaction estimate is directly related to the damage estimate, so the degree of certainty is very important

LIQUEFACTION AREAL EXTENT METHODOLOGY

Introduction

This section presents a methodology for estimating pipeline losses from permanent ground deformation It includes consideration for estimating liquefaction susceptibility, probability, and areal extent, and applies that information to pipeline loss estimation

Liquefaction Susceptibility

This reduced set of variables has been selected so that the methodology is applicable to conduct regional loss studies First, establish three levels of liquefaction susceptibility· none/low, medium, and high From a loss estimation perspective, none/low can be ignored, and medium usually ignored as it typically only represents less than 1 percent of estimated losses In general, liquefaction susceptibility would take into account (criteria in parenthesis for high susceptibility) groundwater table depth (< 12 feet below grade), blow count N_1 (< 12), and depth to liquefiable deposit (< 25 feet below grade)

Liquefaction Probability and Magnitude Scaling Factor

The curves shown in Figure 1 define the probability of liquefaction, P_L, as a function of peak ground acceleration, PGA These curves are defined as the probability of liquefaction occurring at a point in a soil mass in controlled field test conditions.

A family of curves are proposed for a range of earthquake magnitudes Ultimately, separate curves would be required for a range of soils such as clean sands, silty sands, etc These curves could likely be developed from existing information such as Liao (1986) The PGA scale has been purposely not provided These curves show the form expected in a finalized methodology. Additional curves can be added for earthquakes of other magnitudes These curves are included to address the magnitude scaling factor, to compensate for the duration/number of earthquake cycles for earthquakes of varying magnitude

Liquefaction Areal Extent

Apply a factor to estimate areal extent of liquefaction, P_{AE}, from probability of liquefaction (above) as defined in equation 2, below P_{AE} is the conditional probability that an arbitrary surface location will exhibit liquefaction below grade

$$P_{AE} = A_L / A_T \qquad (1)$$

where

> A_L = Area of liquefaction where it is evident that liquefaction has occurred by field observation such as where sand boils appear, or ground has subsided or moved laterally as evidenced by cracking
>
> A_T = Total area with same susceptibility to liquefaction (low, moderate, or high as defined above), subjected to the same approximate PGA

It is the intent that this correction takes the probability of liquefaction developed for a volume of soil in a controlled condition and corrects it to estimate the areal extent of liquefaction occurring in an earthquake The occurrence of liquefaction is defined as identified by field observation, as that is the basis on which most pipeline damage data has been generated Field identification can include evidence of sand being ejected from below the surface and/or ground cracking from vertical and/or horizontal permanent ground deformation The person making the field observations is expected to understand the liquefaction phenomena, and be aware of local ground water conditions

The curve is expected to take the general form shown in Figure 2 Surface expression of liquefaction is expected to be influenced by the thickness of the layer of liquefiable (and liquefied) material Other conditions may also have an effect such as variability of the liquefiable deposit The final curve should reflect as many variables as applicable

Maximum Permanent Ground Deformation

Apply the Liquefaction Severity Index methodology, LSI, to estimate the maximum PGDs within the study area Correct the LSI for slope or proximity to a free face If there is adequate information, apply the Multiple Linear Regression, MLR, analysis technique to estimate the maximum permanent ground deformation, PGD (note that it is suggested only to correct LSI for slope/free face proximity, and not subsurface data because slope/free face proximity information is more readily available in GIS format).

Map the mean permanent ground deformation, PGD_m (one-half times the maximum PGD as a starting point) based on the LSI or the MLR.

Pipe Parameters and Permanent Ground Deformation Pipe Exposure

Measure the pipe length, L_P, of each pipe type category (defined by material and joint type) within each area with a defined range of PGD_m (such as 0-1 inch, 1-5 inches, etc.) Note that pipe type category may include more than one type of pipe, but they would all be expected to respond similarly in an earthquake

Pipeline Damage Algorithms

Read the failure rate for the average of the range of PGD_m for each pipe type using the appropriate pipe damage algorithm, presented in terms of percent of length requiring replacement P_R(as a function of PGD), or failures per km F_K(as a function of PGD) Typical pipe damage algorithms are shown in Figures 3 and 4

Pipeline Repair / Replacement

Calculate the pipe length to be replaced

$$P_{AE} \times L_P \times P_R = \text{Pipe Length to be Replaced} \qquad (2)$$

for each PGD_m range/pipe type category for each range of PGD Alternatively, calculate the total number of expected pipe failures

$P_{AE} \times L_P \times F_K$ = Expected Pipe Failures (3)

for each PGD_m/pipe type category

Further Corrections

Provide further corrections for: 1) pattern of liquefaction deformation, 2) pipe orientation to PGD, 3) corrosion condition/maintenance history, 4) number of connections/unit length, and 5) for welded steel pipe, wall thickness/pipe radius

DISCUSSION AND UNRESOLVED ISSUES

This proposed methodology identifies two concepts that will have to be developed with time, areal extent of liquefaction, and mean PGD (PGD_m) As it is defined, areal extent of liquefaction would have to be developed using empirical field data gathered following earthquakes, in conjunction with liquefaction hazard maps for the same area that have defined liquefaction susceptibility relationships.

PGD_m is selected as being representative of the PGD which is seen by pipelines in the immediate area Trying to develop a density function for the distribution of PGD, using the LSI as a maximum, was not thought to be useful due to the uncertainties associated with the density function as well as the pipeline damage algorithm itself. Using one-half the PGD is considered only a starting point

It is apparent that pipeline damage associated with liquefaction is not only related to PGD, but to the breakage pattern and size of soil blocks that develop when lateral spreading occurs Methods are needed to enable lifeline earthquake engineers to estimate soil block patterns, and then to relate pipeline damage to those patterns Other parameters will also affect pipe strain as it is related to soil block patterns and movement including the coefficient of friction between the soil and pipe

Ultimately, we may have to revert back to the generalized damage pipeline damage estimation approach originally proposed by Katayama It is very difficult to be able to clearly define soil parameters/sources of permanent ground deformation along every length of pipeline We currently have techniques to quantify liquefaction/lateral spread, landslide, and fault displacement-associated PGDs There are two examples where mapping of these hazards have failed First, in the study of the Seattle water system (Ballantyne, 1990), there were a number of clusters of pipeline failures following the 1949 and 1965 Seattle earthquakes in areas that today are mapped as competent glacial deposits Based on evaluation of leak repair records, it is likely that there was localized liquefaction in those areas resulting in some PGD and pipeline failure There was no reported indication of liquefaction on the surface

Second, the Northridge Earthquake There was significant surface cracking throughout the San Fernando Valley There were in the order of 700 transmission and distribution pipeline failures in the valley (as well as an equal number of service failures) However there was only limited liquefaction reported, and not widely distributed While there has not been a decisive report, there have been discussions that the cracking is of tectonic origin. As a lifeline earthquake engineer, it will be very difficult to estimate the extent of surface cracking for any given earthquake scenario.

POST-EARTHQUAKE SOIL FAILURE/DAMAGE DATA NEEDS

In order to make the proposed methodology a reality, specific soil failure and pipeline damage data will be required such as the following

- Inventory of areas where liquefaction has occurred
- Liquefaction susceptibility maps
- Definitive mapping of PGD
- Pipeline locations relative to PGD
- Pipeline damage mechanisms, and damage descriptions (leak, break, leakage rate)

Post-earthquake investigators are urged to gather this type of data. Some of this information currently exists such as from the Loma Prieta and Nihonkai Chubu earthquakes. The Japanese lifeline community has been more aggressive that their U S counterparts in gathering this type of data

CONCLUSIONS

Pipeline earthquake loss estimation has developed from simple damage algorithms incorporating damage from "all" earthquake hazards, to more sophisticated algorithms that segregate damage mechanisms

We have proposed a methodology to enable the lifeline community to better estimate pipeline damage from PGD in future earthquakes as a damage data base is developed using the proposed parameters

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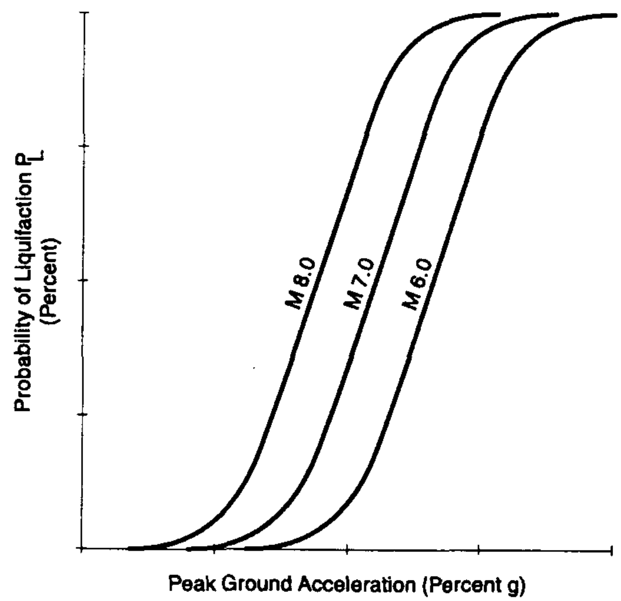

Figure 1
Liquefaction Probability Versus PGA for a Range of Earthquake Magnitudes

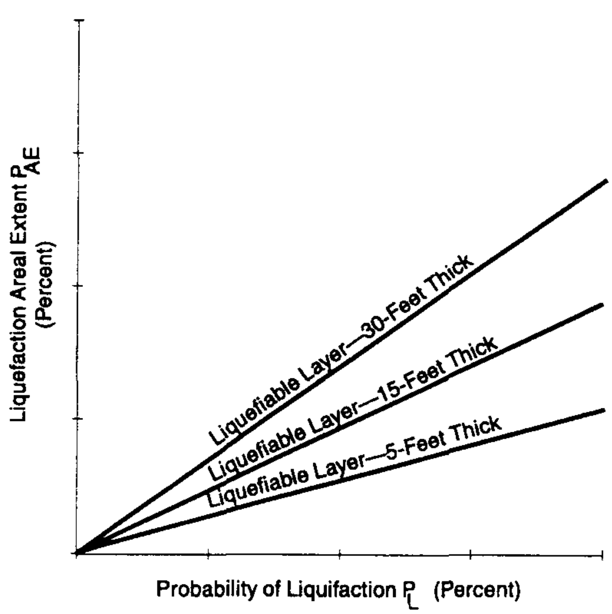

Figure 2
Liquefaction Areal Extent Versus Liquefaction Probability for a Range of Liquefiable Layer Thicknesses

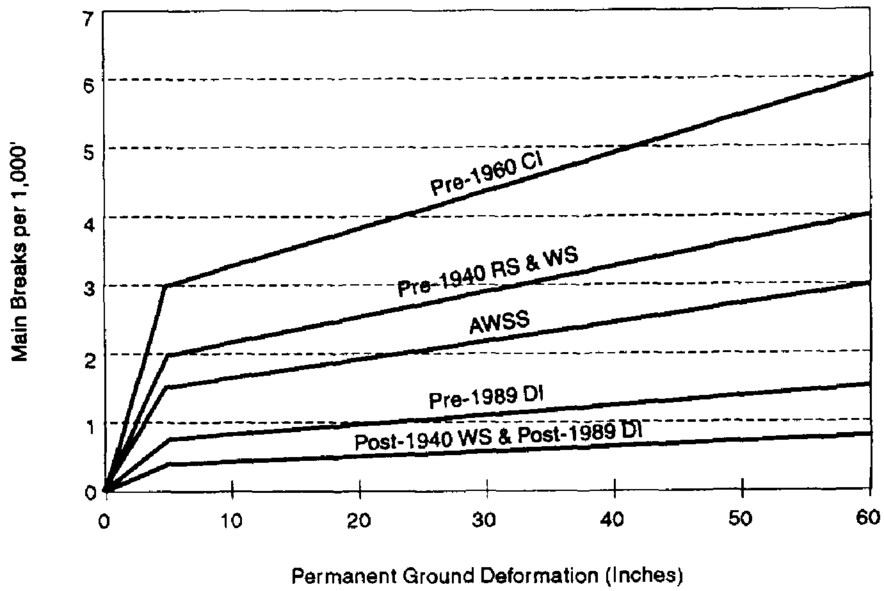

Figure 3
Main Breaks Versus Permanent Ground Deformation for Welded Steel, Cast Iron and Ductile Iron Water Pipelines (Harding-Lawson, 1990)

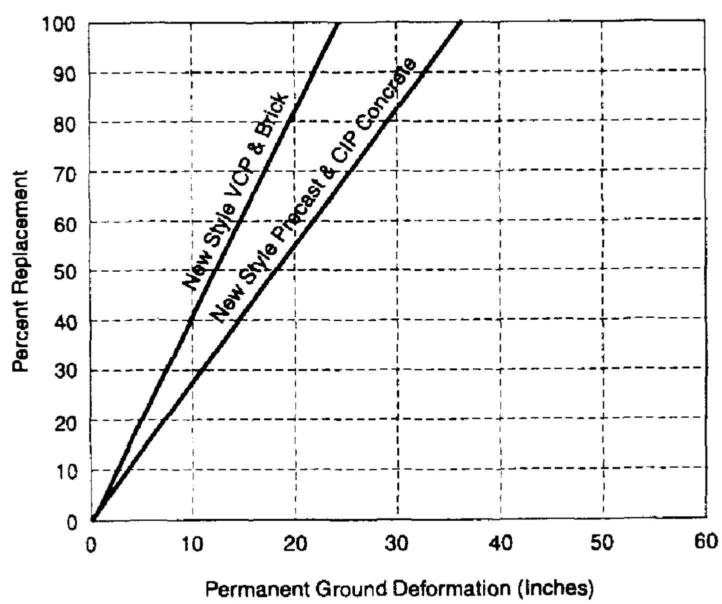

Figure 4
Percent Replacement Versus Permanent Ground Deformation for Gravity Sewer Pipelines (Harding-Lawson, 1990)