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A PRACTICAL APPROACH TO QUALITATIVE SEISMIC RISK ASSESSMENT OF ONSHORE ENERGY PIPELINES

S.D. Koduru[1] and A.M. Fraser[2]

ABSTRACT

Permanent ground displacement due to an earthquake event is one of the primary causes of failure for buried pipelines. Ground displacements impose significant deformations on buried energy pipelines, which could result in loss of containment either due to rupture of a girth weld or due to excessive wrinkling of the pipe body. This paper presents a practical approach for estimating the probability of pipeline failure in the event of permanent ground displacements imposed by surface fault rupture or ground failure due to liquefaction. The methodology was developed to address the challenges of seismic risk assessment over large remote geographical areas, where transmission energy pipelines are typically located, by leveraging publicly available data sources. The approach is illustrated through a case study of a pipeline located in Southern California.

[1]Senior Research Engineer, Integrity and Operations, Pipelines and Structures, C-FER Technologies (1999) Inc. Edmonton, Canada T6B 3T9 (s.koduru@cfertech.com)
[2]Research Engineer, Integrity and Operations, Pipelines and Structures, C-FER Technologies (1999) Inc. Edmonton, Canada T6B 3T9

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A Practical Approach to Qualitative Seismic Risk Assessment of Onshore Energy Pipelines

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Permanent ground displacement due to an earthquake event is one of the primary causes of failure for buried pipelines. Ground displacements impose significant deformations on buried energy pipelines, which could result in loss of containment either due to rupture of a girth weld or due to excessive wrinkling of the pipe body. This paper presents a practical approach for estimating the probability of pipeline failure in the event of permanent ground displacements imposed by surface fault rupture or ground failure due to liquefaction. The methodology was developed to address the challenges of seismic risk assessment over large remote geographical areas, where transmission energy pipelines are typically located, by leveraging publicly available data sources. The approach is illustrated through a case study of a pipeline located in Southern California.

Introduction

Ground displacement is a significant threat to the structural integrity of onshore energy pipelines. Uneven ground displacement along a buried pipeline can impose inelastic strains, which could lead to pipeline failure and loss of containment if the strains exceed the strain limit of the pipeline. Therefore, identification of locations susceptible to permanent ground displacements is essential for the estimation of pipeline reliability during an earthquake event.

In the event of an earthquake, permanent ground displacement can result primarily from two different modes of ground failure: displacement due to surface fault rupture, and lateral spreading due to liquefaction. To evaluate ground displacement due to fault rupture, fault-crossing locations must be known, and an estimate of the permanent ground displacement due to surface rupture at each fault crossing must be calculated [1]. This requires not only geospatial data for detailed fault mapping along the pipeline alignment, but also the surface fault rupture likelihood for each identified fault.

To evaluate liquefaction susceptibility, there are several qualitative and quantitative methods available in the literature [2] [3]. Quantitative methods are heavily dependent on site-specific geotechnical parameters for the evaluation of the cyclic stress ratio and cyclic resistance ratio.

[1]Senior Research Engineer, Integrity and Operations, Pipelines and Structures, C-FER Technologies (1999) Inc. Edmonton, Canada T6B 3T9 (s.koduru@cfertech.com)
[2]Research Engineer, Integrity and Operations, Pipelines and Structures, C-FER Technologies (1999) Inc. Edmonton, Canada T6B 3T9

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Qualitative methods depend upon regional factors such as sedimentation process, age of deposits, geological history, water table depth, grain-size distribution, density, depth of burial, ground slope, and nearness of a free face [4].

While detailed quantitative approaches are advantageous for quantitative risk evaluation at specific locations, their application to long stretches of energy transmission pipelines is impractical. Therefore, during pipeline seismic risk assessment, qualitative methods are typically adopted to assess ground failure potential on a regional basis. However, even the qualitative factors may not always be known.

This study presents an application of qualitative seismic risk assessment to a buried energy transmission pipeline located in Southern California. The framework for seismic risk assessment of buried pipelines is described at first, followed by a detailed description of the available approaches to estimate fault rupture displacement and qualitative methods to assess regional liquefaction susceptibility. The study concludes with an example application of the methodology to a pipeline located in Southern California. A brief discussion is also included regarding the availability of the open-source data on a regional scale, and the approaches developed to address information gaps to utilize all the available data.

Background and Scope

A measure of pipeline operating risk is given by the probability of pipeline failure multiplied by the consequences associated with failure. For buried energy transmission pipelines, the loss of product containment due to the structural failure of pipe is defined as the pipeline failure event. In the context of seismic risk assessment, the probability of pipeline failure is dependent on the occurrence of intervening events, such as liquefaction, in addition to the occurrence of an earthquake. Therefore, the required probability can be modelled as,

$$P(LoC) = P(LoC|\ ground\ failure) \cdot P(ground\ failure|\ EQ) \cdot P(EQ) \tag{1}$$

where P*(LoC*) is the probability of loss of containment, *P*(*LoC*| *ground failure*) is the probability of loss of containment given ground failure (e.g., due to surface fault rupture or liquefaction), *P*(*ground failure*| *EQ*) is the probability of occurrence of ground failure in the event of an earthquake and finally, *P*(*EQ*) is the probability of occurrence of an earthquake.

The estimation of *P*(*LoC*| *ground failure*) requires quantification of the permanent ground displacement due to a ground failure event and the pipeline capacity to withstand the applied displacements. The methodology for this estimation is well-developed within the pipeline industry, e.g., see [5]. *P*(*EQ*) is the earthquake occurrence probability at a region level, which can be obtained from seismic hazard assessments performed by the USGS [6] and GSC[7] in North America.

The estimation of *P*(*ground failure*| *EQ*) is dependent both on the susceptibility of a location to ground failure and the occurrence of an earthquake of sufficient intensity to trigger the ground failure. The scope of this study is to develop methods to estimate *P*(*ground failure*| *EQ*), where ground failure is either due to surface fault rupture or liquefaction. The focus is on regional level

risk estimation where risk screening is the primary assessment objective, and the available data is often insufficient for a detailed quantitative analysis. The methodology is illustrated through a case study involving risk assessment of transmission pipelines located in the highly seismic region of Southern California. This region was selected to demonstrate the challenges associated with data availability even in one of the well-studied seismic regions in North America.

Methodology

Fault Crossings

Following the format in Eq. (1), the probability of pipeline failure at a fault crossing is,

$$P(LoC) = \sum_i P(LoC|\ PGD) \cdot P(PGD|\ SRc) \cdot P(SRc|\ SR) \cdot\ P(SR|\ M_i) \cdot P(M_i) \tag{2}$$

where $P(LoC|\ PGD)$ is the probability of loss of containment due to permanent ground displacement, $P(PGD|\ SRc)$ is the permanent ground displacement imposed on the pipeline due to surface rupture of a fault where it intersects pipeline, $P(SRc|SR)$ is the probability of intersecting surface rupture given that surface rupture occurs, $P(SR|M_i)$ is the probability of rupture extension to surface in the case of an earthquake of magnitude M_i due to that fault rupture, and $P(M_i)$ is the probability of occurrence of an earthquake of magnitude M_i, where i is the possible earthquake magnitudes for a given fault.

$P(M_i)$ is determined by the occurrence of fault rupture and the associated earthquake magnitudes. This needs a detailed mapping of the fault locations in addition to the magnitude and frequency of occurrence relationships specific to each fault. $P(SR|M_i)$ can be determined using an empirical formulation developed by Wells and Coppersmith [8], as reported in Petersen et. al [9],

$$P(SR|M) = \frac{e^{a+bM}}{1+e^{a+bM}} \tag{3}$$

where M is the moment magnitude, and a and b are constants of value -12.51 and 2.053, respectively. To determine $P(SRc|SR)$, the probability that surface rupture of a finite length intersects the specific pipeline crossing location is required. Assuming that surface rupture is equally likely along the entire fault length, this probability can be modelled as,

$$P(SRc|SR) = SRL/(FL - SRL) \tag{4}$$

where SRL is the length of surface rupture, and FL is the total length of the fault. SRL can be calculated using the empirical equation developed by Wells and Coppersmith [10],

$$\log(SRL) = c + d \cdot M \tag{5}$$

where SRL is the surface rupture length in km, M is the moment magnitude, and c and d are constants of value -3.22 and 0.69, respectively. In the absence of data for fault lengths, it can be conservatively assumed that a surface rupture will always coincide with the pipeline crossing, and thus, $P(SRc|SR) = 1.0$. Similarly, it can be assumed that there is no uncertainty in the prediction of amount of PGD given the occurrence of surface rupture, such that $P(PGD|\ SRc) = 1.0$. Hence, a

deterministic relationship between *PGD* and *M* given by [10] is employed to predict the amount of *PGD*, as given below,

$$\log(PGD) = e + f \cdot M \tag{6}$$

where *PGD* is the average permanent ground displacement along the fault in meters, and *e* and *f* are constants of value -4.80 and 0.69, respectively. As noted earlier, there are several detailed approaches for determining $P(LoC|PGD)$ in the literature [5]. These approaches involve detailed finite element (FE) analysis to compute the axial strains experienced by the pipeline, which are then compared against the strain limit of the pipeline to determine if failure would occur. FE modelling has the benefit of accounting for additional key variables that are not considered in simplistic models, however, it requires additional effort for data collection and computation.

For the purpose of risk screening, the simplest approach is to utilize empirical relationships, such as the one proposed by Eidinger [11],

$$P(LoC|PGD) = 0.70 \cdot \frac{PGD}{60}, \ P \leq 0.95 \tag{7}$$

where *PGD* is the average displacement along the fault in inches. Eq.(7) does not require data related to soil properties, pipeline properties, depth of burial, and the angle of the fault crossing.

Liquefaction

In contrast to fault crossing, liquefaction susceptibility is independent of the fault location. Liquefaction susceptibility is primarily dependent on the soil susceptibility to liquefaction and ground shaking intensity. Therefore, the probability of pipeline failure is modelled as,

$$P(LoC) = \sum_i P(LoC|PGD) \cdot P(PGD|L) \cdot P(L|PGA_i) \cdot P(PGA_i) \tag{8}$$

where $P(PGD|L)$ is the probability of permanent ground displacement due to liquefaction, $P(L|PGA_i)$ is the probability of liquefaction due to a given peak ground acceleration, and $P(PGA_i)$ is the probability of occurrence of a peak ground acceleration for each *i* of return periods.

$P(PGA_i)$ along the length of the pipeline can be determined from seismic hazard maps available for North America [6] [7]. To determine $P(L|PGA_i)$ requires the assessment of soil susceptibility along the length of the pipeline. Youd and Idriss [2] summarized empirical methods for evaluating soil resistance to liquefaction based on field testing results from the Standard Penetration Test (SPT), the Cone Penetration Test (CPT), the shear wave velocity (Vs) and the Becker Penetration Test (BPT). They have also presented the methodology to evaluate the cyclic stress ratio, which is a measure of seismic demand, based on spectral accelerations and the earthquake magnitude. These quantitative methods have been used in the estimation of the probability of liquefaction occurrence, e.g., see [3]. Application of this methods requires either the results of field tests or the shear wave velocities. Although shear wave velocities have been mapped for most urban areas (e.g., [12]), this information is often unavailable for remote areas traversed by the energy transmission pipelines.

Given a qualitative classification of soil susceptibility to liquefaction as either 'high', 'medium' or 'low', an appropriate relationship for $P(L| PGA_i)$ can be determined based on the relationships in HAZUS [13]. The susceptibility classification is usually performed based on the sedimentation categories and the age of geological deposits [4]. In the absence of data regarding the geological deposits and water table depth, it is conservative to assume younger deposits with sedimentation depth greater than 10m and water table depth is not below 10m.

For a qualitative classification of soil susceptibility to liquefaction, Bray et al [14] and Seed et al. [15] recommend a criteria based on Plasticity Index (PI), Liquid Limit (LL), water content (Wc) and fines content (FC). In the absence of the data required to apply the qualitative criteria as-is, modifications are considered to enable the classification with partially available data. Table 1 shows the modified criteria developed in this study.

Table 1. Modified criteria for soil susceptibility to liquefaction

Soil Susceptibility	**Criteria**		
High	Sand > 50%		
	Sand < 50%	PI ≤ 12	Wc/LL≥0.85
	Sand < 50%	PI ≤ 12	LL≤ 37
Moderate	Sand < 50%	12<PI≤ 20	Wc/LL≥0.80
	Sand < 50%	12<PI≤ 20	LL≤ 47
Low	Sand < 50%	PI>20	Wc/LL < 0.80
	Sand < 50%	PI>20	LL > 47

In the absence of detailed site-specific data, such as ground slope, grain size distribution, fines content, soil layer thickness, and magnitude-distance relationships to the earthquake sources, it is difficult to employ the empirical relationships developed by Youd et al. [16]. Therefore, it is conservatively assumed that $P(PGD| L) = 1.0$, and *PGD* is deterministically evaluated based on the empirical relationships for *PGD* and *PGA* given by HAZUS [13]. Once the amount of *PGD* is determined, $P(LoC| PGD)$ can be determined using Eq.(7), as discussed previously.

Numerical Example

Pipeline Description

A set of pipelines in Southern California were selected from the U.S. Energy Information Administration (EIA) maps of natural gas and crude oil pipelines. The EIA map provides a coarsely defined route for a large portion of the pipelines in the US. The region surrounding Santa Clarita was chosen for this example as there are several key pipelines that supply Los Angeles running through it, as shown in Fig. 1[17].

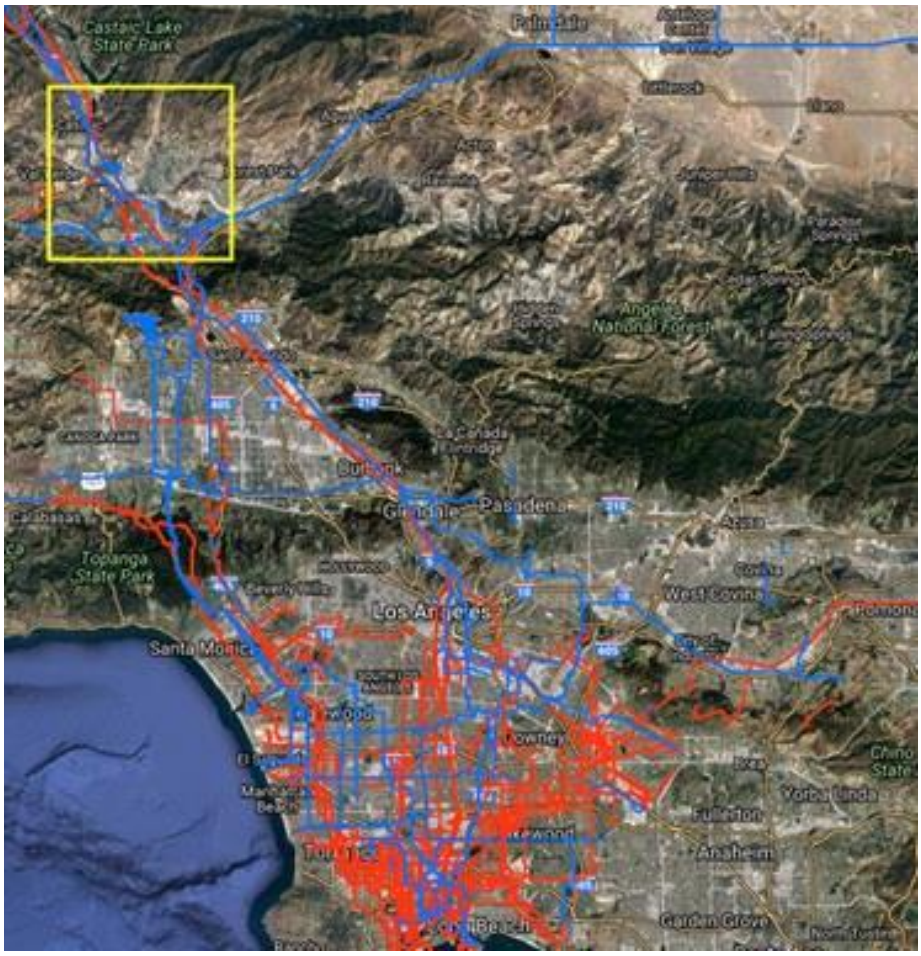

Figure 1. Overview of pipelines in Los Angeles County [17]

Fault Crossings

In addition to being a key pathway for pipelines into Los Angeles, the Santa Clarita region also plays host to portions of the San Gabriel, Northridge, and Holser faults. These fault traces are shown in Fig 2, in addition to the simplified pipeline routes from the EIA. The magnitude and frequency of occurrence relationships for these three faults were selected using the time independent models from the Third Uniform California Earthquake Rupture Forecast (UCERF3) [18]. The time independent models provide an averaged frequency of occurrence over a time interval, and were available for the fault sources included in this study.

Once the probability of occurrence of earthquake magnitude is known, using Eq.3, the annual probability of surface rupture for each fault is determined. Assuming that $P(SRc|SR) = 1.0$, $P(PGD|SRc) = 1.0$ and using Eq.6 and 7, the annual probability of pipeline failure for a given earthquake magnitude is determined at each fault, as shown in Fig. 3. The total annual probability of failure for a pipeline crossing is calculated by determining the cumulative probability of failure for all moment magnitudes, shown in Table 2.

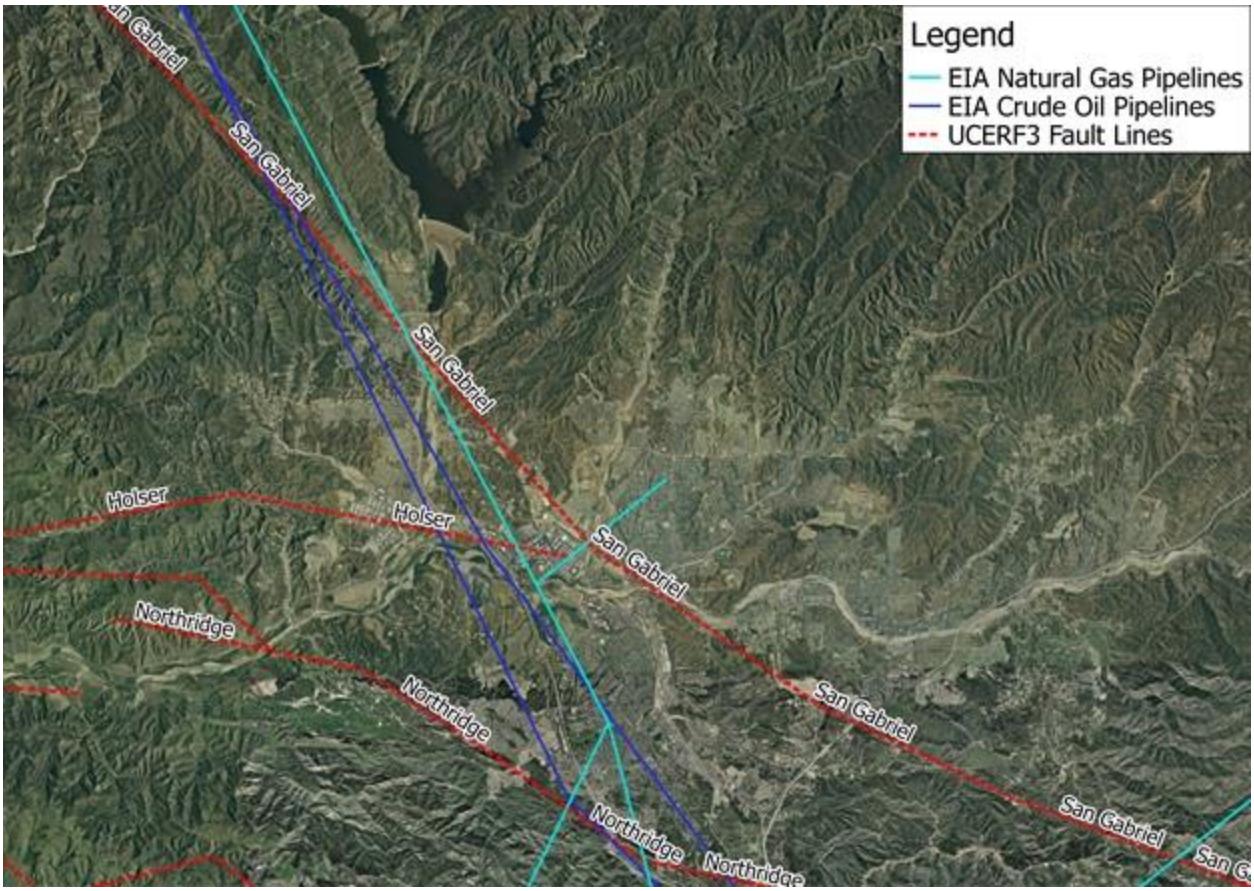

Figure 2. Overview of pipelines and fault traces in the Santa Clarita region.

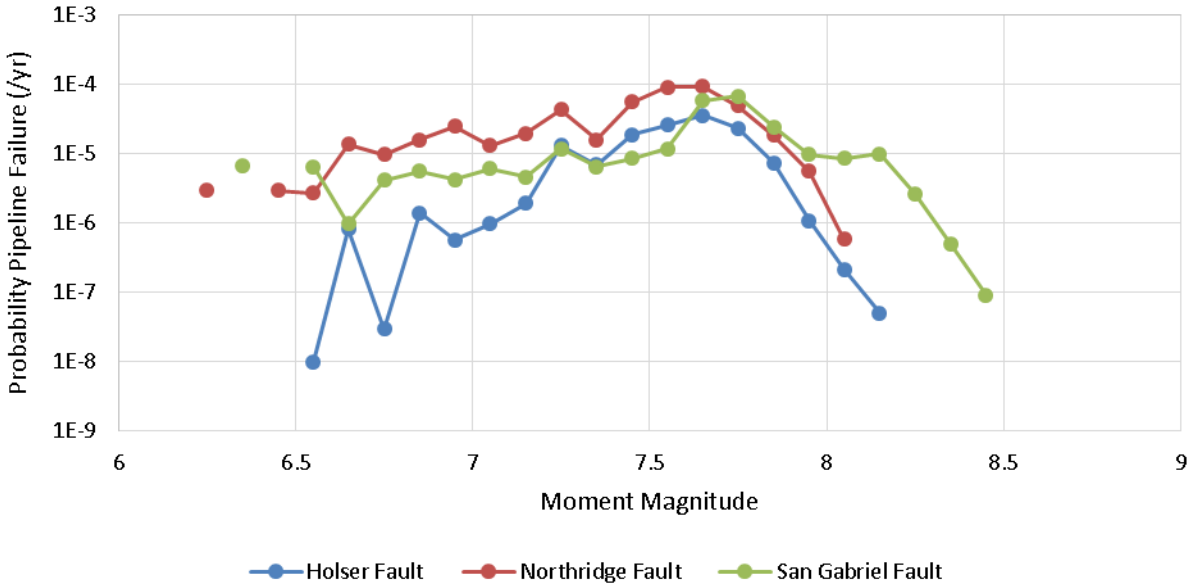

Figure 3. Annual probability of pipeline failure versus moment magnitude for fault crossings in Santa Clarita.

Table 2. Total annual probability of pipeline failure for fault crossings in Santa Clarita.

Fault Crossing	Annual Probability of Earthquake Occurrence	Annual Probability of Pipeline Failure at Fault Crossing
Holser	1.72E-04	1.40E-04
Northridge	8.81E-04	4.85E-04
San Gabriel	4.79E-04	2.62E-04

Liquefaction

The data required to assess the soil properties surrounding the selected pipelines in Santa Clarita were obtained from the Soil Survey Geographical Database (SSURGO) published by the National Cooperative Soil Survey [19]. The criteria proposed in Table 1 was then used to classify the susceptibility of the region to liquefaction, as shown in Fig 4. The susceptibility classified as "N/A" (shown in gray) have the sand content less than 50%, but data was not available for the WC or LL.

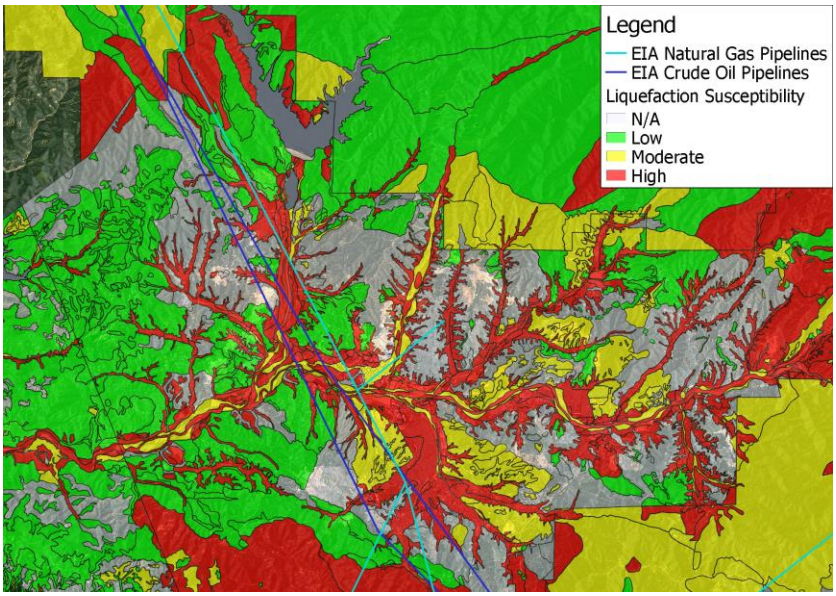

Figure 4. Liquefaction susceptibility of soils in Santa Clarita region.

To validate the results produced using this methodology, the liquefaction susceptibility classifications were compared to the liquefaction susceptibility maps that have been produced for portions of California by the California Geological Survey (CGS) [20]. The CGS maps do not classify using the same categories proposed in this paper (such as high, moderate, low), instead, the maps differentiate between regions that are susceptible to liquefaction and those that are not susceptible. The comparison is shown in Fig 5. The predictions obtained using this methodology are shown to match fairly well with the susceptibility map produced by the CGS. The proposed methodology provides a categorization that is typically conservative, because of the assumptions that are made to reduce the data requirements. In particular, this methodology will be overly conservative in regions that have sandy soils with deep groundwater, as the ground water table

depth is assumed to be within 10m from the ground surface.

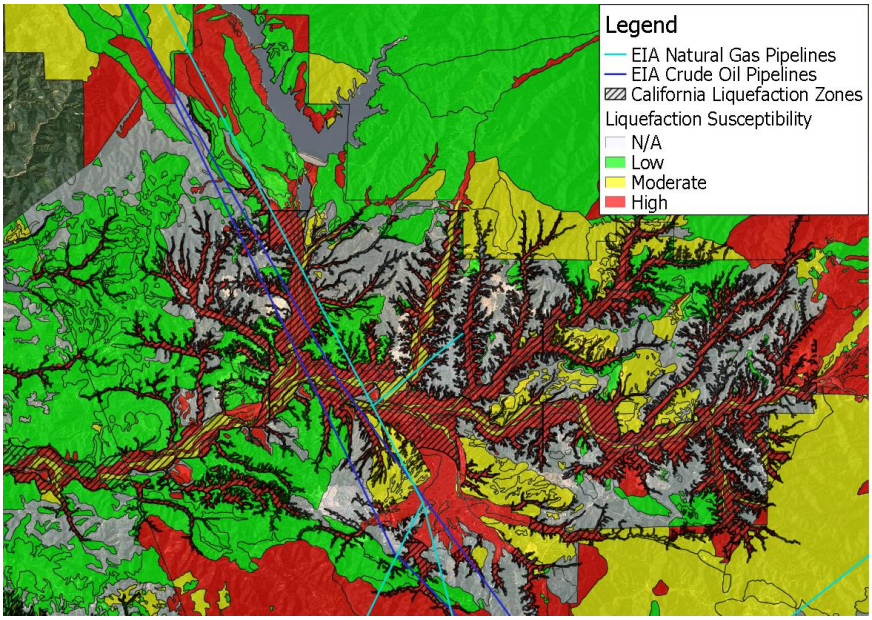

Figure 5. Comparison of liquefaction susceptibility prediction from CGS with the predictions from the methodology in this study.

Once the soil susceptibility is categorized, the probability of pipeline failure is evaluated using the HAZUS functions for PGD and the PGD relationship to failure given in Eq. 7. Table 3 shows the annual probability of pipeline failure at PGA equal to 0.6g, which is estimated to occur at a rate of 1 in 500 years for this region, for liquefaction susceptible soils of all categories.

Table 3. Total annual probability of pipeline failure due to liquefaction.

PGA	Soil Liquefaction Susceptibility	Annual Probability Failure
0.6g	High	5.70E-4
0.6g	Medium	2.80E-4
0.6g	Low	8.50E-5

Conclusions

A practical methodology has been developed to assess the probability of pipeline failure due to permanent ground displacement caused by surface fault rupture and ground failure due to liquefaction. The methodology is intended for seismic risk screening of pipelines over large geographical regions and remote locations where limited public data is available for seismic hazard characterization. It is noted that due to the conservatism inherent in some of the adopted simplifications, it may provide conservative estimates of failure probabilities. Additional data collection and analysis is recommended for a more rigorous evaluation of pipelines in areas of high seismic risk.

References

1. O'Rourke, M.J., Liu, X. Seismic Design of Buried and Offshore Pipelines. *Multidisciplinary Center for Earthquake Engineering Research (MEER) Monograph No. 4.* 2012; MEER, University at Buffalo, State University of New York, Buffalo, NY

2. Youd, T.L., Idriss, I.M. Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils. *Journal of Geotechnical and Geoenvironmental Engineering* 2001; 297-313.

3. Boulanger, R.W., and Idriss, I.M., *CPT and SPT Based Liquefaction Triggering Procedures*, Report No. UCD/CGM-14/01 2001. Center for Geotechnical Modeling, University of California, Davis.

4. Youd, T.L., and Perkins, D.M, Mapping liquefaction-induced ground failure potential. ASCE Journal of Geotechnical Engineering Division, 1978; *104*. 433-446.

5. Nessim, M., Yoosef-Ghodsi, N., Honegger, D., Zhou, J. and Wang, S. Application of Reliability Based Design and Assessment to Seismic Evaluations. *International Pipeline Conference*, Calgary, Alberta, September 27-October 1 2010, IPC2010-31557.

6. Petersen, M.D., Moschetti, M.P., Powers, P.M., Mueller, C.S., Haller, K.M., Frankel, A.D., Zeng, Y., Rezaeian, S., Harmsen, S.C., Boyd, O.S., Field, N., Chen, R., Rukstales, K.S., Luco, N., Wheeler, R.L., Williams, R.A., and Olsen, A.H., *Documentation for the 2014 update of the United States national seismic hazard maps: U.S. Geological Survey Open-File Report 2014–1091*, 2014. *http://dx.doi.org/10.333/ofr20141091*

7. Halchuk, S., Allen, T.I., Adams, J., and Rogers, G.C., *Fifth Generation Seismic Hazard Model Input Files as Proposed to Produce Values for the 2015 National Building Code of Canada*; Geological Survey of Canada, Open File 7576. 2014. doi:10.4095/293907

8. Wells, D. L., and Coppersmith, K.J. Likelihood of surface rupture as a function of magnitude, *Seismological Research Letters* 1993; **64**, 54.

9. Petersen, M.D, Dawson, T.E., Chen,,R., Cao, T., Wills, C.J., Schwartz, D.P. and Frankel, A.D. Fault Displacement Hazard for Strike-Slip Faults. *Bulletin of the Seismological Society of America* 2011; **101** (2): 805-825.

10. Wells, D. L., and Coppersmith K.J. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, *Bulletin of the Seismological Society of America* 1994; **84**, 974–1002.

11. Eidinger, J. *Seismic Fragility Formulations for Water Systems*. 2001.American Lifelines Alliance, G&E Engineering Systems Inc.96pp

12. Hunter, J. A., R. A. Burns, R. L. Good, J. M. Aylsworth, S. E. Pullan, D. Perret, and M. Douma . *Borehole shear wave velocity measurements of Champlain Sea sediments in the Ottawa–Montreal region*, 2007 Open File Rept. 5345, Geological Survey of Canada, Ottawa,

13. FEMA, *Multi-Hazard Loss Estimation Methodology Earthquake Model, HAZUS-MH2.1* 2017

14. Bray J.D., Sancio, R.B., Reimer, M., and Durgunoglu, H.T., Liquefaction of fine grained soils, *In* Proceedings of the 11th International Conference on Soil Dynamics andEarthquake Engineering and 3rd International Conference on Earthquake Geotechnical Engineering, Berkeley, Calif., 7–9 January 2004.

15. Seed, R.B., Cetin, K.O., Moss, R.E.S., Kammerer, A.M., Wu, J., Pestana,J.M., Riemer, M.F. Recent advances in soil liquefaction engineering and seismic site response evaluation, Proceedings of 4th International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics 2001. Mar26-31 San Diego CA

16. Youd, T.L., Hansen, C.M. and Bartlett, S.F. Revised Multilinear Regression Equations for Prediction of Lateral Spread Displacement." Journal of Geotechnical and Geoenvironmental Engineering, 2002; **128** (12): 203-222.

17. Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA) National Pipeline Mapping System (NPMS). Available online at https://www.npms.phmsa.dot.gov/Default.asp. Accessed [11/12/2017].

18. Field, E.H., Biasi, G.P., Bird, P., Dawson, T.E., Felzer, K.R., Jackson, D.D., Johnson, K.M., Jordan, T.H., Madden, C., Michael, A.J., Milner, K.R., Page, M.T., Parsons, T., Powers, P.M., Shaw, B.E., Thatcher, W.R., Weldon, R.J., II, and Zeng, Y., *Uniform California earthquake rupture forecast, version 3 (UCERF3)—The time-independent model: U.S. Geological Survey Open-File Report 2013–1165, 97 p., California Geological Survey Special Report 228, and Southern California Earthquake Center Publication 1792*, 2013 http://pubs.usgs.gov/of/2013/1165/.

19. Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Soil Survey Geographic (SSURGO) Database. Available online at https://sdmdataaccess.sc.egov.usda.gov. Accessed [03/15/2017].

20. CGS Liquefaction Susceptibility maps Available online at https://maps.conservation.ca.gov/cgs/ Accessed [11/12/2017].