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Energy Research and Development Division

FINAL PROJECT REPORT

Performance-Based Earthquake Engineering Assessment Tool for Natural Gas Storage and Pipeline Systems

Validation Report

Gavin Newsom, Governor
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PREPARED BY:

Primary Authors:
Chris Bain, Jonathan D. Bray, Daniel Hutabarat

University of California, Berkeley
453 Davis Hall, MC-1710
Berkeley, California 94720-1710

Thomas D. O'Rourke

Cornell University
422 Hollister Hall
Ithaca, New York 14853

Scott Lindvall

Lettis Consultants International, Inc.
27441 Tourney Road, Suite 220
Valencia, California 91355

Barry Zheng

Slate Geotechnical Consultants
2927 Newbury St. Suite A
Berkeley, California

Preston Jordan, Tsubasa Sasaki, Keurfon Luu, Yingqi Zhang, William Foxall, Jonny Rutqvist

Lawrence Berkeley National Laboratory
1 Cyclotron Road
Berkeley, California 94720

David McCallen, Sherif Elfass

University of Nevada, Reno
1664 N. Virginia Street
Reno, Nevada 89557

Tara Hutchinson, Elide Pantoli

University of California, San Diego
SME Building, 3rd Floor, Suite 341
San Diego, California 89557

Contract Number: PIR-18-003

PREPARED FOR:
California Energy Commission

Yahui Yang
Project Manager

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan
Executive Director

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Natural Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater natural gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency.
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity.
- Energy-Related Environmental Research
- Natural Gas-Related Transportation.

The *Validation Report* is an interim report for the Performance-Based Earthquake Engineering Assessment Tool for Natural Gas Storage and Pipeline Systems project (PIR-18-003) conducted by the University of California, Berkeley. The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

ABSTRACT

This report is one of a series of reports documenting the methods and findings of a multi-year, multi-disciplinary project conducted by the Pacific Earthquake Engineering Research Center (PEER) with the Lawrence Berkeley National Laboratory (LBNL) and funded by the California Energy Commission (CEC). The overall project is titled *Performance-based Earthquake Engineering Assessment Tool for Natural Gas Storage and Pipeline Systems* henceforth referred to as the *OpenSRA* Project.

The overall goal of the *OpenSRA* Project is to create an open-source, research-based seismic risk assessment tool for natural gas infrastructure that can be used by utility stakeholders to better understand state-wide risks, prioritize mitigation, plan new gas infrastructure, and help focus post-earthquake repair work.

The project team includes researchers from UC Berkeley, LBNL, UC San Diego, University of Nevada Reno, the NHERI SimCenter at UC Berkeley, and Slate Geotechnical Consultants and its subcontractors Lettis Consultants International (LCI) and Thomas O'Rourke of Cornell University. Focused research to advance the seismic risk assessment tool was conducted by Task Groups, each addressing a particular area of study and expertise, and collaborating with the other Task Groups.

The scope of this report is to implement and evaluate the analytical procedures used in *OpenSRA* for selected validation cases. The viability of the *OpenSRA* software tool is demonstrated through trial applications for several important representative existing natural gas pipelines and storage facilities. Its use is validated by comparing their estimated performance with that observed during historic earthquakes. The focus of the validation report is on the seismic performance of the underground natural gas, oil, and water pipelines within the utility corridor along Balboa Boulevard during the 1971 San Fernando and 1994 Northridge earthquakes. Comprehensive data about the subsurface conditions, pipelines, and earthquake effects are freely available for this case so the results of this validation can be shared in depth in this report. The viability of the *OpenSRA* software tool was evaluated at three additional demonstration sites: the Honor Rancho and McDonald Island gas storage facilities and Cordelia Junction. The data shared by the utilities for the McDonald Island and Cordelia Junction sites is restricted under non-disclosure agreements (NDAs). Hence, the results of the validation of *OpenSRA* at these sites is only summarized in this report.

The *OpenSRA* software tool and the analytical procedures used in it are shown to provide reliable estimates of the seismic performance of the natural gas systems examined on the demonstration sites.

Keywords: Fragilities, risk, case history, liquefaction, lateral spreading, landslide

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EXECUTIVE SUMMARY

Introduction

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Project Purpose

The purpose of this report is to evaluate the methods selected and developed for assessing geohazards and their impact on natural gas infrastructure. The methods are evaluated on their ability to estimate satisfactorily the occurrence or non-occurrence of geohazards, the severity of the potential geohazards, and their impact on the natural gas infrastructure at each of the validation sites.

Project Approach

There is a requirement in this project to assess natural gas systems at the statewide, regional, and site-specific scales. Because there is variation in the resolution of the data as well as the uncertainty of the ground deformation estimates, four levels of available data are identified, and different analytical methods are utilized for each level.

Level 1 analyses utilize data that are geospatially continuous at a uniform resolution over the entire state of California. These analyses have lower data resolution and are not informed by detailed site data, which leads to very high epistemic uncertainty of earthquake effects.

Level 2 analyses utilize data produced at regional scales collected at higher resolution than Level 1 data and are not necessarily geospatially continuous over the entire state of California. These analyses may be informed by subsurface data or estimated engineering properties. Level 2 analyses have high epistemic uncertainty, but less than that at Level 1.

Level 3 analyses utilize site-specific data such as Cone Penetration Test (CPT) data or 1:24,000 scale or larger geologic maps to evaluate geohazards or the response of natural gas infrastructure to ground shaking or ground deformation. Level 3 data enable assessment with medium epistemic uncertainty, which is less than possible with Level 2 data.

Level 4 analyses utilize high-quality geotechnical laboratory test data such as strength tests on “undisturbed” soil samples to enable the performance of advanced numerical analyses. They have the least uncertainty in evaluating the response of natural gas infrastructure to ground shaking or ground deformation. Level 4 analyses are beyond the current scope of the *OpenSRA* Project.

This report implements analysis methods at Levels 1 – 3 at the Balboa Boulevard demonstration site. The viability of the *OpenSRA* software tool was evaluated at three additional demonstration sites: the Honor Rancho and McDonald Island gas storage facilities and Cordelia Junction. The data shared by the utilities for the McDonald Island and Cordelia Junction sites is restricted under non-disclosure agreements (NDAs). Hence, the results of the validation of *OpenSRA* at these sites is only summarized in this report.

Project Results

The results of the validation study at Balboa Boulevard indicate significant value in collecting Level 2 or Level 3 data for evaluating geohazards. Liquefaction, lateral spreading, and landslide analyses are very sensitive to data such as the depth to groundwater, which is difficult to estimate at statewide scales. At the Balboa Boulevard site, the Level 1 groundwater model does not capture the local effect of the Mission Hills Fault causing water to perch behind a concealed fault structure. Using Level 2 data, the elevated groundwater table can be more reasonably estimated which improves the analysis. Level 3 data locates accurately the groundwater table during the Northridge earthquake, which greatly improves the liquefaction analysis at the Balboa Boulevard site.

The *OpenSRA* assessment at the Honor Rancho natural gas storage facility estimated negligible probabilities of leaks and ruptures at the well heads in response to the shaking intensity at the site as estimated by ShakeMap for the 1971 San Fernando and 1994 Northridge earthquake, consistent with the lack of observed damage. *OpenSRA* and full physics-based modeling of fault rupture through the caprock estimates negligible leakage along the fault, which is consistent with expected performance of the caprock.

Analyses of the surface infrastructure subsystems at McDonald Island estimated that the probabilities of leakage and rupture of the wellheads and piping subsystems are small, even for very strong ground motions. The probability of failure for vertical and tall pressure vessels at McDonald Island is likewise relatively small for an event such as the 1989 Loma Prieta earthquake (mean PGA as estimated by ShakeMap equals 0.08 g), consistent with the lack of observed damage. However, a hypothetical event with PGA ten times that of Loma Prieta (i.e., PGA=0.8 g) has a mean probability of failure of 34% for the pressure vessels at this site.

A gas transmission pipeline crossing an active, rainfall-induced landslide at Cordelia Junction was assessed for the ground motions as estimated by ShakeMap for the 1989 Loma Prieta and 2014 South Napa earthquakes. *OpenSRA* estimates the probability of tensile leakage and rupture to be negligible for both events while the mean probability of compressive ruptures is estimated to be relatively low (less than 10%) for both events. These results are consistent with the lack of observed coseismic displacement following both events; however, significant uncertainties in the geotechnical strength parameters and ground shaking intensity lead to high epistemic uncertainty in the probability of compressive ruptures. The probability of compressive failure for both events is estimated to range from 0% at the 5th epistemic fractile to approximately 40% at the 95th epistemic fractile.

An assessment for a hypothetical earthquake which produces PGA=0.5 g at the Cordelia Junction site estimates significantly higher probabilities of compressive ruptures and increased likelihood of tensile leakage and rupture, but still relatively low. An assessment of the pipeline alignment after it was rerouted around the active landslide estimates zero probability for tensile and compressive failures for the hypothetical earthquake, demonstrating the reduced risk to the pipeline compared to its prior alignment across the active landslide.

CHAPTER 1: Introduction

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The overall goal of the *OpenSRA* Project is to create an open-source, research-based seismic risk assessment tool for natural gas infrastructure that can be used by utility stakeholders to better understand state-wide risks, prioritize mitigation, plan new gas infrastructure, and help focus post-earthquake repair work.

The probabilistic seismic risk tool developed in this project follows the widely accepted risk methodology of Cornell (1968). A seismic source characterization is used to develop a suite of earthquake scenarios with associated rates of occurrence to represent the seismic hazard. Fault ruptures and the resulting ground shaking are generated for each earthquake scenario to represent the seismic loading, which includes a map of ground motion parameters. This scenario-based seismic parameter map is overlaid on the infrastructure system, and the seismic loading is related to the capacities of the infrastructure to calculate the seismic performance of the natural gas system for the scenario. By repeating the process for all the scenarios in the suite, the tool can evaluate the seismic risk to the system.

A user-driven research approach was used to develop *OpenSRA* to be applied easily by regulators and utilities, and to include updated models and methods for the seismic demands and capacities that control the seismic risk for natural gas systems. The project includes several innovative approaches that improve the basic methodology and distinguish this project’s approach from standard approaches currently used. Current risk studies developed by the utilities use risk scoring approaches that are highly subjective and qualitative. They do not incorporate properly the uncertainties in the seismic demand and in the fragility of the system and its components. Targeted research was conducted in this project to improve the characterization of the uncertainty of key inputs to the seismic risk assessment tool. The seismic risk methodology employed in this project provides quantitative estimates of the probabilistic seismic risk. For risk-informed decision-making processes, the reliability of the risk estimates needs to be considered because this can be significant, particularly for large, rare earthquakes.

The project team includes researchers from UC Berkeley, LBNL, UC San Diego, University of Nevada Reno, the PEER Center, the NHERI SimCenter, and Slate Geotechnical Consultants and its subcontractors Lettis Consultants International (LCI) and Thomas O’Rourke of Cornell University. Focused research to advance the seismic risk assessment tool was conducted by Task Groups, each addressing a particular area of study and expertise, and collaborating with the other Task Groups. The Task Groups are as follows:

Task A: Fault displacement

Task B: Liquefaction-induced deformation and seismically induced slope displacement

Task C: Performance of natural gas storage well casings and caprock

Task D: Performance of gas storage and pipeline system surface infrastructure

Task E: Smart gas infrastructure sensing of wells and pipeline connections performance

Task F: Synthesis of component fragilities into a system performance model

The scope of this report is to evaluate the analytical procedures used in *OpenSRA* for selected validation cases. The viability of the tool is demonstrated through trial applications at several important representative existing natural gas pipelines and storage facilities. The software's use is validated by comparing the estimated infrastructure performance at these sites with that observed during historic and hypothetical earthquakes. The focus of the validation report is on the seismic performance of the underground natural gas, oil, and water pipelines within the utility corridor along Balboa Boulevard during the 1971 San Fernando and 1994 Northridge earthquakes. Comprehensive data about the subsurface conditions, pipelines, and earthquake effects are freely available for this case so the results of this validation can be shared in depth in this report. The viability of the *OpenSRA* software tool was evaluated at three additional demonstration sites: the Honor Rancho and McDonald Island gas storage facilities and Cordelia Junction. The data shared by the utilities for the McDonald Island and Cordelia Junction sites is restricted under non-disclosure agreements (NDAs). Hence, the results of the validation of *OpenSRA* at these sites is only summarized in this report.

CHAPTER 2:
Project Approach

2.1 Validation Approach

This report evaluates the performance of the methods selected and developed for use in *OpenSRA* at four demonstration sites in California which contain documented case histories of pipeline response to ground deformations or seismic shaking. The primary demonstration site presented in this report is the utility corridor at Balboa Boulevard (herein called the Balboa Boulevard site), which contains several natural gas, oil, and water transmission pipelines. The other demonstration sites summarized in this report are the Honor Rancho Natural Gas Storage Facility (herein called the Honor Rancho site), the McDonald Island Natural Gas Storage Facility (herein called the McDonald Island site), and the Cordelia Junction Natural Gas Pipeline Site (herein called the Cordelia Junction site).

OpenSRA requires the analysis of seismic risk at site-specific to statewide scales. To do this, procedures to evaluate geohazards are categorized into four levels:

1. Level 1 analyses utilize data that are geospatially continuous at a uniform resolution over the entire state of California. These analyses have lower data resolution and are not informed by detailed site data, which leads to very high epistemic uncertainty of earthquake effects.
2. Level 2 analyses utilize data produced at regional scales collected at higher resolution than Level 1 data and are not necessarily geospatially continuous over the entire state of California. There is minimal, generic subsurface data or estimated engineering properties. Level 2 analyses have high epistemic uncertainty, but less than that at Level 1.
3. Level 3 analyses utilize site-specific data such as Cone Penetration Test (CPT) data, 1:24,000 scale or larger geologic maps, or soil/rock index tests. Subsurface data are available to evaluate geohazards or the response of natural gas infrastructure to ground shaking or ground deformation using performance-based liquefaction, lateral spreading, slope displacement, and settlement procedures. Level 3 data enable assessment with medium epistemic uncertainty, which is less than possible with Level 2 data.
4. Level 4 analyses utilize high-quality geotechnical laboratory test data such as strength tests on “undisturbed” soil samples to enable advanced numerical analyses to be performed. Due to the high level of data required they will not be employed commonly in making systemwide seismic risk assessments. Instead, they will be used on project-specific efforts. They will have the least epistemic uncertainty in evaluating the response of natural gas infrastructure to ground shaking or ground deformation. Level 4 analyses are beyond the current scope of the *OpenSRA* Project.

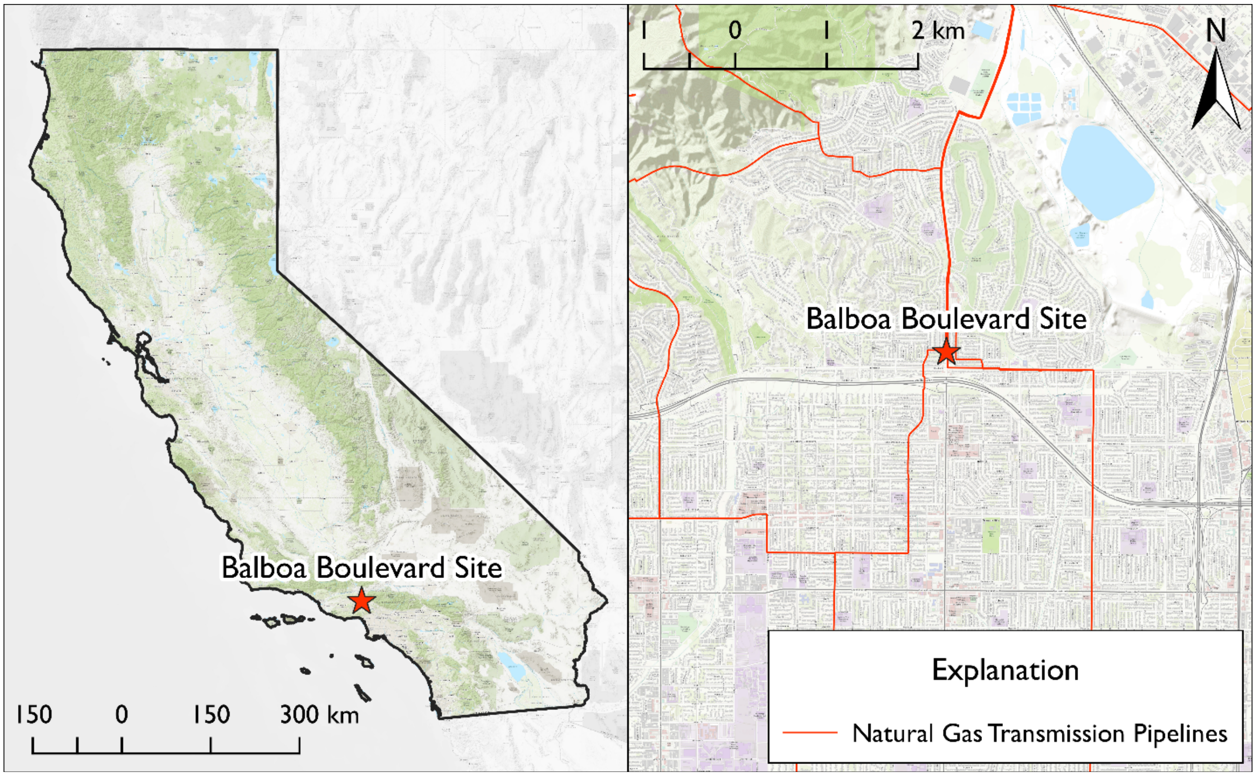
This report assesses the demonstration sites at several analysis levels to compare and to evaluate the results and provide insights into the uncertainties associated with the selected procedures.

2.2 Balboa Boulevard Demonstration Site

2.2.1 Introduction to Balboa Boulevard Case History

Balboa Boulevard in the San Fernando Valley of California between Lorillard and Rinaldi Streets (approximate latitude/longitude: 34.280892, -118.502137) contains several natural gas, water, and oil transmission pipelines. The site experienced strong ground motions from two earthquakes in the twentieth century: the 1971 M_W 6.6 San Fernando and the 1994 M_W 6.7 Northridge earthquakes. No ground deformation was reported at the site following the San Fernando earthquake while significant lateral ground deformation resulted in the rupture of four pipelines, including two natural gas lines, during the Northridge earthquake. Balboa Boulevard is an important and useful demonstration site for evaluating the procedures in *OpenSRA* because of the site's history experiencing strong ground motions from two earthquakes; one that resulted in ground and pipe failures and one that did not, the robust knowledge of the subsurface conditions from United States Geological Survey (USGS) explorations, and the in-depth knowledge of the pipeline properties, which are available publicly. Figure 1 displays a general site location map with locations of natural gas transmission pipelines in the San Fernando Valley.

Figure 1: General Location Map of Balboa Boulevard Demonstration Site



Location of Balboa Boulevard demonstration site in the northern San Fernando Valley with map of natural gas transmission pipelines

2.2.2 Geologic, Geotechnical, and Groundwater Data

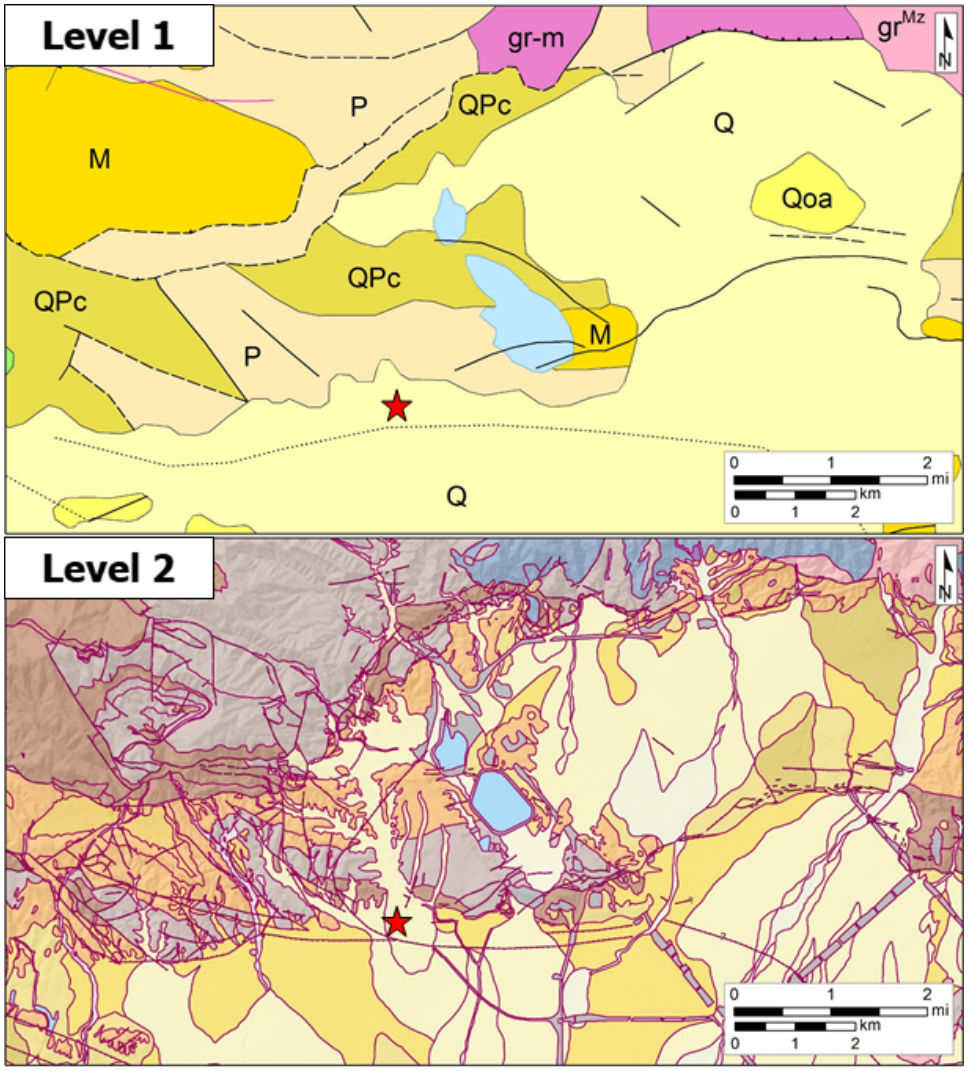
The geologic, geotechnical, and groundwater data available at the Balboa Boulevard demonstration site are used to perform ground failure assessments at Levels 1 – 3. The focus of this report is comparing and contrasting the quality and resolution of the data at different analysis levels to evaluate their impact on the estimated probability of liquefaction triggering, lateral spread displacement, and landslide displacement, including assessment of the uncertainty associated with these estimates. A thorough review of the data availability is presented in the Bain et al. (2022c) PEER report.

Level 1 geologic maps include the 1:750,000 scale statewide map from California Geological Survey (Geologic Map of California, 2010), which maps the Balboa Boulevard site as Q, Quaternary Alluvium, and the Wills et al. (2015) statewide geologic map, developed for the purpose of mapping the time-averaged shear wave velocity in the upper 30 m of the subsurface, V_{S30}, at the statewide scale, which maps the site as Qal3, Quaternary Alluvium with topographic slope greater than 2%. The Level 2 geologic map is the 1:100,000 scale Bedrossian et al. (2012) map, which maps the site as Qyf, Young Alluvial Fan Deposits. At Levels 1 and 2, there is no geotechnical or subsurface data available.

At Level 3, CPTs and soil exploratory borings are available from the USGS (Bennett et al., 1998; Holzer et al., 1999). Bennett et al. (1998) and Holzer et al. (1999) divide the soil underlying Balboa Boulevard into four units from the ground surface downward as: A, B, C, and D. Bennett et al. (1998) describes unit A as an approximately 1-meter-thick artificial fill consisting of road and agricultural soil. Unit B consists of late Holocene sheet flood and debris flow deposits typical to alluvial fans, which were actively aggregating prior to human intervention to channelize and control stormwater runoff. Unit C is described as late Pleistocene to middle Holocene fluvial deposits. Unit D is described as Pleistocene age dense and firm sand, silt, and clay fluvial deposits, which may be a part of the Saugus formation. The transition from Holocene to Pleistocene sediments is marked by a significant increase in CPT tip resistance and standard penetration test (SPT) blow counts.

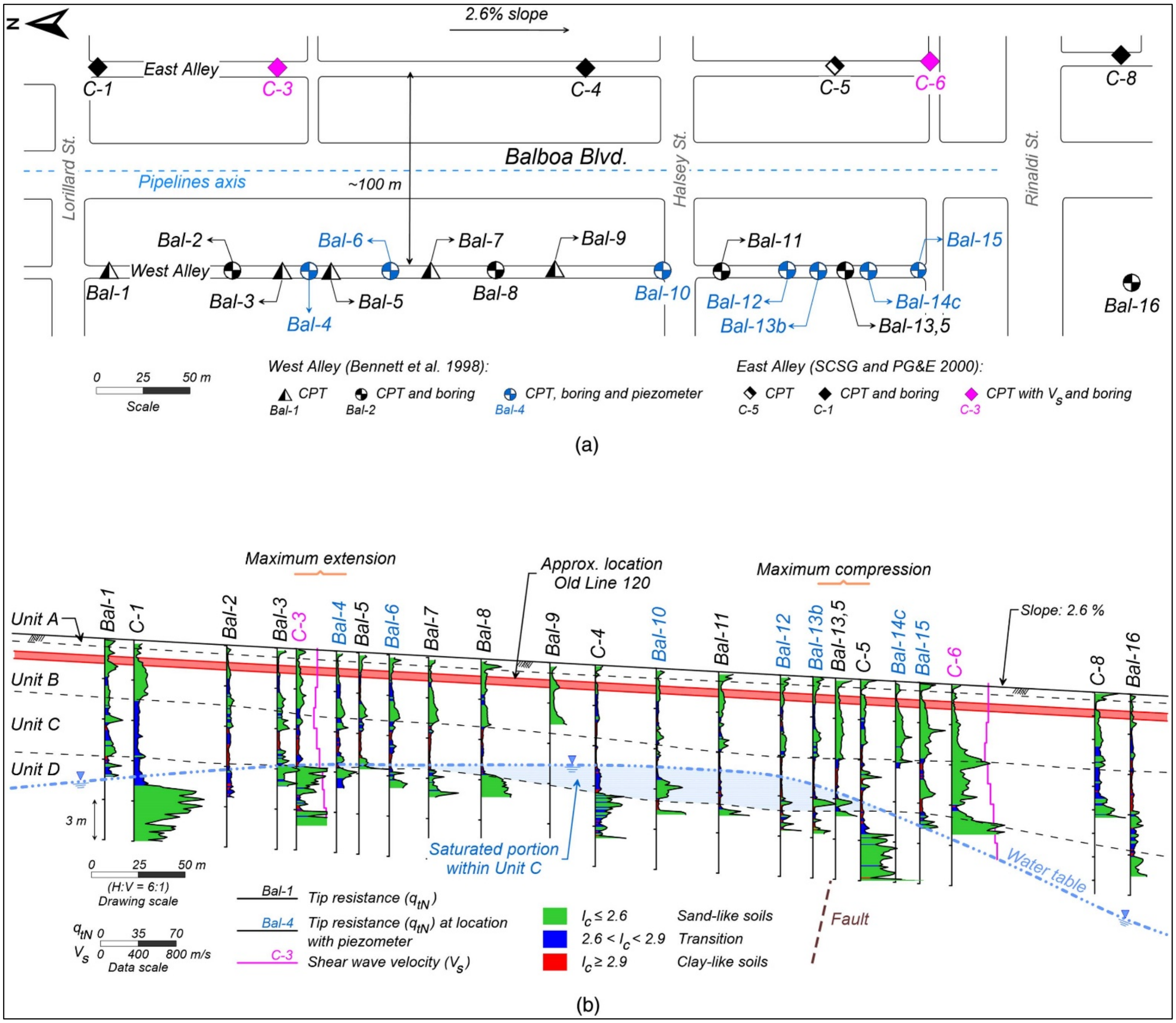
The differences between the Level 1 and Level 2 maps are displayed in Figure 2, which shows the significant detail gained moving from the small scale statewide geologic map (CGS, 2010) to the larger scale geologic map from Bedrossian et al. (2012). The red star denotes the location of the Balboa Boulevard site. Figure 3 shows the Level 3 site-specific geologic cross-section, geotechnical data, and groundwater model from Pretell et al. (2021).

Figure 2: Comparison of Level 1 and Level 2 Geologic Maps



Comparison of Level 1 1:750,000 scale statewide geologic map (CGS, 2010) and Level 2 1:100,000 scale Bedrossian et al. (2012) geologic map

Figure 3: Level 3 Geologic, Geotechnical, and Groundwater Data



Level 3 geologic, geotechnical, and groundwater data from Pretell et al. (2021)

The groundwater data availability and quality and its impact on the liquefaction triggering and lateral spread displacement evaluation at each analysis level is similarly investigated. At Level 1, the depth to the groundwater table is estimated using a groundwater table model with 250-m resolution described by Fan & Miguez-Macho (2010). This model estimates the depth to groundwater at the Balboa Boulevard demonstration site to be approximately 46 m. At Level 2, the depth to groundwater can be estimated using mapped liquefaction hazard zones, which denote areas where liquefiable soils may exist, and the groundwater table may be less than approximately 12 m deep. Using this information, a more precise depth to groundwater distribution, albeit still with large aleatory variability and epistemic uncertainty, can be developed. At Level 3, USGS measurements of the depth to groundwater along the alignment of the buried pipelines allow for analysis with greater accuracy. The USGS measurements show a water table that varies from approximately 7.2 to 10 m deep. The Level 3 groundwater model is shown with the blue dashed line in Figure 3.

2.2.3 Infrastructure Data

At the time of the 1971 San Fernando earthquake, at least five pipelines are known to have been installed at the Balboa Boulevard site while at the time of the 1994 Northridge earthquake, eight pipelines are known to have been installed. Pipelines at Balboa Boulevard, including important properties and characteristics, are presented in Table 1. Table 2 lists additional pipeline properties necessary for evaluations using Level 2 and Level 3 data. Typical pipeline properties with an appropriate amount of uncertainty are assumed at Level 1.

Table 1: Summary of Pipelines Properties at Balboa Boulevard

Name (#)	Installation Date	Type	Material & Welds	Outside Diameter (mm)	SMYS⁺ (MPa)	Coating	Adhesion Factor
Old Line 120 (1)	1930[1]	Natural Gas[1]	Grade B Steel with Early SEAW*[1]	560[1]	185	Coal Tar Enamel[1]	0.7[3]
New Line 120 (2)	1994[1]	Natural Gas[1]	X-60 Steel with Modern SEAW*[1]	610[1]	415	Fusion Bonded Epoxy[1]	0.7[3]
Gas Distribution Line (3)	1957[1]	Natural Gas[1]	X-42 Steel with Oxyacetylene Girth Welds[1]	168[1]	185	Coal Tar Enamel	0.7[3]
Line 3000 (4)	1956[1]	Natural Gas[1]	X-52 Steel with Modern SEAW*[1]	762[1]	360	Coal Tar Enamel[1]	0.7[3]
Line 3003 (5)	1958[1]	Natural Gas[1]	X-52 Steel with Modern SEAW*[1]	762[1]	360	Coal Tar Enamel[1]	0.7[3]
Granada Trunk Line (6)	1956[2]	Water[2]	Grade C Steel with Welded Slip Joint & Mechanical Coupling[2]	1257[2]	205	2.54 cm Cement Mortar beneath Coal Tar Enamel[2]	0.7[3]
Rinaldi Trunk Line (7)	1978[2]	Water[2]	Grade C or D Steel with Welded Slip Joints[2]	1723[2]	205 – 230	2.54 cm Cement Mortar beneath Coal Tar Enamel[2]	0.7[3]
Mobil Oil Line (8)	1991[1]	Oil[1]	X-52 Steel with Modern SEAW*[1]	406[1]	360	Polyethylene[1]	0.7[3]

* Shielded Electric Arc-Welded Circumferential Girth Welds

⁺ SMYS = Specified Minimum Yield Stress

[1] SoCalGas & PG&E (2000)

[2] Ziotopoulou et al. (2021)

[3] Estimated from Tomlinson (1957) curve for clay with Su≈48 kPa

Table 2: Summary of Additional Pipelines Properties at Balboa Boulevard

Name (#)	Wall Thickness, t (mm)	Cross-Sectional Area, a (mm^2)	D/t	Internal Operating Pressure (MPa)	Young's Modulus (GPa)	Cover (m)
Old Line 120 (1)	7.1[1]	12333	79	1.34[1]	200	1.0[1]
New Line 120 (2)	6.4[1]	12136	95	1.3	200	1.2*[1]
Gas Distribution Line (3)	4.8[1]	2461	35	0.3	200	1.2*[1]
Line 3000 (4)	9.5[1]	22458	80	3.2	200	5.2[t1] 2.4[c1]
Line 3003 (5)	9.5[1]	22458	80	3.2	200	2.4[t1]
Granada Trunk Line (6)	6.5[2]	25536	193	1.2	200	1.1[2]
Rinaldi Trunk Line (7)	9.5[2]	51140	181	0.6	200	1.5[2]
Mobil Oil Line (8)	9.5[1]	11834	43	3.45[1]	200	4.0[t] 1.8[c]

* Assumed Value

[t] Soil Cover at Tensile Deformation Zone

[c] Soil Cover at Compressive Deformation Zone

[1] SoCalGas & PG&E (2000)

[2] Ziotopoulou et al. (2021)

2.2.4 Pipeline Fragility Functions and Pipeline Critical Strain Analysis

An important aspect of this research is developing appropriate fragility functions and critical strain limits for the pipelines at the Balboa Boulevard site. As described in the Bain et al. (2022a) report, strain-based tensile and compressive fragility functions were developed for girth-welded continuous steel pipelines. The resulting fragilities for estimating the probability of tensile leakage and tensile rupture are presented as Equation (2.1) and Equation (2.2) and have aleatory variability, β_r=0.3 and epistemic uncertainty, β_u=0.2. β_r represents the aleatory variability due to inherent randomness in the loading conditions (e.g., eccentricities in the pipe alignment) and pipe properties (e.g., weld quality). β_u represents the epistemic uncertainty in the mean or median value (i.e., uncertainty resulting from whether the model is correct).

$$Prob(Tensile\ Leakage) = 1 - \Phi\left(\frac{-\ln(\varepsilon_p) + \ln(2.34)}{0.3}\right) \tag{2.1}$$

$$Prob(Tensile\ Rupture) = 1 - \Phi\left(\frac{-\ln(\varepsilon_p) + \ln(4.68)}{0.3}\right) \tag{2.2}$$

The resulting fragility to estimate the probability of compressive rupture is presented as Equation (2.3) and has aleatory variability, β_r=0.5 and epistemic uncertainty, β_u=0.25.

$$Prob(Compressive\ Rupture) = 1 - \Phi\left(\frac{-\ln(\varepsilon_{p-eq}) - 1.617 * \ln\left(\frac{D}{t}\right) + 2.130}{0.5}\right) \tag{2.3}$$

Using these fragility functions, estimates for critical strain limits are made for each of the pipelines and presented in Table 4 for the 90%, 50%, and 10% probabilities of exceedance. Further explanation for these values as well as an analysis of appropriate Ramberg-Osgood parameters is found in Bain et al. (2022c) PEER report.

Table 3: Estimated Critical Strain Limits for Pipelines at Balboa Boulevard at 90%, 50%, and 10% Probabilities of Exceedance for Tensile-Induced Leakage, Tensile-Induced rupture, and Compressive-Induced rupture

Name (#)	Tensile Critical Pipe Strain Limits Corresponding to Leakage			Tensile Critical Pipe Strain Limits Corresponding to Rupture			Compressive Critical Pipe Strain Limits Corresponding to Rupture		
	90%	50%	10%	90%	50%	10%	90%	50%	10%
Old Line 120 (1)	0.15% for joints with severe weld flaws			0.15% for joints with severe weld flaws			0.38%	0.72%	1.37%
	1.0% for joints without severe weld flaws			1.0% for joints without severe weld flaws			0.38%	0.72%	1.37%
New Line 120 (2)	1.59%	2.32%	3.44%	3.19%	4.68%	6.88%	0.28%	0.54%	1.02%
Gas Distribution Line (3)	0.80%	1.17%	1.72%	1.17%	2.34%	3.44%	1.42%	2.69%	5.11%
Line 3000 (4)	1.59%	2.32%	3.44%	3.19%	4.68%	6.88%	0.37%	0.71%	1.34%
Line 3003 (5)	1.59%	2.32%	3.44%	3.19%	4.68%	6.88%	0.37%	0.71%	1.34%
Granada Trunk Line (6)	0.80%	1.17%	1.72%	1.17%	2.34%	3.44%	0.09%	0.17%	0.32%
	MC[1]			MC[1]			MC[1]		
Rinaldi Trunk Line (7)	0.80%	1.17%	1.72%	1.17%	2.34%	3.44%	0.10%	0.19%	0.36%
Mobil Oil Line (8)	1.59%	2.32%	3.44%	3.19%	4.68%	6.88%	1.02%	1.93%	3.66%

[1] Mechanical Coupling – This type of joint has negligible resistance to axial pullout and failure is defined by a displacement criterion. Estimating a critical strain limit is not appropriate.

2.3 Honor Rancho Natural Gas Storage Facility Demonstration Site

The Honor Rancho Natural Gas Storage Facility in Los Angeles County (California, USA) serves as a demonstration site for assessing the fragility of gas storage wells and caprocks. From 1955 to 1975, 23 wells were drilled for oil and gas production in this field. In 1975, the field was converted to gas storage and 38 wells were completed to the storage zone (i.e., the

Wayside 13 sand unit) (Southern California Gas Company, 2009; Jeanne et al., 2020). The Honor Rancho Underground Storage Facility was also the subject of a project led by LBNL to develop a risk management system for underground gas storage infrastructure (Zhang et al., 2022). As part of that study, Jeanne et al. (2020) performed a study on the potential impact on the caprock integrity and on the stability of the reservoir bounding faults, considering the impact of irreversible geomechanical behavior during the initial reservoir depletion and subsequent pressure cycling. That study did not consider the seismic impact on wells and caprocks.

Two major surface fault systems are mapped near the facility, which is in a high ground shaking hazard zone. The San Gabriel fault delineates the northeastern margin of the field, but in the recent CCST (2018) assessment of underground gas storage in California, the likelihood that surface faults intersect Honor Rancho storage wells is judged to be relatively low. However, blind (buried) faults have also been documented within the Honor Rancho storage complex and one interpretation suggests that at least one of these faults intersects storage wells and may be seismically active. This component of *OpenSRA* was demonstrated using scenarios involving local and distant earthquakes and displacements on faults transecting the storage complex. Additionally, the 1971 San Fernando and 1994 Northridge earthquake scenarios were analyzed to confirm that *OpenSRA* estimates negligible damage for these scenarios to be consistent with field observations.

For this demonstration and validation of *OpenSRA* at the Honor Rancho Gas Storage facility, only publicly available data were used. The subsurface well data for Honor Rancho that were used including well location and well design information (e.g., cemented or not cemented casing) are all publicly available data online at California Geologic Energy Management Division (CalGEM) of the California Department of Conservation. LBNL acquired such data from all California UGS facilities to develop the typical well configurations (modes) that were used for the analysis of impact on gas storage wells. Moreover, regarding potential caprock leakage, the publicly available data used were a map of the elevation of the base of the caprock retaining the stored gas at Honor Rancho as well as average pressure. The elevation of the base of the caprock is available from California Division of Oil and Gas (1991). Thus, this validation for the Honor Rancho Storage facility also demonstrates the use of publicly available data on wells and caprocks that are generally available for other California gas storage facilities.

2.4 McDonald Island Natural Gas Storage Facility Demonstration Site

Details of the assessment at the McDonald Island demonstration site located near the Sacramento-San Joaquin River Delta are covered by a non-disclosure agreement (NDA) with the Pacific Gas & Electric (PG&E) Company. Accordingly, the results of the validation exercise at this site are only summarized in this report and Pantoli et al. (2022) PEER report.

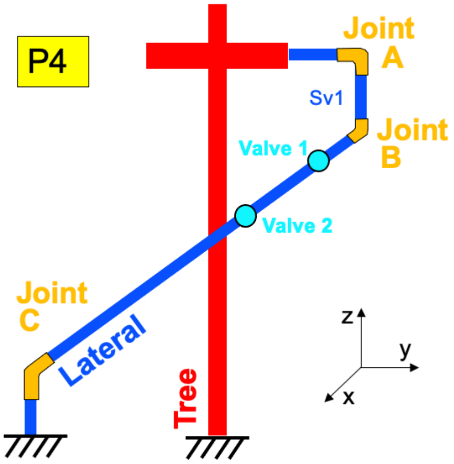
The approach to generate fragility curves for the surface infrastructure involved analysis of the most vulnerable and common surface subsystems separately, as detailed in the Pantoli et al., (2022) report. Namely, the analysis was performed on two common subsystems essential to operations at McDonald Island: the wellhead tree and connected piping (WTP) and vertical pressure vessels (VPV). These subsystems were selected with input from the Technical Advisory Committee (TAC) and noted to be widespread at McDonald Island and other gas storage facilities. For the WTP subsystem, three possible configurations of pipes were considered and for each of these configurations, the joints were considered either all elbows or all tees, for a total of six cases. Importantly, transitions in structural piping are the most vulnerable locations likely to be damaged. The VPVs were considered either fixed at the base or connected to the base using anchors designed to stretch and thus minimize seismically induced rotations. Modern VPVs are constructed using the latter method.

The subsystems at this demonstration site had the following key geometric features:

1. Wellhead type 1: Configuration P4, see **Error! Not a valid bookmark self-reference.**, with a mix of elbows and tees. Height of the wellhead tree = 2.74 m; length of the horizontal run of the pipe = 2.44 m; weight of the valves = 1.20 kN.
2. Wellhead type 2: Configuration P4 with a mix of elbows and tees. Height of the wellhead tree = 3.96 m; length of the horizontal run of the pipe = 4.88 m; weight of the valves = 2.54 kN.
3. Pressure vessel with stretch length in the anchors. Total height of the vessel = 10.97 m; Diameter of the vessel 2.26 m; thickness = 14.0 cm; diameter of the anchor = 3.18 cm.

It is noted that since the WTP subsystems includes a mix of tees and elbows, both conditions of all-tees and all-elbows were analyzed.

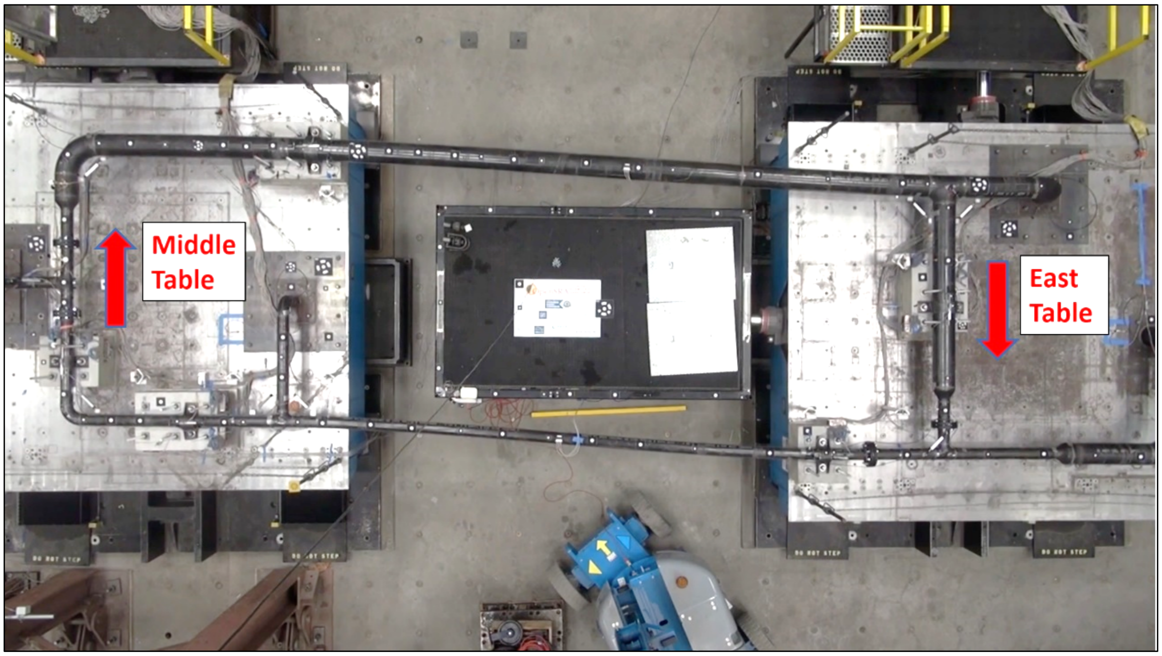
Figure 4: Schematic of the P4 configuration of the WTP subsystem



The probability of leakage and rupture in the pipes of the wellheads was determined by evaluating the tensile strain for the type of pipe, namely 10 cm diameter Schedule 80, while the probability of rupture of the pressure vessels was associated with breakout limits of the anchors at the base of the vessels. The earthquake selected for this demonstration site was the 1989 M_w 6.9 Loma Prieta, with mean PGA as estimated by ShakeMap equal to 0.08 g. The aleatory variability is estimated to equal β_r=0.3 for the WTP subsystem and β_r=0.45 for the VPV subsystem, while the epistemic uncertainty is estimated to equal β_u=0.25 for both subsystems. For the WTP subsystem, these values are estimated from those relative to the pipelines explained in the sections above. For the VPV subsystem, the aleatory variability was estimated by considering the variability of the main parameters used in the analysis, notably the material properties. Additional details may be found in Pantoli et al. (2022).

Experimental assessment of a representative subsystem was conducted using two shake tables. The subsystem was subjected to 200% of the biaxial ground motions recorded during El Centro 1941 earthquake producing 0.42 g and 0.56 g in the longitudinal and latitudinal directions, respectively. The subsystem was also subjected to differential displacement, as shown in Figure 5, which exceeded twice the relative displacement amplitude expected between the existing raised platforms at the McDonald Island facility. These experiments estimate that the subsystem would not experience any damage or loss in pressure during earthquake motions. Some components experienced yielding during the application of the differential displacements; however, no loss in pressure was observed. More details of these experiments can be found in the Elfass et al. (2022) report.

Figure 5. Piping deformation at extreme relative shake table displacement



2.5 Cordelia Junction Natural Gas Pipeline Demonstration Site

Details of the assessment at the Cordelia Junction demonstration site located near Fairfield, California are covered by a non-disclosure agreement (NDA) with the Pacific Gas & Electric (PG&E) Company. Accordingly, the results of the validation exercise at this site are only summarized in this report and the Bain et al. (2022c) PEER report.

The Cordelia Junction demonstration site includes a 610 mm outside diameter, 7.9 mm wall thickness, X-52 and X-60 grade steel natural gas transmission pipeline that was installed in 1966, which crossed a rainfall-induced active landslide before being rerouted around the landslide in 2017. The pipeline also crosses an active fault capable of rupturing to the ground surface. The native earth slopes at the site did not undergo noticeable permanent displacement during either the 1989 M_w 6.9 Loma Prieta earthquake or the 2014 M_w 6.0 South Napa earthquake, which occurred when the pipeline crossed the landslide.

OpenSRA is used to evaluate the seismic risk to the pipeline in its original orientation (when it crossed the active landslide) for the ground shaking experienced at the site as estimated by ShakeMap during the Loma Prieta and South Napa earthquakes. Additionally, the original pipeline alignment that crossed the landslide and the post-2017 pipeline alignment that does not cross the landslide are assessed for a hypothetical M_w 6.9 earthquake that produces ground shaking with PGA=0.5 g at the site to assess the relative seismic risk reduction achieved from the pipeline relocation.

CHAPTER 3: Project Results

3.1 Balboa Boulevard Demonstration Site Assessment Results

3.1.1 Liquefaction Triggering and Lateral Spread Displacement Assessment

To enable Level 1 assessments of liquefaction triggering with uniform data resolution across the entire state of California, models from Zhu et al. (2015) and Zhu et al. (2017) are applied. These models are described in detail in the Bain et al. (2022a) and (2022b) reports. These regional-scale methods use inputs that are proxies for geotechnical, geologic, and groundwater conditions to quantitatively assess the probability of liquefaction triggering at the statewide scale. Zhu et al. (2015, 2017) state their models capture general trends observed at the regional scale for a few earthquakes. They do not provide quantitative assessments of the performance of their models. As no subsurface data are used to inform the models, Level 1 liquefaction triggering assessments are judged to have very high epistemic uncertainty. For this assessment, both the Zhu et al. (2015, 2017) models are evaluated and given equal weighting.

At Level 1, the Hazus (FEMA, 2020) lateral spread displacement model, described in the Bain et al. (2022a) and (2022b) reports, can be used to estimate liquefaction-induced lateral spread displacement. The Hazus (FEMA, 2020) model is the only model currently available capable of estimating lateral spread displacement at the statewide scale. At Level 1, the Zhu et al. (2017) procedure is used to estimate the relative liquefaction susceptibility category (e.g., none, very low, low, moderate, high, very high). The expected lateral spread displacement is obtained by multiplying the probability of liquefaction triggering by the estimated lateral spread displacement.

Using the Level 1 Zhu et al. (2015, 2017) liquefaction triggering models and the Hazus (FEMA, 2020) lateral spread displacement model, and assuming the mean Level 1 input parameters, the estimated lateral spread displacement equals 1.0 cm for the San Fernando earthquake and 2.5 cm for the Northridge earthquake, which are negligibly small values for both earthquakes.

At Level 2, liquefaction triggering can be assessed using Youd & Perkins (1978)-type geologic based assessments in conjunction with the Hazus (FEMA, 2020) liquefaction triggering methodology. Youd & Perkins (1978)-type assessments characterize the relative liquefaction susceptibility of mapped surficial geologic deposits based on the depositional environment and age of the deposits. This procedure can be applied across selected regions, such as the San Francisco Bay area or in and around Los Angeles, that have large scale geologic mapping that differentiates Quaternary units. Lateral spread displacement is again estimated using the procedure from Hazus (FEMA, 2020) or it can be estimated using the new procedure introduced in the Bain et al. (2022a) and (2022b) reports, which estimates a distribution of Lateral Displacement Index (LDI) using models conditioned on surficial geology, depth to groundwater (GWT), peak ground acceleration (PGA), and earthquake magnitude (M_W). The distribution of LDI is converted to a distribution of lateral spread displacement using the topographic relationships from Zhang et al. (2004), as described in the Bain et al. (2022a) and (2022b) reports.

Using the Level 2 Hazus (FEMA, 2020) liquefaction triggering model and the Hazus (FEMA, 2020) lateral spread displacement model, and assuming the mean Level 2 input parameters, the estimated lateral spread displacement equals 4.6 cm for the San Fernando earthquake and 17 cm for the Northridge earthquake. The estimated lateral spread displacement for the San Fernando earthquake is still negligibly small at Level 2 but is significantly greater for the Northridge earthquake at Level 2 compared to Level 1.

At Level 3, site-specific subsurface data such as CPTs are available. Several probabilistic liquefaction triggering procedures are available for use with CPT data such as the Ku et al. (2012) probabilistic modification to the Robertson & Wride (1998) as updated by Robertson (2009) procedure and the Boulanger & Idriss (2016) procedure. CPT-based procedures for estimating potential lateral spread displacements are also available, such as the Zhang et al. (2004) method. With CPT data, the estimated probability of liquefaction triggering at each measurement increment is used to estimate the fractional contribution to the total lateral displacement at that increment. The total lateral spread displacement estimate is obtained by summing the fractional displacements. Note that no overall probability of liquefaction triggering is obtained by following this process.

Using the Boulanger & Idriss (2016) probabilistic liquefaction triggering method, the Zhang et al. (2004) lateral spread displacement model, and assuming the mean Level 3 input parameters along with a non-negligible displacement threshold of 5 cm, the average lateral spread displacement equals 14 cm for the San Fernando earthquake and 51 cm for the Northridge earthquake. The displacement reported for each earthquake is the average of the of the lateral spread displacements from all CPTs with estimated displacement greater than 5 cm (three CPTs for the San Fernando earthquake, nine CPTs for the Northridge earthquake). Displacements estimated with the Zhang et al. (2004) method are an index for site performance; that is, the larger the estimated displacement, the worse the site is expected to perform. Furthermore, for lateral spread displacement to occur, there must exist in the subsurface a relatively thick and continuous layer of saturated, loose sand. Therefore, we implement a non-negligible displacement threshold of 5 cm to distinguish between locations where lateral spread displacements are likely to be negligibly small or not manifest at all, and locations where lateral spread displacements are both more likely to manifest and are more likely to be severe.

The Level 3 assessment suggests much higher lateral spread displacement hazard for both the San Fernando and Northridge earthquakes compared to the Level 1 and Level 2 lateral movement assessments. The mean estimated displacement for the Northridge earthquake is equal to the average displacement measured following the Northridge earthquake (approximately 40 – 60 cm). The estimated mean probability of liquefaction triggering (P_L) and calculated mean lateral spread displacement at Levels 1, 2, and 3 for the San Fernando and Northridge earthquakes are summarized in Table 4. Also, Table 4 lists the expected mean lateral spread displacement (mean probability of liquefaction triggering multiplied by the calculated mean lateral spread displacement) at Levels 1, 2, and 3 for both earthquakes.

Table 4: Estimated Mean Probability of Liquefaction Triggering and Mean Lateral Spread Displacement

Earthquake	**San Fernando**			**Northridge**		
	P_L (%)	**Mean Calc. Lat. Disp. (cm)**	**Mean Expected Disp. (cm)**	**P_L (%)**	**Mean Calc. Lat. Disp. (cm)**	**Mean Expected Disp. (cm)**
Level 1	6.0%	17.1 cm	**1.0 cm**	13.5%	18.2 cm	**2.5 cm**
Level 2	5.6%	82.4 cm	**4.6 cm**	5.7%	299 cm	**17 cm**
Level 3	N/A	14.4 cm	**14 cm**	N/A	50.6 cm	**51 cm**

Mean probability of liquefaction triggering and mean lateral spread displacement at the Balboa Boulevard demonstration site as estimated using the described Level 1, Level 2, and Level 3 methods for the San Fernando and Northridge earthquakes.

3.1.2 Liquefaction Triggering and Lateral Spread Displacement Assessment Discussion

The Levels 1 – 3 assessments at Balboa Boulevard for the San Fernando earthquake suggest negligible displacement at Levels 1 and 2 and elevated lateral displacement hazard with mean displacement of 14 cm at Level 3. The Level 1 and 2 assessments underestimate the liquefaction-induced lateral movement hazard at the site because they do not capture well the geotechnical and groundwater conditions at the site. The Level 3 assessment with CPTs indicate deposits of loose, liquefiable sands exist in the subsurface and the Level 3 groundwater data suggests small variations in the depth to the groundwater table can "turn on" or "turn off" liquefaction. Repeated measurements of the groundwater table over time would significantly reduce uncertainty and greatly improve the reliability of the assessments.

The Levels 1 – 3 assessments for the Northridge earthquake show progressively better estimates for the amount of lateral spread displacement at each level. The assessment improves at each successive level primarily because the uncertainty in the geotechnical conditions and the depth to the groundwater are reduced at each level. To assess the sensitivity of each input parameter at each analysis level, tornado plots are shown in Figure 6 through Figure 11. Tornado plots show the sensitivity to each of the variables in an assessment. The larger the box, the more sensitive the assessment is to that variable.

The tornado plot for the Level 1 lateral spread displacement assessment for the San Fernando earthquake is shown in Figure 6. The tornado plot for the Level 1 lateral spread displacement assessment for the Northridge earthquake is shown in Figure 7.

Figure 6: Level 1 Lateral Spread Displacement Assessment Tornado Plot for the San Fernando Earthquake

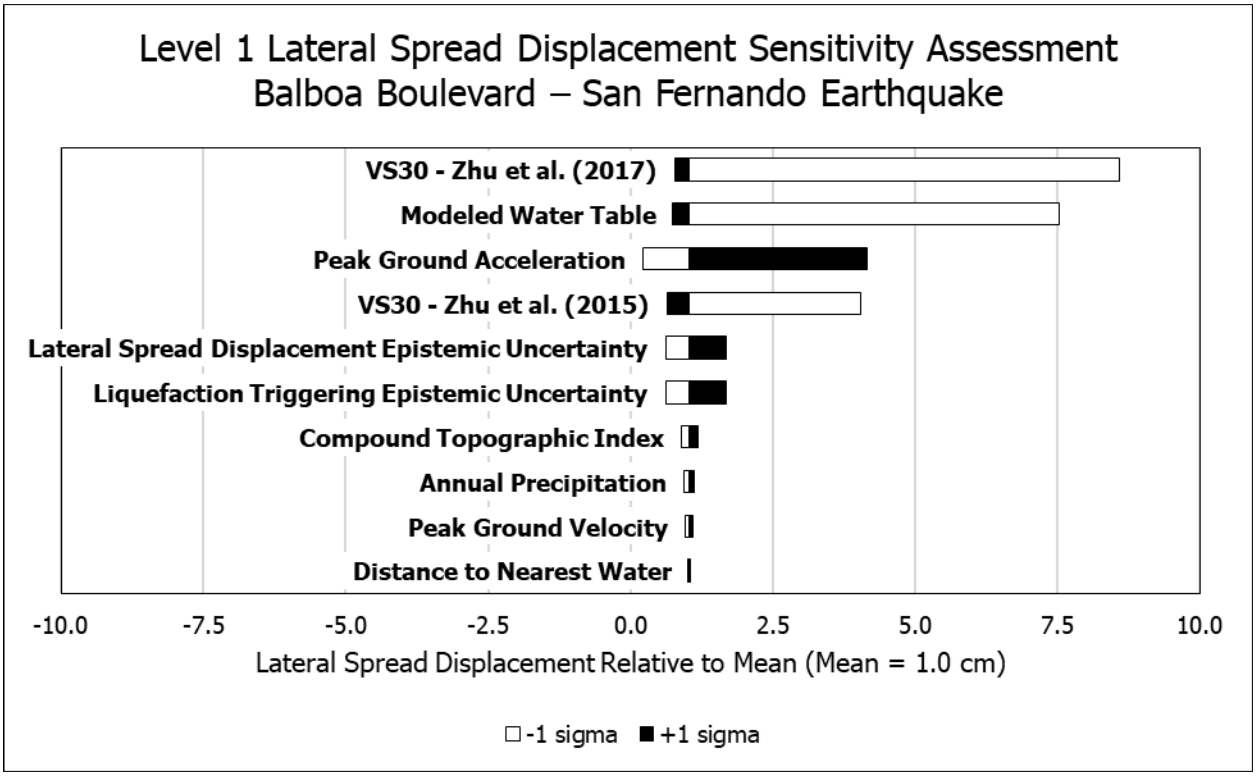
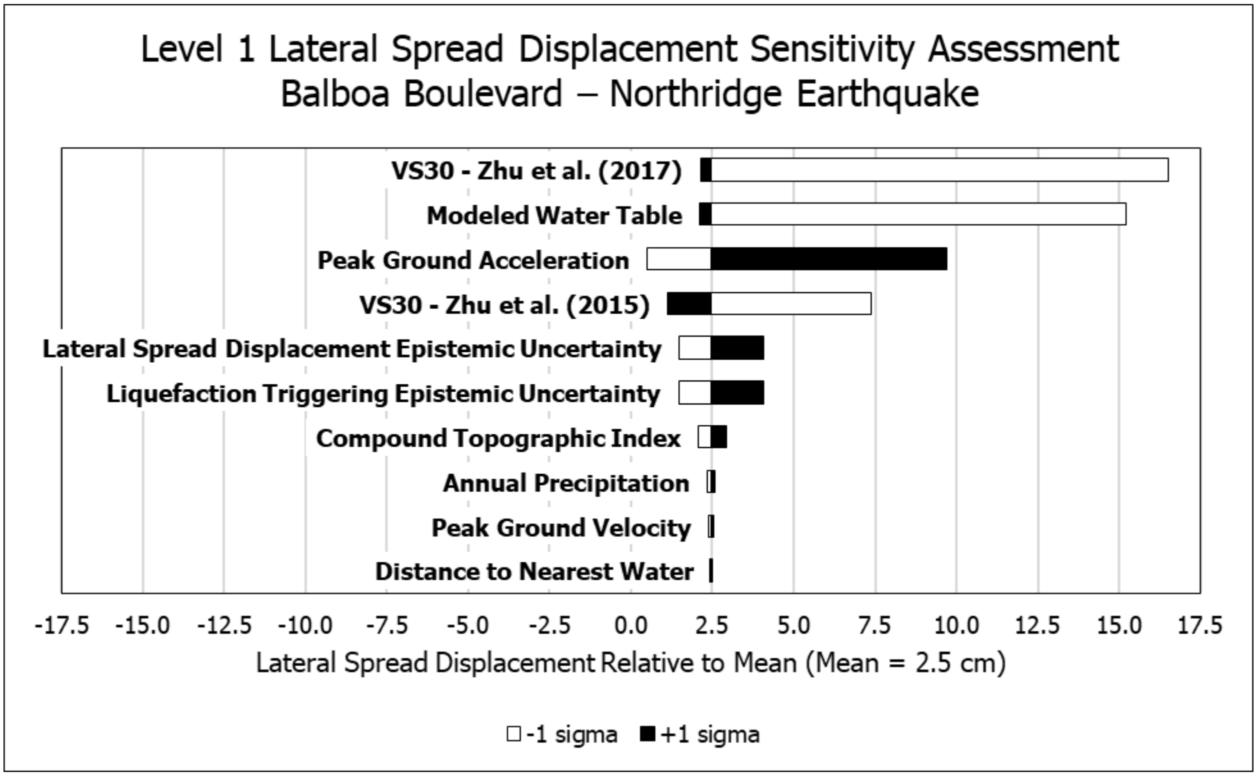


Figure 7: Level 1 Lateral Spread Displacement Assessment Tornado Plot for the Northridge Earthquake



At Level 1, the lateral spread displacement assessment for both earthquakes is most sensitive to the V_{S30} (a proxy for the soil depositional environmental and thus, geotechnical properties). The lateral spread displacement is also very sensitive to the modeled water table parameter in the Zhu et al. (2017) liquefaction triggering procedure.

The tornado plot for the Level 2 lateral spread displacement assessment for the San Fernando earthquake is shown in Figure 8. The tornado plot for the Level 2 lateral spread displacement assessment for the Northridge earthquake is shown in Figure 9.

Figure 8: Level 2 Lateral Spread Displacement Assessment Tornado Plot for the San Fernando Earthquake

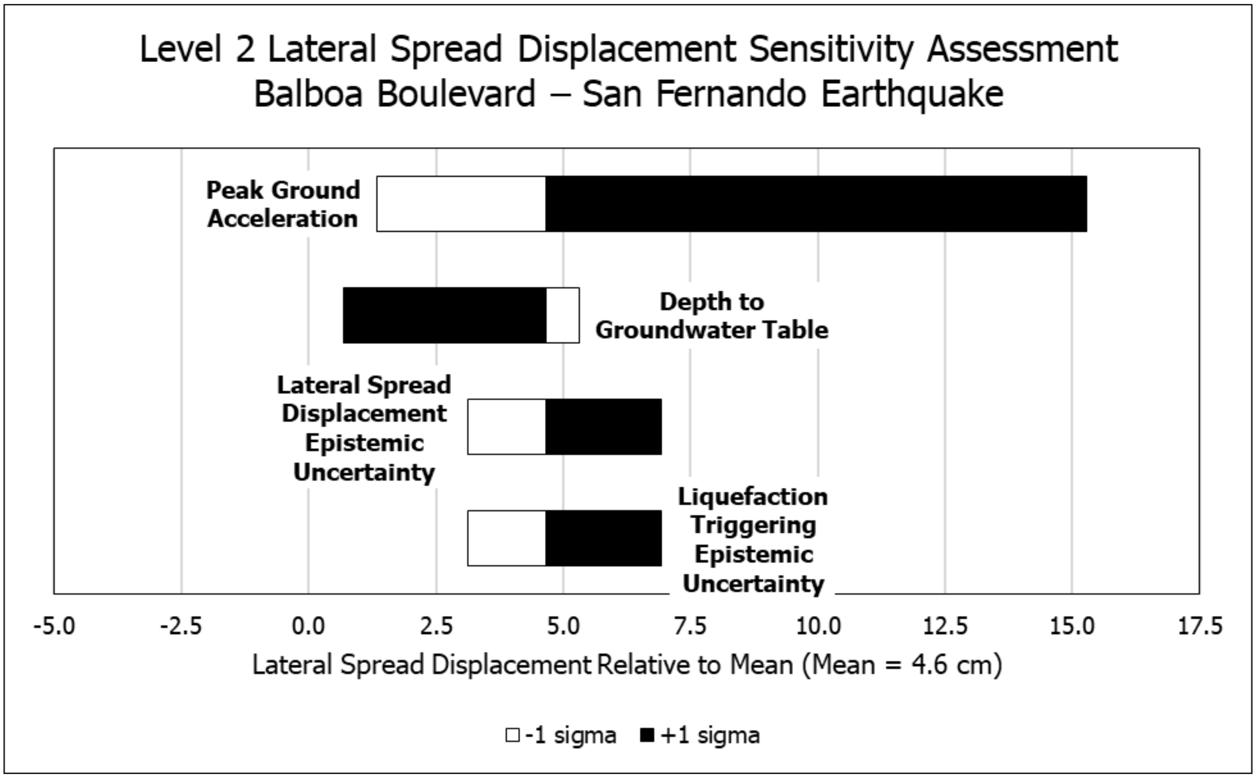
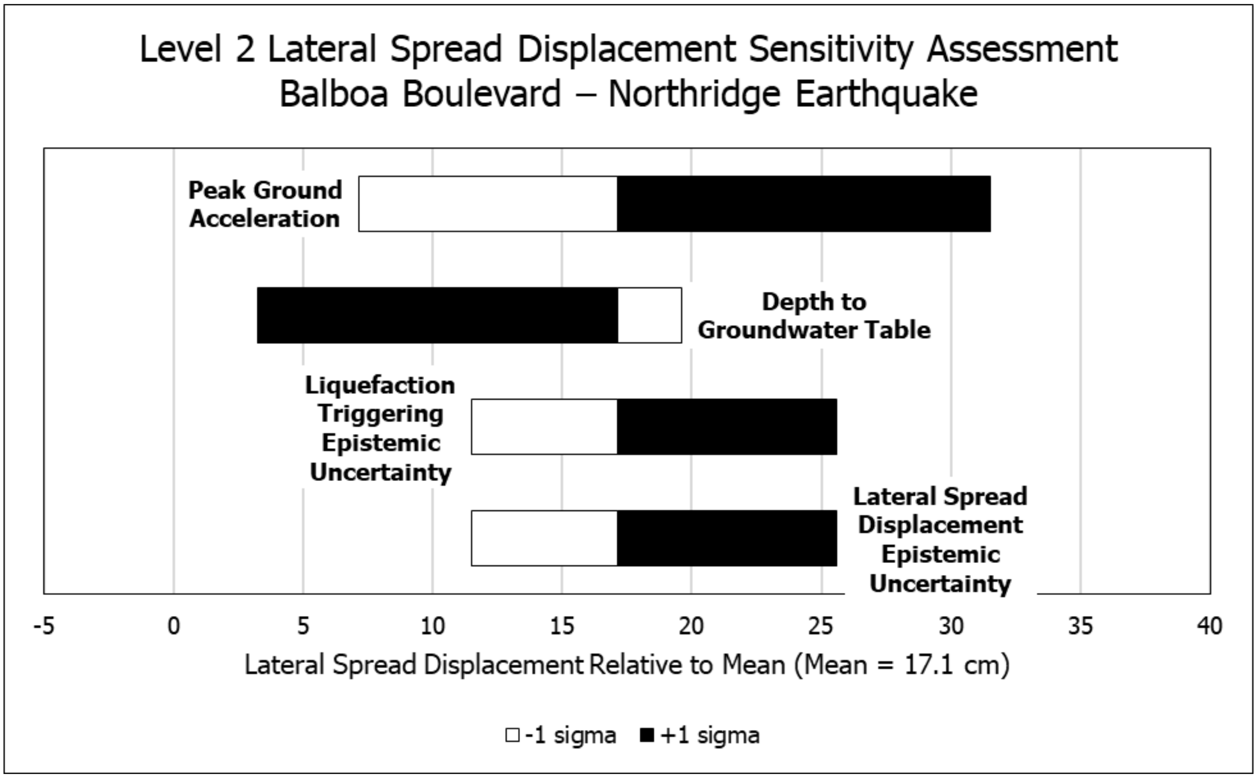


Figure 9: Level 2 Lateral Spread Displacement Assessment Tornado Plot for the Northridge Earthquake



Compared to the Level 1 assessment, at Level 2, the lateral spread displacement assessment is most sensitive to the PGA for both the San Fernando and Northridge earthquakes. The sensitivity to the depth to the groundwater table is reduced to about the same as the epistemic uncertainty in the liquefaction triggering and lateral spread displacement models. The reduced uncertainty in the depth to the groundwater table (see Bain et al., 2022c report for further information) improves the reliability of the estimates at Level 2.

The tornado plot for the Level 3 lateral spread displacement assessment for the San Fernando earthquake is shown in Figure 10. The tornado plot for the Level 3 lateral spread displacement assessment for the Northridge earthquake is shown in Figure 11. The uncertainties in the application of the Level 3 analysis due to key sources of uncertainty (e.g., depth to groundwater table and PGA) for each CPT are provided in Figures 10 and 11.

Figure 10: Level 3 Lateral Spread Displacement Assessment Tornado Plot for the San Fernando Earthquake

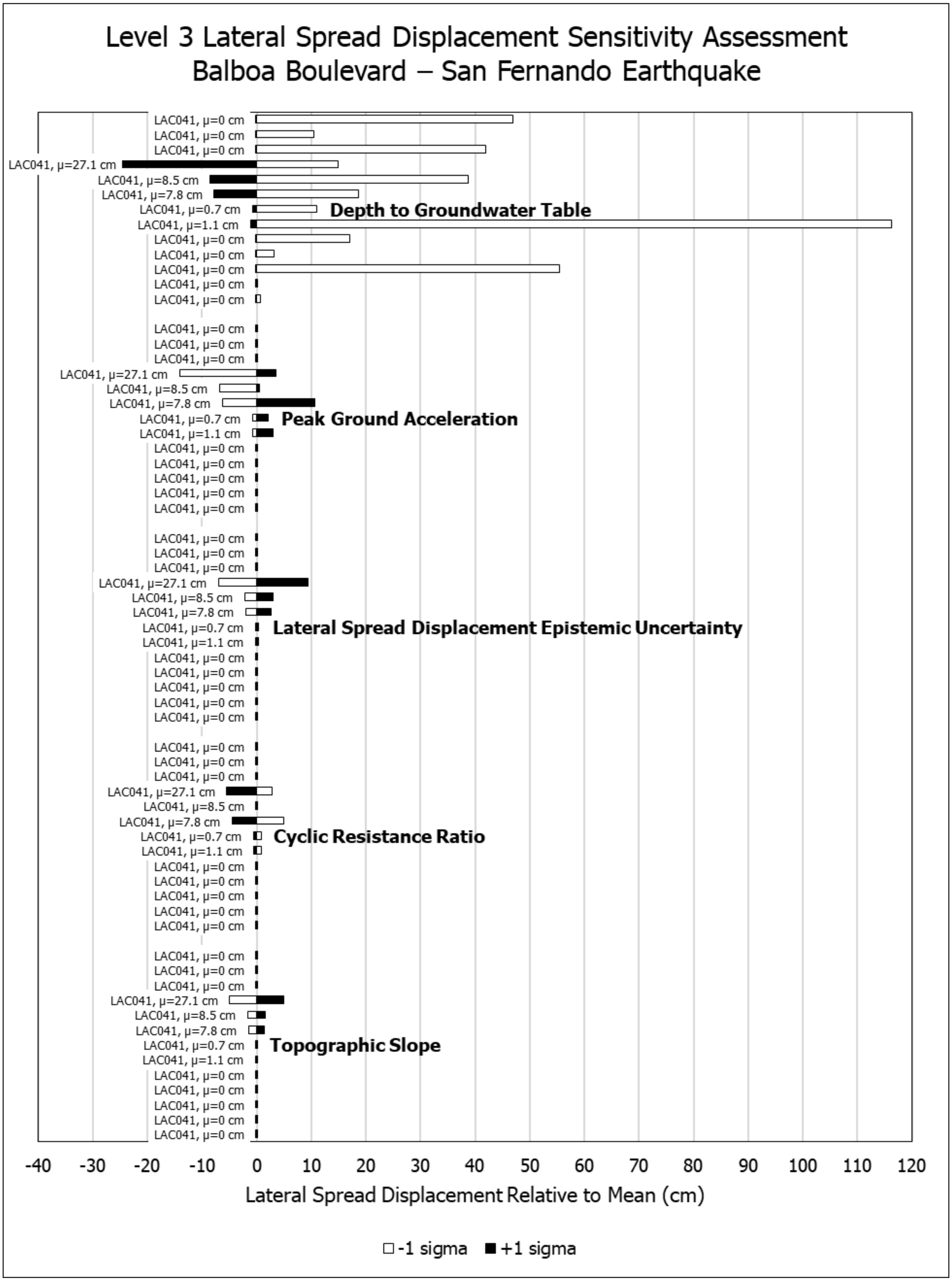
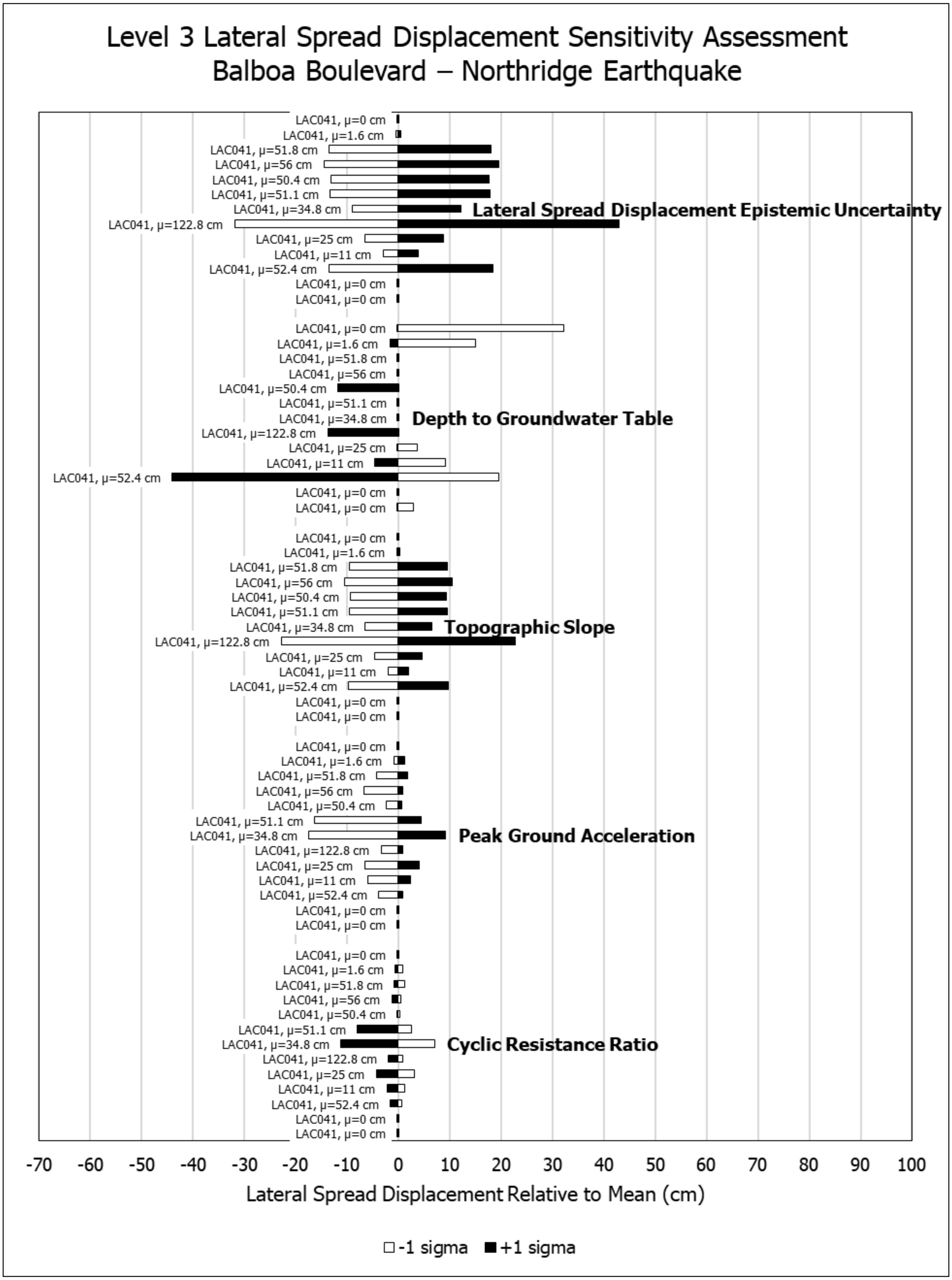


Figure 11: Level 3 Lateral Spread Displacement Assessment Tornado Plot for the Northridge Earthquake



The Level 3 sensitivity analysis for the San Fernando earthquake is dominated by the uncertainty in the depth to the groundwater table whereas the sensitivity to the depth to the groundwater table is significantly reduced for the Northridge earthquake. The assessment for the Northridge earthquake is most sensitive to the lateral displacement model epistemic uncertainty.

Overall, the results across the analysis levels indicate relatively higher hazard for the Northridge earthquake compared to the San Fernando earthquake, consistent with the observed performance of the site. The accuracy of the lateral spread displacement hazard assessment for the Northridge earthquake improved with each successive analysis with the Level 3 assessment (51 cm of mean displacement estimated) comparing favorably with the observed permanent ground displacement (i.e., about 40 – 60 cm).

The assessments for the San Fernando earthquake show slightly increasing hazard at each successive level. Level 1 and Level 2 assessments do not capture the elevated groundwater table and the geotechnical conditions at the site. The Level 3 assessment for the San Fernando earthquake captures the groundwater conditions better (albeit still with greater uncertainty compared to the Northridge earthquake). Additionally, the Level 3 assessment shows loose, liquefiable sands in the subsurface, information that is not possible to infer from Level 1 or Level 2 data alone. No lateral spread movements were observed at the site during the San Fernando earthquake, which is consistent with the small amounts of lateral spread displacements estimated at this site for the San Fernando earthquake, although the mean value from the Level 3 analysis is slightly higher than the 5 cm threshold of meaningful displacement, which is likely due to the uncertainty in the groundwater conditions.

3.1.3 Slope Stability Analyses

Slope stability is evaluated using the procedures from Bray & Macedo (2019) and Jibson (2007) with varying data quality differentiating the Levels 1 through 3 data used in the analyses. At each of the analysis levels, no seismic slope displacement is estimated to occur; hence, it is not estimated be an issue at Balboa Boulevard because it is relatively flat. This is consistent with the performance at the site during the 1971 San Fernando and 1994 Northridge earthquakes.

3.1.4 Underground Pipeline Performance Assessment in Response to Earthquake Shaking

Underground pipeline performance in response to earthquake shaking and permanent ground deformation are examined at Levels 1 – 3. At Levels 1 and 2, pipeline performance in response to earthquake shaking is evaluated following the procedure of O’Rourke (2020), which estimates performance in terms of repair rate (see the Bain et al., 2022c report for further information regarding this fragility function). For the Level 1 assessment, neither site specific pipeline nor geotechnical data are assumed to be available, as would be typical for such analyses at other locations. In this case, typical pipeline characteristics (with significant uncertainty on these parameters) are assumed to perform the assessment. A typical natural gas pipeline for the purpose of performing a Level 1 assessment is assumed to be steel with shielded electric arc-welded circumferential girth welds. The mean repair rates (repairs per km) using the Level 1 assumptions are estimated for the 16th, median (50th) , and 84th percentile ground motions from the San Fernando and Northridge earthquakes as estimated by ShakeMap. The results of these evaluations are summarized in Table 5.

Table 5: Estimated Repair Rates at Level 1 due to Earthquake Shaking

Earthquake	San Fernando			Northridge		
Pipelines	**RR for 16th Percentile PGV (repairs/km)**	**RR for Median PGV (repairs/km)**	**RR for 84th Percentile PGV (repairs/km)**	**RR for 16th Percentile PGV (repairs/km)**	**RR for Median PGV (repairs/km)**	**RR for 84th Percentile PGV (repairs/km)**
All Natural Gas Pipelines at Site	0.003	0.008	0.023	0.020	0.048	0.119

N/A = Pipeline not installed at time of San Fernando earthquake
RR = Repair Rate

For the Level 2 assessment, we assume there is knowledge of the pipeline properties, as would be typical for such analyses at other locations. The mean repair rates (repairs per km) using the Level 2 assumptions are estimated for the 16th, median (50th), and 84th percentile ground motions from the San Fernando and Northridge earthquakes as estimated by ShakeMap. The results of these evaluations are summarized in Table 6.

Table 6: Estimated Repair Rates at Level 2 Due to Earthquake Shaking

Earthquake	San Fernando			Northridge		
Pipelines	**RR for 16th Percentile PGV (repairs/km)**	**RR for Median PGV (repairs/km)**	**RR for 84th Percentile PGV (repairs/km)**	**RR for 16th Percentile PGV (repairs/km)**	**RR for Median PGV (repairs/km)**	**RR for 84th Percentile PGV (repairs/km)**
1	0.011	0.031	0.091	0.079	0.193	0.477
2	N/A	N/A	N/A	0.020	0.048	0.119
3	0.053	0.155	0.455	0.393	0.966	2.384
4	0.003	0.008	0.023	0.020	0.048	0.119
5	0.003	0.008	0.023	0.020	0.048	0.119
6	0.053	0.155	0.455	0.393	0.966	2.384
7	N/A	N/A	N/A	0.039	0.097	0.238
8	N/A	N/A	N/A	0.020	0.048	0.119

N/A = Pipeline not installed at time of San Fernando earthquake
RR = Repair Rate

The probability of a length of pipeline experiencing a failure (either a leak or a break) can be estimated by assuming that the incidence of pipeline failures is a Poisson process. Equation (3.1) presents the Poisson probability mass function.

$$P(x = k) = \frac{\lambda^k * e^{-\lambda * L}}{k!} \tag{3.1}$$

where $P(x = k)$ is the Poisson probability that the number of failures in the segment of pipeline being analyzed, x, is equal to k, λ is the repair rate in number of failures per length of pipeline, and L is the length of the segment of pipeline segment being analyzed. Because even a single failure in a pipeline segment is an undesirable damage state, the probability of at least one failure occurring can be calculated as the inverse of the probability Poisson probability mass function calculated with $k = 0$, as presented in Equation (3.2).

$$P_f = 1 - e^{-\lambda * L} \tag{3.2}$$

where P_f is the probability of at least one failure, where a failure is either a leak or break.

Applying Equation (3.2) with $L = 0.5\ km$ (the approximate distance along Balboa Boulevard between Lorillard and Rinaldi Streets) for the repair rates tabulated in Table 5 and in Table 6 yields estimated probabilities of experiencing at least one failure (either a leak or break) as presented in Table 7 and in Table 8, for Level 1 and 2, respectively.

Table 7: Estimated Probabilities of Failure at Level 1

Earthquake	**San Fernando**			**Northridge**		
Pipelines	**P_f for 16th Percentile PGV (%)**	**P_f for Median PGV (%)**	**P_f for 84th Percentile PGV (%)**	**P_f for 16th Percentile PGV (%)**	**P_f for Median PGV (%)**	**P_f for 84th Percentile PGV (%)**
All Natural Gas Pipelines at Site	0.1	0.4	1.1	1.0	2.4	5.8

Table 8: Estimated Probabilities of Failure at Level 2

Earthquake	**San Fernando**			**Northridge**		
Pipelines	**P_f for 16th Percentile PGV (%)**	**P_f for Median PGV (%)**	**P_f for 84th Percentile PGV (%)**	**P_f for 16th Percentile PGV (%)**	**P_f for Median PGV (%)**	**P_f for 84th Percentile PGV (%)**
1	0.5	1.5	4.4	3.8	9.2	21.2
2	N/A	N/A	N/A	1.0	2.4	5.8
3	2.6	7.5	20.3	17.8	38.3	69.6
4	0.1	0.4	1.1	1.0	2.4	5.8
5	0.1	0.4	1.1	1.0	2.4	5.8
6	2.6	7.5	20.3	17.8	38.3	69.6
7	N/A	N/A	N/A	1.9	4.7	11.2
8	N/A	N/A	N/A	1.0	2.4	5.8

N/A = Pipeline not installed at time of San Fernando earthquake

The Level 1 assessment to estimate repair rates and probabilities of failure due to earthquake shaking does not capture important differences in the pipeline properties that significantly affects the seismic risk of the buried pipelines.

At Level 2, the repair rates and probabilities of failure due to earthquake shaking indicate that the steel pipelines constructed using modern shielded electric arc welding techniques are unlikely to experience a failure (P_f*=0.1%* to *1.1%* for the San Fernando earthquake and P_f*=1.0%* to *5.8%* for the Northridge earthquake) when considering the minus- to plus-one standard deviation ground motion levels. The Rinaldi trunk line, with water welded girth welds, is also estimated to experience relatively low repair rates and probabilities of failure for the Northridge earthquake (P_f*=1.9%* to *11.2%*).

Old Line 120 (pipeline 1), constructed using an early shielded electric arc welding process, is assumed to perform like pipelines constructed using the unshielded electric arc welding technique. This pipeline is expected to perform worse than the other steel natural gas lines with P_f*=0.5%* to *4.4%* for the San Fernando earthquake and P_f*=3.8%* to *21.2%* for the Northridge earthquake. It is estimated that the pipelines most likely to experience a failure from transient ground deformations are the Granada trunk line and the gas distribution line with P_f*=2.6%* to *20.3%* for the San Fernando earthquake and P_f*=17.8%* to *69.6%* for the Northridge earthquake.

Overall, the Level 2 assessment using the mean ground motions indicates a less than 50% probability of failure for each of the pipelines for both earthquakes, consistent with post-earthquake reconnaissance observations. None of the observed failures at Balboa Boulevard resulting from the Northridge earthquake are thought to be a direct result of transient pipe strains induced by propagating seismic waves.

At level 3, underground pipeline performance in response to earthquake shaking is evaluated by estimating the maximum transient pipe strains that could develop in each pipe using the method from O'Rourke & El Hamdi (1988), which accounts for soil/pipe interface slippage. This approach utilizes a linear spring to model the soil resistance to axial pipeline movement. The strain in the pipe at the corresponding maximum soil resistance to sliding is taken as the maximum possible pipe strain due to transient ground strain. With this approach, it is estimated that none of the pipelines would experience transient strains high enough to result in leakage or failure (see the Bain et al., 2022c report for more information).

3.1.5 Underground Pipeline Performance in Response to Permanent Ground Deformation

To assess the pipeline performance in response to estimated permanent ground deformations from lateral spreading at Level 1, the procedure for estimating pipeline repair rates caused by permanent ground deformations from O'Rourke (2020) is evaluated. This method employs a cutoff of 2 to 4 inches (~5 to ~10 cm) whereby ground displacement less than the selected cutoff (10 cm for this report) does not cause pipeline damage. For a Level 1 assessment, there is no knowledge of the pipeline properties; however, the estimated mean expected displacement for both the San Fernando and Northridge earthquakes is less than the 10 cm cutoff value, so the O'Rourke (2020) method estimates the mean repair rate for each pipeline is 0 repairs/km for both earthquakes. When considering the full epistemic uncertainty in the earthquake shaking level, probability of liquefaction triggering calculation, and the lateral spread displacement calculation in a probabilistic framework, as is being implemented within *OpenSRA*, non-zero probabilities of pipeline breaks and leaks are likely at high epistemic fractiles.

Alternatively at Level 1, the method for estimating pipe strain for pipelines whose axis roughly aligns with the direction of permanent ground displacement presented in the Bain et al. (2022a) and (2022b) reports can be used. Again, because a Level 1 assessment would not include knowledge of the pipeline or subsurface properties, typical values for the required inputs (which have very high epistemic uncertainty) are used to estimate the pipe strain. Table 9 summarizes the mean generic input values and the uncertainty in those values to use the model described in the Bain et al. (2022a) report at Level 1. Because the backfill soil type is not known at Level 1, pipe strain is estimated using both the sand and clay models and weighted equally.

Table 9: Mean Input Variables and Uncertainty at Level 1 to Estimate Pipe Strain

Infrastructure Variables						
Parameter	**Mean**	**σ**	**COV (%)**	**Limit_{LOW}**	**Limit_{HIGH}**	**Distribution**
D (mm)	610		25	102	1067	Normal
t (mm)	10.2		40	2.5	20.3	Normal
σ_y (MPa)	359000		15	240000	600000	Normal
n	14	3		$\mu-2\sigma$	$\mu+2\sigma$	Normal
r	8.5	1.5		$\mu-2\sigma$	$\mu+2\sigma$	Normal
Geotechnical Variables – Clay Model						
Parameter	**Mean**	**σ**	**COV (%)**	**Limit_{LOW}**	**Limit_{HIGH}**	**Distribution**
α (unitless)	0.75	0.14		0.5	1.0	Normal
S_u (kPa)	40		45	20	120	Lognormal
Geotechnical Variables – Sand Model						
Parameter	**Mean**	**σ**	**COV (%)**	**Limit_{LOW}**	**Limit_{HIGH}**	**Distribution**
γ_t (kN/m^3)	19		9	16	21.5	Lognormal
H (m)	1.2		15	0.6	6	Lognormal
Φ′ (°)	38		15	30	45	Lognormal
δ	0.75	0.14		0.5	1.0	Normal
Other Model Parameters						
Parameter	**Mean**	**σ**	**COV (%)**	**Limit_{LOW}**	**Limit_{HIGH}**	**Distribution**
L (m)	100		90	10	400	Lognormal

Generic input variables to estimate pipe strain for case of pipeline axis roughly parallel to direction of ground displacement.

Table 10 summarizes the estimated pipe strain and probabilities of tensile leakage, tensile rupture, and compressive rupture (assuming zero internal pressure, which introduces a slightly unconservative bias) at Level 1. The pipe strains in Table 10 were estimated using only the mean values reported in Table 9. A probabilistic risk assessment using *OpenSRA* will consider the full uncertainty in each of the model parameters by performing the pipe strain assessment for one-thousand samples of the parameters to provide the user with an estimate of the epistemic uncertainty.

Table 10: Mean Pipe Strain Estimates and Probabilities of Tensile Leakage, Tensile Rupture, and Compressive Rupture at Level 1

Mean Pipe Strain Estimates for San Fernando Earthquake (%)			Mean Pipe Strain Estimates for Northridge Earthquake (%)			Probability of Tensile Leakage (%)		Probability of Tensile Rupture (%)		Probability of Compressive Rupture (%)	
Clay	**Sand**	**Mean**	**Clay**	**Sand**	**Mean**	**SF**	**NR**	**SF**	**NR**	**SF**	**NR**
0.07	0.03	**0.05**	0.07	0.03	**0.05**	0.0	0.0	0.0	0.0	0.0	0.0

At Level 2, the pipe strain assessment using the model described in the Bain et al. (2022a) report for ground deformation zones that displace in roughly the same direction as the pipeline axis assumes knowledge of the pipeline infrastructure properties and knowledge of the soil backfill type and burial depth. There is no site-specific geotechnical data. Table 11 summarizes the estimated mean pipe strain for each pipeline using the Level 2 lateral spread displacement estimate and the Level 2 pipeline infrastructure knowledge. The reported pipe strain estimates are equivalent in the tensile and compressive deformation zones.

Table 11: Mean Pipe Strain Estimates and Probabilities of Tensile Leakage, Tensile Rupture, and Compressive Rupture at Level 2

		Mean Tensile and Compressive Pipe Strain Estimates (%)		Probability of Tensile Leakage		Probability of Tensile Rupture		Probability of Compressive Rupture	
Pipe	**Backfill**	**SF**	**NR**	**SF**	**NR**	**SF**	**NR**	**SF**	**NR**
1	Native Clay	0.12	>20	0.00	1.00	0.00	1.00	0.00	1.00
2	Sand	N/A	0.15	N/A	0.00	N/A	0.00	N/A	0.00
3	Native Clay	1.01	4.78	0.00	0.99	0.00	0.53	0.02	0.87
4	Native Clay	0.09	1.33	0.00	0.03	0.00	0.00	0.00	0.76
5	Native Clay	0.09	1.33	0.00	0.03	0.00	0.00	0.00	0.76
6	Native Clay	0.13	>20	0.00	1.00	0.00	1.00	0.11	1.00
7	Native Clay	N/A	>20	N/A	1.00	N/A	1.00	N/A	1.00
8	Structural Backfill	N/A	0.15	N/A	0.00	N/A	0.00	N/A	0.00

N/A = Pipeline not installed at time of San Fernando earthquake
SF = San Fernando Earthquake
NR = Northridge Earthquake

Finally, the pipe strain assessment using the same pipe response model employed at Level 1 and Level 2 is repeated at Level 3 with the average displacement estimated from the CPTs for each earthquake (14 cm for San Fernando earthquake and 51 cm for Northridge earthquake) and the estimated length of the ground deformation zone from the CPTs. For the estimated mean shaking as estimated by ShakeMap during the San Fernando earthquake (PGA=0.5 g) and mean groundwater table elevation assumed to be 2 m below the level measured following the Northridge earthquake (see Bain et al., 2022c for further information), lateral displacement is estimated to exceed 5 cm at only three CPTs; therefore, given the spacing of the CPTs, the length of the ground deformation zone is estimated to equal approximately 100 m for the San Fernando earthquake (see the Bain et al., 2022c report for further information). For the Northridge earthquake, lateral spread displacement is estimated to exceed 5 cm at nine CPTs. With this information, the length of the ground deformation is estimated to be 300 m for the Northridge earthquake (see the Bain et al., 2022c report for further information). Table 12 summarizes the pipe strain estimates and estimated probabilities of tensile leakage, tensile rupture, and compressive rupture at Level 3. Note that the reported pipe strain estimates are equivalent in the tensile and compressive deformation zones.

Table 12: Mean Pipe Strain Estimates and Probabilities of Tensile Leakage, Tensile Rupture, and Compressive Rupture at Level 3

		Mean Tensile and Compressive Pipe Strain Estimates (%)		**Probability of Tensile Leakage**		**Probability of Tensile Rupture**		**Probability of Compressive Rupture**	
Pipe	**Backfill**	**SF**	**NR**	**SF**	**NR**	**SF**	**NR**	**SF**	**NR**
1	Native Clay	0.12	>20	0.00	1.00	0.00	1.00	0.00	1.00
2	Sand	N/A	0.15	N/A	0.00	N/A	0.00	N/A	0.00
3	Native Clay	1.42	18.61	0.05	1.00	0.00	1.00	0.10	1.00
4	Native Clay	0.09	3.59	0.00	0.92	0.00	0.19	0.00	1.00
5	Native Clay	0.09	3.59	0.00	0.92	0.00	0.19	0.00	1.00
6	Native Clay	0.13	>20	0.00	1.00	0.00	1.00	0.11	1.00
7	Native Clay	N/A	>20	N/A	1.00	N/A	1.00	N/A	1.00
8	Structural Backfill	N/A	0.15	N/A	0.00	N/A	0.00	N/A	0.00

N/A = Pipeline not installed at time of San Fernando earthquake
SF = San Fernando Earthquake
NR = Northridge Earthquake

No pipelines experienced tensile or compressive leaks or ruptures as a result of either earthquake shaking or permanent ground motion during the San Fernando earthquake. The Old Line 120 natural gas transmission line, the gas distribution line, and the Granada and Rinaldi water trunk lines experienced both tensile and compressive ruptures as a result of permanent ground deformation during the Northridge earthquake.

Comparing the relative risk between the pipelines, the Level 3 analysis indicates that the four pipelines that experienced tensile failures during the Northridge earthquake are at relatively higher risk for experiencing tensile leakage and tensile rupture compared to the pipelines that did not experience tensile leakage or tensile rupture. Similarly, the four pipelines which experienced compressive failures during the Northridge earthquake are at relatively high risk for experiencing compressive rupture. Pipelines 4 and 5 are also estimated to have high probability of experiencing compressive rupture during the Northridge earthquake even though they did not fail. An independent, detailed assessment by O'Rourke & Liu (2012) also estimates these lines were close to experiencing compressive failure.

Comparing the estimated probability of failure with the observed failures from the Northridge earthquake, we see that the methods used in Level 3 can estimate which lines will fail, but those from Level 1 and 2 underestimate failure.

3.1.6 *OpenSRA* Results for Balboa Boulevard Demonstration Site

As Level 2 and Level 3 data are available at Balboa Boulevard, risk assessments were performed at these levels to assess the performance of the *OpenSRA* software. As neither landslide displacement nor liquefaction-induced settlements are expected to be a significant hazard at the site, only the risk from lateral spread displacement was evaluated with *OpenSRA*.

The Level 2 assessment was performed using the Hazus (FEMA, 2020) liquefaction triggering model to estimate the probability of liquefaction triggering with depth-to-groundwater-specific liquefaction hazard classifications for the geologic units in the Bedrossian et al. (2012) geologic map provided by Scott Lindvall (Lindvall, 2022). For more information about the depth-to-groundwater-specific liquefaction hazard classifications, see the Bain et al. (2022c) report. At Level 2, because there are no polygons of potential ground deformation zones, it is not clear if potential ground displacements are tensile or compressive; therefore, we conservatively assume that all pipe strains are compressive. To derive percentiles for the probability of compressive rupture, each of the variables necessary to perform an assessment are sampled from their respective distributions many times and the risk calculation is performed. As the liquefaction hazard classification is an input necessary to use the Hazus (FEMA, 2020) models and it can change based on the sampled depth to groundwater, *OpenSRA* changes the liquefaction hazard classification for each depth to groundwater sample.

Mean percentiles, as well as 5th, 16th, 50th, 84th, and 95th percentiles, for the probability of compressive rupture are reported for each pipeline for the Level 2 assessment for the 1971 San Fernando earthquake in Table 13 and for the 1994 Northridge earthquake in Table 14.

Table 13: Level 2 Probability of Compressive Rupture Percentiles from *OpenSRA* for the San Fernando Earthquake

			Lateral Spreading - San Fernando					
			Probability of Compressive Rupture Fractiles					
Pipe	**D (mm)**	**t (mm)**	**5th**	**16th**	**50th**	**84th**	**95th**	**mean**
3003	762	9.5	0.00	0.00	0.01	0.07	0.14	0.03
3000	762	9.5	0.00	0.00	0.02	0.10	0.17	0.04
Mobil Oil	406	9.5	0.00	0.00	0.00	0.04	0.09	0.02
GTL	1257	6.5	0.00	0.00	0.02	0.11	0.19	0.05
OL 120	560	7.1	0.00	0.00	0.00	0.05	0.12	0.02
NL 120	610	9.5	0.00	0.00	0.00	0.02	0.07	0.01
Gas Distribution	168	4.8	0.00	0.00	0.00	0.02	0.06	0.01
RTL	1723	9.5	0.00	0.00	0.01	0.09	0.17	0.04

Table 14: Level 2 Probability of Compressive Rupture Percentiles from *OpenSRA* for the Northridge Earthquake

			Lateral Spreading - Northridge					
			Probability of Compressive Rupture Fractiles					
Pipe	**D (mm)**	**t (mm)**	**5th**	**16th**	**50th**	**84th**	**95th**	**mean**
3003	762	9.5	0.00	0.00	0.03	0.11	0.19	0.05
3000	762	9.5	0.00	0.00	0.04	0.14	0.20	0.07
Mobil Oil	406	9.5	0.00	0.00	0.00	0.06	0.14	0.03
GTL	1257	6.5	0.00	0.00	0.04	0.16	0.24	0.07
OL 120	560	7.1	0.00	0.00	0.02	0.11	0.20	0.05
NL 120	610	9.5	0.00	0.00	0.02	0.09	0.17	0.04
Gas Distribution	168	4.8	0.00	0.00	0.00	0.05	0.13	0.02
RTL	1723	9.5	0.00	0.00	0.03	0.14	0.23	0.06

The Level 2 results from *OpenSRA* presented in Table 13 and Table 14 show that the risk for each of the pipelines is slightly higher for the Northridge earthquake compared to the San Fernando earthquake. Using the limited data available at Level 2, each of the pipelines are estimated to have non-zero probabilities of compressive rupture, which is significantly affected by the pipeline D/t ratio. The pipelines with the largest D/t ratios (Granada and Rinaldi trunk lines, Lines 3000 and 3003) have the highest probabilities of rupturing, which is consistent with field observations for the water trunk lines but is not consistent with observations for the gas lines. The Gas Distribution Line is estimated to have low probability of rupturing, which is inconsistent with field observations. The results presented in Table 13 and Table 14 are the average of all the segments for each pipeline at the site.

At Level 3, the publicly available CPTs from the USGS are used to estimate a spatial distribution of lateral spread displacement. To do this, lateral spread displacement is calculated at each CPT from many combinations of the sampled input parameters necessary to use the Zhang et al. (2004) model. The sampled parameters include the probability of liquefaction triggering at each depth increment, the uncertainty in the topographic slope sampled from the digital elevation model (DEM), and the model epistemic uncertainty, among other parameters. The mean displacement at each CPT estimated from the many combinations sampled input parameters are used with a spatial correlation to estimate the lateral spread displacement at grid points up to 100 m from each CPT. The area with lateral spread displacements greater than 5 cm is then polygonised and the pipe strain is estimated in the pipe segments that cross the polygon boundary. Pipe straining occurs at locations of differential ground displacement; the segments of the pipeline within the lateral spread polygon are assumed to move with the ground, thus not experiencing differential movement. The average slope aspect is sampled within the polygon to estimate its direction of slip and the average displacement at the grid points within the polygon is taken as the average slip of the whole polygon. More information about the procedure to estimate the spatial extent of lateral spread displacements can be found in the Bain et al. (2022c) report.

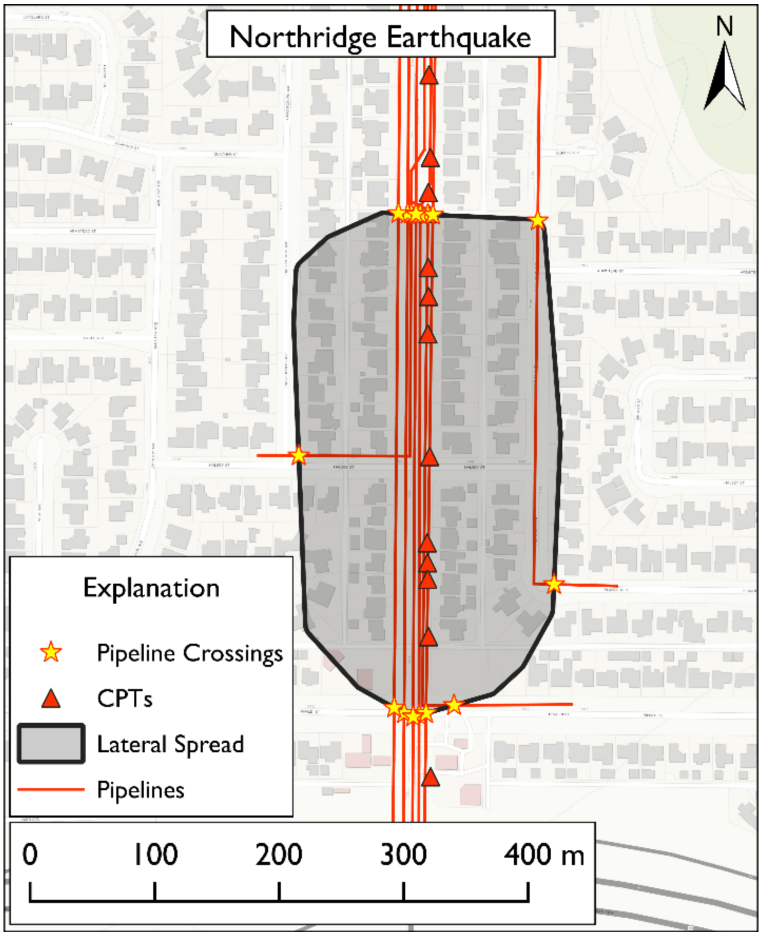
The average displacement is estimated to be less than 5 cm for the 1971 San Fernando earthquake, so no lateral displacement polygon is generated for this event, and there are no pipeline leaks or ruptures. Hence, a table of Level 3 results is not included for the San Fernando earthquake as the probabilities of pipeline leaks or ruptures are zero. These results are consistent with observations at the site for the San Fernando earthquake.

Figure 12 shows the estimated lateral spread displacement polygon for the Northridge earthquake at Balboa Boulevard. The Level 3 risk assessment with *OpenSRA* successfully recovers the approximate spatial extent of the lateral spread that occurred along Balboa Boulevard during the Northridge earthquake. Additionally, *OpenSRA* successfully estimated both the approximate range of ground displacement and the approximate slip direction of the lateral spread from a slope aspect map.

Mean percentiles, as well as 5th, 16th, 50th, 84th, and 95th percentiles, for the probability of tensile leakage, tensile rupture, and compressive rupture are reported for each pipeline for the Level 3 assessment for the 1994 Northridge earthquake in Table 15. The four pipes which broke during the Northridge earthquake (Old Line 120, the Gas Distribution Line, and the Granada and Rinaldi water trunk lines) were estimated to have high probabilities of both tensile and compressive ruptures in the approximate locations along Balboa Boulevard where the breaks were observed. Line 3000 and New Line 120, which did not break during the Northridge earthquake, are estimated to have relatively high probability of compressive failure. This is consistent with previous studies on Line 3000, which found it was close to buckling (O’Rourke & Liu, 2012). New Line 120 exits the lateral spread zone to the to the east rather than passing straight through it. By exiting the lateral spread zone to the east, *OpenSRA* estimates that it is placed into pure shear and the pipe strain is estimated assuming a strike-slip compression mechanism, leading to higher estimates for the pipe strain. Line 3003, which is of the same vintage and design as Line 3000, is estimated using *OpenSRA* to have zero probability of compressive failures because it does not cross the compressive deformation zone. The Mobil Oil line is estimated to have low probability of compressive rupture.

Thus, the Level 3 results at Balboa Boulevard are satisfactory. At the mean level, no lateral spreading is estimated to occur during the San Fernando earthquake which is consistent with observations of the site. Conversely, *OpenSRA* reasonably estimates the lateral spread hazard at the site for the Northridge earthquake and the risk for each of the pipelines.

Figure 12: Estimated Spatial Extent of Lateral Spreading at Level 3 for the Northridge Earthquake



Estimated spatial extent of lateral spreading for the Northridge Earthquake from CPTs at Balboa Boulevard.

Table 15: Level 3 Probability of Compressive Rupture, Tensile Leakage, and Tensile Rupture Percentiles from *OpenSRA* for the Northridge Earthquake

			Lateral Spreading - Northridge					
			Probability of Compressive Rupture Fractiles					
Pipe	**D (mm)**	**t (mm)**	**5th**	**16th**	**50th**	**84th**	**95th**	**mean**
3003	762	9.5	0.00	0.00	0.00	0.00	0.00	0.00
3000	762	9.5	0.03	0.12	0.33	0.60	0.77	0.36
Mobil Oil	406	9.5	0.00	0.00	0.00	0.05	0.16	0.03
GTL	1257	6.5	0.34	0.63	0.95	1.00	1.00	0.84
OL 120	560	7.1	0.02	0.20	0.58	0.90	1.00	0.56
NL 120	610	9.5	0.01	0.06	0.23	0.48	0.66	0.27
Gas Distribution	168	4.8	0.00	0.00	0.24	0.66	0.93	0.31
RTL	1723	9.5	0.09	0.32	0.71	0.96	1.00	0.66
			Probability of Tensile Leakage Fractiles					
Pipe	**D (mm)**	**t (mm)**	**5th**	**16th**	**50th**	**84th**	**95th**	**mean**
3003	762	9.5	0.00	0.00	0.08	0.64	1.00	0.25
3000	762	9.5	0.00	0.00	0.08	0.63	1.00	0.25
Mobil Oil	406	9.5	0.00	0.00	0.03	0.40	0.83	0.16
GTL	1257	6.5	0.00	0.03	0.49	0.96	1.00	0.49
OL 120	560	7.1	0.00	0.05	0.42	0.86	1.00	0.46
NL 120	610	9.5	0.00	0.00	0.00	0.24	0.59	0.11
Gas Distribution	168	4.8	0.00	0.00	0.18	0.78	1.00	0.32
RTL	1723	9.5	0.00	0.01	0.32	0.77	1.00	0.39
			Probability of Tensile Rupture Fractiles					
Pipe	**D (mm)**	**t (mm)**	**5th**	**16th**	**50th**	**84th**	**95th**	**mean**
3003	762	9.5	0.00	0.00	0.06	0.52	0.99	0.21
3000	762	9.5	0.00	0.00	0.06	0.51	0.99	0.21
Mobil Oil	406	9.5	0.00	0.00	0.02	0.28	0.72	0.13
GTL	1257	6.5	0.00	0.00	0.40	0.92	1.00	0.45
OL 120	560	7.1	0.00	0.01	0.37	0.83	1.00	0.41
NL 120	610	9.5	0.00	0.00	0.00	0.15	0.49	0.08
Gas Distribution	168	4.8	0.00	0.00	0.10	0.69	1.00	0.27
RTL	1723	9.5	0.00	0.00	0.27	0.75	1.00	0.35

3.2 *OpenSRA* Results for the Honor Rancho Natural Gas Storage Facility Demonstration Site

OpenSRA was first validated for the earthquake ground shaking as estimated by ShakeMap for the 1971 San Fernando and 1994 Northridge earthquakes. Fragility models for shaking induced failures of the conductor casing, surface casing, production casing, and well tubing all have aleatory variability, β_r=0.2 and epistemic uncertainty, β_u=0.25. *OpenSRA* estimated negligible damage for these scenarios, which is consistent with field observations. The estimated bending moment in the well casings and tubing was significantly less than the estimated damage threshold. The lack of damage for these distant earthquakes is also consistent with historic data as only one instance of seismic damage to gas storage wells in California has been reported (CCST, 2018). Moreover, historic data on the effects of earthquakes in oil fields, such as from the 1983 Coalinga earthquake, suggest that ground shaking only impacts a very small subset of wells and primarily in the uppermost 100 meters (Hughes et al., 1990). *OpenSRA* and the background full-physics modeling estimate the largest ground motion impact in the shallowest part of the wells.

There are no known cases of an earthquake rupturing a fault which intersects a gas storage facility or wells in California or anywhere in the world for validating *OpenSRA*. Instead, *OpenSRA* results for such scenarios are compared with the results of full-physics modeling for verification the fragility functions implemented into *OpenSRA*. Ground motion (shaking) impacts from nearby M_w 5 and M_w 6 earthquakes leading to an average PGA of 0.18 g and 0.45 g, respectively, were considered as intensity measures. The performance of the casing systems at 22 sites were assessed using *OpenSRA* and showed that the risk of damage for the conductor, surface, and production casings is low for the two earthquake scenarios considered.

The analysis of direct fault shear across wells were demonstrated for reverse faulting causing tensile shearing across a well that was assumed to intersect the San Gabriel fault at the northeastern margin of the field. This involved the use of public data on well trajectories (wells may deviate from the vertical considerably) and calculation of the angle of intersection between the well trajectory and the fault plane. Fragility models for fault offset induced failures of well casing and well tubing have β_r=0.186 and β_r=0.392, respectively and β_u=0.103 and β_u=0.261, respectively. Considering the fault angle of intersection and an assumed fault displacement, *OpenSRA* results were verified by comparison against previous full-physics modeling results.

Finally, the assessment of caprock leakage was demonstrated for an assumed fault rupture through caprock. For the nominal case of current storage pressure below the hydrostatic water pressure, the full-physics modeling showed that no significant leakage would occur up along the permeable fault. Gas storage pressures above the hydrostatic water pressure would be required for leakage, but the rate would be expected to be small. A sensitivity analysis has indicated caprock leakage is not particularly sensitive to any of the parameters tested; therefore, the probability of failure distribution for caprock leakage will be similar to the probability of failure distribution for seismic events.

3.3 OpenSRA Results for the McDonald Island Natural Gas Storage Facility Demonstration Site

The probabilities of leakage and rupture of the two types of WTP subsystems and rupture for the VPV subsystems located at this demonstration site are presented in Table 16. These results indicate a very small probability of failure for ground motion intensity as estimated by ShakeMap for the 1989 Loma Prieta earthquake. This is primarily because failure is strongly correlated with PGA, which was estimated to be relatively low at the site for this event.

For both the WTP and VPV subsystems, the mean probabilities of leakage and rupture are negligible. These results are consistent with the lack of observed damage at the site following the Loma Prieta earthquake.

The PGA at the site for the Loma Prieta earthquake was amplified by a factor of ten to evaluate the results from *OpenSRA* for very strong ground shaking at the site. Results of this evaluation are presented in Table 17. For the WTP subsystems, the mean probabilities of leakage and rupture are still negligible. The mean probability of rupture for the VPV subsystem is estimated to increase to approximately 34%. These results are consistent with the expected performance of these subsystems.

Table 16: Probability of Leakage and Rupture Percentiles for the WTP Subsystem and Probability of Rupture Percentiles for the VPV Subsystem from *OpenSRA* for the Loma Prieta Earthquake

	Probability of Leakage Fractiles for the WTP Subsystem					
	5th	**16th**	**50th**	**84th**	**95th**	**mean**
Elbows: Site 1	0.00	0.00	0.00	0.00	0.00	0.00
Elbows: Site 2	0.00	0.00	0.00	0.00	0.00	0.00
Tees: Site 1	0.00	0.00	0.00	0.00	0.00	0.00
Tees: Site 2	0.00	0.00	0.00	0.00	0.00	0.00
	Probability of Rupture Fractiles for the WTP Subsystem					
	5th	**16th**	**50th**	**84th**	**95th**	**mean**
Elbows: Site 1	0.00	0.00	0.00	0.00	0.00	0.00
Elbows: Site 2	0.00	0.00	0.00	0.00	0.00	0.00
Tees: Site 1	0.00	0.00	0.00	0.00	0.00	0.00
Tees: Site 2	0.00	0.00	0.00	0.00	0.00	0.00
	Probability of Rupture Fractiles for the VPV Subsystem					
	5th	**16th**	**50th**	**84th**	**95th**	**mean**
Pressure Vessels with Stretch Length	0.00	0.00	0.00	0.01	0.07	0.01

Table 17: Probability of Leakage and Rupture Percentiles for the WTP Subsystem and Probability of Rupture Percentiles for the VPV Subsystem from *OpenSRA* for the Hypothetical, Amplified Loma Prieta Earthquake

	Probability of Leakage Fractiles for the WTP Subsystem					
	5th	**16th**	**50th**	**84th**	**95th**	**mean**
Elbows: Site 1	0.00	0.00	0.00	0.01	0.01	0.01
Elbows: Site 2	0.00	0.00	0.00	0.00	0.01	0.00
Tees: Site 1	0.00	0.00	0.00	0.01	0.08	0.02
Tees: Site 2	0.00	0.00	0.00	0.04	0.17	0.03
	Probability of Rupture Fractiles for the WTP Subsystem					
	5th	**16th**	**50th**	**84th**	**95th**	**mean**
Elbows: Site 1	0.00	0.00	0.00	0.00	0.01	0.00
Elbows: Site 2	0.00	0.00	0.00	0.00	0.00	0.00
Tees: Site 1	0.00	0.00	0.00	0.01	0.04	0.01
Tees: Site 2	0.00	0.00	0.00	0.01	0.06	0.01

	Probability of Rupture Fractiles for the VPV Subsystem					
	5th	**16th**	**50th**	**84th**	**95th**	**mean**
Pressure Vessels with Stretch Length	0.00	0.04	0.28	0.65	0.89	0.34

3.4 OpenSRA Results for Cordelia Junction Natural Gas Pipeline Demonstration Site

OpenSRA was used to assess a 610 mm outside diameter, 7.9 mm wall thickness, X-52 and X-60 grade steel natural gas transmission pipeline at a site near Cordelia Junction. The pipeline data and the results of the seismic risk assessment for this site are covered under an NDA with the Pacific Gas & Electric (PG&E) Company. Accordingly, the pipeline data and results of the risk assessment are only summarized in this report.

Prior to 2017, the pipeline at the site crossed a rainfall-induced landslide before being rerouted around the landslide. The pipeline also crosses an active fault capable of producing surface rupture. *OpenSRA* was used to assess the performance of the pipeline in its pre-2017 alignment for the ground shaking experienced at the site for the 1989 M_w 6.9 Loma Prieta earthquake and the 2014 M_w 6.0 South Napa earthquake (as estimated by ShakeMap) and for a hypothetical M_w 6.9 earthquake that produces PGA=0.5 g at the site. The post-2017 pipeline alignments were also assessed for the hypothetical ground shaking level.

The assessment at Level 2 and Level 3 using the pre-2017 alignment show no compressive ruptures, tensile ruptures, or tensile leaks for the 1989 and 2014 earthquakes. The *OpenSRA* assessment is consistent with the lack of noticeable permanent ground displacement observed at the site during the Loma Prieta and South Napa earthquakes, which occurred when the pipeline crossed the landslide. These results are not unexpected because the PGA at the site during both earthquakes was low (less than or equal to approximately 0.1 g). No breaks were estimated for the pipeline in its post-2017 alignment as it does not cross a landslide feature.

The risk assessment was repeated for the pre- and post-2017 pipe alignments for intense ground shaking with PGA=0.5 g for a hypothetical earthquake. The seismic risk assessment of the pre-2017 pipeline alignment for this level of ground shaking produced a high probability of failure resulting from seismic slope displacement of the active landslide, whereas the post-2017 alignment that was rerouted in stable ground away from the active landslide showed zero probability of failure of the buried natural gas pipeline.

Overall, the results from the *OpenSRA* risk assessment at the Cordelia Junction demonstration site at the location of the active landslide are consistent with field observations for the Loma Prieta and South Napa case histories and they are consistent with expectations for how the site would perform for the hypothetical M_w 6.9 earthquake producing ground shaking intensity PGA=0.5 g.

The expected performance of the buried natural gas pipeline segment that crosses the active fault is also consistent with the results of the *OpenSRA* risk assessment at this site, which shows low probability of failure.

CHAPTER 4: Conclusions/Recommendations

The *OpenSRA* software and the analytical procedures used in it provide reliable estimates of the seismic performance of the natural gas systems examined in the four demonstration sites. The *OpenSRA* software also provided similar results as the detailed calculations described in this report for the Balboa Boulevard site.

4.1 Performance of *OpenSRA*

The in-depth assessment of the Balboa Boulevard site emphasized the importance of measuring the depth to the groundwater table and in collecting site-specific, subsurface geotechnical data. At Level 1, the groundwater elevation model significantly underestimates the values measured in the post-event surveys for the 1994 Northridge earthquake because the Level 1 data do not capture the elevated groundwater table due to local effect of the Mission Hills Fault. Additionally, the V_{S30} parameter (a proxy for geotechnical conditions) does not adequately characterize the loose, liquefiable sands inferred from the Level 3 CPT data. Accordingly, the lateral displacement hazard is underestimated at Level 1 for the 1994 Northridge earthquake.

Level 2 data indicates the groundwater table is shallower than the Level 1 data indicates and there is reduced uncertainty. Accordingly, the lateral spread displacement hazard is estimated to increase at Level 2 for both earthquakes. However, the uncertainty in the groundwater table at Level 2 remains high, so the estimate of performance during the 1994 Northridge earthquake remains poor.

At Level 3, the importance of measuring the depth to groundwater is acutely demonstrated. The 1971 San Fernando and 1994 Northridge earthquakes were of similar magnitude (M_w 6.6 and M_w 6.7, respectively) and both produced intense shaking at the Balboa Boulevard site (mean PGA=0.5 g and 0.8 g, respectively). If the groundwater table is assumed to be at the same elevation during the San Fernando earthquake as during the Northridge earthquake, similar lateral spread displacements would have been estimated. However, the Level 3 subsurface groundwater data indicates the groundwater table is about 2 meters higher during the 1994 Northridge earthquake than during the 1971 San Fernando earthquake. With the higher groundwater table during the Northridge earthquake, liquefaction is triggered, and significant lateral ground displacements occur that adversely affect buried pipeline performance, which is consistent with post-earthquake observations for the Northridge earthquake. With the lower groundwater table in 1971, liquefaction and lateral spreading are estimated to be essentially "turned off", which produced lower estimates of ground displacement and good buried pipeline performance, which are consistent with post-earthquake observations for the San Fernando earthquake.

OpenSRA estimated negligible damage to wells at the Honor Rancho Natural Gas Storage Facility demonstration site for ground motions corresponding to the 1971 San Fernando and

1994 Northridge earthquakes. Comparison of *OpenSRA* results to full-physics modeling for a more intense hypothetical case of an earthquake occurring within the Honor Rancho storage facility provided validation of the fragility functions implemented in *OpenSRA*. In general, *OpenSRA* estimates a low risk for damage from the ground shaking hazard, while in an unlikely case of direct fault shear across a well, significant damage could occur to that well. Estimates of caprock leakage were also demonstrated with *OpenSRA*, but if storage pressure is below the hydrostatic water pressure, no significant gas leakage is estimated to occur.

Assessment of the WTP subsystems at McDonald Island showed negligible probabilities of failure in response to the shaking intensity estimated to have occurred during the 1989 Loma Prieta earthquake, which is consistent with observations. When the ground motion intensity is increased ten-fold, the probabilities of failure increase slightly, but mean probabilities of rupture are still small (approximately 1% to 2%). The probability of rupture for the VPV subsystems is similarly small in response to the estimated Loma Prieta ground motion intensity (mean probability of rupture is approximately 1.4%) but increases significantly when assessed for the amplified ground motion intensity (mean probability of rupture is approximately 34%).

The assessment at Cordelia Junction focused on the performance of a pipeline that crossed a rainfall-induced landslide before being realigned in 2017. The results from *OpenSRA* show low probabilities of compressive or tensile pipe ruptures for the ground motions as estimated by ShakeMap for the 1989 Loma Prieta and 2014 South Napa earthquakes. These results are consistent with observations at the site, which experienced no coseismic slope displacement during either earthquake, due primarily to the low intensity ground shaking at the site (<0.1 g).

An additional analysis at Cordelia Junction assessed the performance of the pre-2017 pipe alignment and the post-2017 pipe alignment, which avoids the active landslide zone, for a hypothetical M_w 6.9 earthquake that produces PGA=0.5 g ground shaking at the site. The results show no breaks for the post-2017 pipe alignment while the pre-2017 pipe alignment showed a high probability of breaks.

4.2 Applicability of Research at Demonstration Sites to General Purpose Applications of *OpenSRA*

The application of *OpenSRA* at the four demonstration sites, which is described in this report, demonstrates how the procedures incorporated into *OpenSRA* for analyzing risk from geohazards can be applied to other sites. There is improved accuracy and reduced uncertainty associated with moving from Level 1 assessments to Level 2 and Level 3 assessments. Level 1 analyses can be performed at a uniform resolution with uniform uncertainty everywhere in the State of California. Level 2 and 3 analyses can be performed anywhere in California where sufficient data is collected to permit a higher-Level assessment. Higher-Level assessments have less aleatory variability and epistemic uncertainty. Consequently, users can expect greater accuracy as higher quality data is collected and more reliable analysis techniques are employed in *OpenSRA*. The benefits of adding data are illustrated in the examination of the Balboa Blvd. site.

Methods for analyzing liquefaction typically have estimated aleatory variability and epistemic uncertainty on the order of $\beta_r \approx 0.8 - 1.0$ and $\beta_u=0.50$ at Level 1, $\beta_r \approx 0.7 - 0.9$ and $\beta_u=0.40$ at Level 2, and $\beta_r \approx 0.5 - 0.7$ and a minimum of $\beta_u=0.25$ at Level 3. Epistemic uncertainty is reduced at Level 3 by applying multiple models to estimate the liquefaction-induced ground movement risk.

The same analytical procedures for assessing risk from seismic slope displacement are employed at Levels 1 to 3, which results in the model aleatory variability not changing at each level. However, the epistemic uncertainty decreases significantly at each successive level as the quality of the input geologic, geotechnical, and topographic data, including landslide polygons, improves. For example, Level 1 seismic slope displacement assessments have significantly more epistemic uncertainty compared to Level 2 or Level 3 assessments because the uncertainty in the geotechnical strength parameters is much higher at Level 1.

For above ground infrastructure, the aleatory variability is estimated to equal $\beta_r=0.3$ for the WTP subsystem and $\beta_r=0.45$ for the VPV, while the epistemic uncertainty is estimated to equal $\beta_u=0.25$ for both the WTP and VPV. Fragility models for shaking induced failures of the conductor casing, surface casing, production casing, and well tubing have aleatory variability, $\beta_r=0.2$ and epistemic uncertainty, $\beta_u=0.25$. Fragility models for fault offset induced failures of well casing and well tubing have $\beta_r=0.186$ and $\beta_r=0.392$, respectively and $\beta_u=0.103$ and $\beta_u=0.261$, respectively.

The described assessments at the demonstration sites represent well general applications of *OpenSRA*. The above ground infrastructure assessments translate to general applications of *OpenSRA* particularly well because of the similarity of the natural gas pipeline and storage components throughout California. The assessment at Cordelia Junction is a good example of a typical pipeline-landslide crossing and translates well to similar analyses of the surface fault rupture hazard across the state. The liquefaction-induced lateral spread displacement assessment at Balboa Boulevard at Levels 1 and 2 is typical of what can be expected for liquefaction-induced displacement analyses throughout California. Level 3 analyses use site-specific data and will vary considerably at each individual site. However, the results of the assessment at Balboa Boulevard, which show improved accuracy improves and reduced uncertainty of the estimates, can be expected at each site when users provide higher level input data at their site. *OpenSRA* automatically determines the analysis level to run based on the data available at the site. For example, a Level 3 seismic ground displacement assessment is not possible without user input; whereas, a Level 1 assessment can be performed without user input, albeit with the expectation of high uncertainty in the results of a Level 1 analysis.

4.3 Recommendations for Further Research

Further research concerning pipeline response to permanent ground deformations should focus on validating the tool at additional sites, such as the Van Norman Utility Corridor, which experienced severe lateral spreading during the San Fernando earthquake.

Research to further validate the performance of *OpenSRA* for assessing the risk to wells and caprocks at Honor Rancho and other gas storage facilities should be performed when new and improved components are added to the analysis, such as other modes of fault activation, ground motion, and leakage.

Regarding the surface subsystem components, additional investigations of surface subsystems focusing on large relative displacements between components is needed. For example, natural gas pipelines often cross rivers above ground on either purpose-built trestle bridges or attached to road bridges. Lateral spreading or coseismic slope displacements can cause relative movement between the portion of the pipe attached to the bridge and the pipe anchored to ground away from the bridge, thus posing risk to the pipeline. Such investigations could be performed using calibrated numerical parametric studies.

While this project focused largely on the transmission system, analyses of select surface components of the distribution system would also be of value. For example, vertical risers and meter sets are commonly damaged during earthquakes and can cause fires. Understanding the response of these systems to strong shaking is critical to evaluating the risk of leaks, which in turn would enable the assessment of the risk of residential fires and allow for gas service to be restored more quickly following earthquakes.

GLOSSARY AND LIST OF ACRONYMS

A	Cross-Sectional Area of Pipe
Abaqus	Finite Element Software
CEC	California Energy Commission
CGS	California Geological Survey
CoV	Coefficient of Variation
CPT	Cone Penetrometer Test
D	Pipe Outside Diameter
GWT	Depth to Groundwater
H	Burial Depth of Midpoint of Pipeline Diameter from Ground Surface
Hazus	Natural Hazard Risk Assessment Tool Distributed by the Federal Emergency Management Agency
L	Length of Ground Deformation Zone
LBNL	Lawrence Berkeley National Laboratory
LCI	Lettis Consultants International
LDI	Lateral Displacement Index
$\mathbf{Limit_{HIGH}}$	Upper Value to Truncate Distribution
$\mathbf{Limit_{LOW}}$	Lower Value to Truncate Distribution
$\mathbf{M_w}$	Moment Magnitude
n	Ramberg-Osgood *n* Parameter
NHERI	Natural Hazards Engineering Research Infrastructure
OpenSRA	Open Seismic Risk Assessment Tool
PEER	Pacific Earthquake Engineering Research Center

PGA	Peak Ground Acceleration (g)
PGD	Permanent Ground Deformation
PGV	Peak Ground Velocity (g)
PG&E	Pacific Gas and Electric Company
Qal3	Quaternary (Holocene) Alluvium with Topographic Slope Greater than 2%
r	Ramberg-Osgood r Parameter
RR	Repair Rate
s_u	Clay Undrained Shear Strength
SoCalGas	Southern California Gas Company
SEAW	Shielded Electric Arc Welds
SMYS	Specified Minimum Yield Stress
t	Pipe Wall Thickness
TAC	Technical Advisory Committee
UC	University of California
USGS	United States Geological Survey
VPV	Vertical Pressure Vessel (Subsystem at McDonald Island)
V_{S30}	Time-averaged shear wave velocity in the upper 30-meters of the subsurface (m/s)
WTP	Wellhead Tree and Connected Piping (Subsystem at McDonald Island)
α	Pipe-Clay Adhesion Factor
β_r	Aleatory Variability
β_u	Epistemic Uncertainty
γ_t	Soil Total Unit Weight

δ	Pipe-Sand Peak Interface Friction Ratio
μ	Mean
σ	Standard Deviation
σ_y	Pipe Yield Stress
Φ'	Sand Friction Angle

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