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PROJECT REPORT

Fault Displacement Hazard Characterization for *OpenSRA*

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

Gavin Newsom, Governor
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PREPARED BY:

Primary Author:
Stephen Thompson

Lettis Consultants International, Inc.

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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.

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- 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.

Fault displacement hazard characterization for OpenSRA is an interim report for the project, Performance-Based Earthquake Engineering Assessment Tool for Natural Gas Storage and Pipeline Systems (Contract Number PIR-18-003) conducted by a research collaborative led by the Pacific Earthquake Engineering Research (PEER) center at U.C. Berkeley. The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development Program.

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ABSTRACT

Tectonic fault rupture during large earthquakes generates localized permanent ground displacement that poses a hazard to California's natural gas infrastructure. This report presents the approaches used to characterize fault displacement hazard for seismic risk assessment in the software tool *OpenSRA*, which is being developed as a performance-based earthquake engineering assessment tool for natural gas storage and pipeline systems. The approaches developed here represent practical solutions to characterize fault displacement hazard across California's extensive network of natural gas transmission pipelines and natural underground storage facilities for purposes of system-wide or regional seismic risk assessments that include contributions to risk from multiple seismic hazards. This report provides recommendations for probabilistic fault displacement hazard analysis (PFDHA) for two types of settings: first, for surface and near-surface environments where active faults intersect pipelines and other surface or near-surface infrastructure; second, for deep environments where active faults intersect oil and gas wells used in natural underground gas storage facilities. The methodologies presented here emphasize simple approaches with large uncertainties with the intention that PFDHA model improvements may be added to *OpenSRA* on an as-needed basis and documented in later project reports.

Keywords: Seismic hazard, seismic risk, fault displacement, fault rupture, OpenSRA, probabilistic methods

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CHAPTER 1: Introduction

1.1 Background

California's natural gas infrastructure is vulnerable to damage from large earthquakes. Earthquakes cause a variety of phenomena that are hazardous to natural gas storage facilities and transmission and distribution pipelines. These phenomena include dynamic strong ground shaking and a variety of permanent ground failures, such as liquefaction and landsliding, which are related to ground shaking and underlying soil and rock conditions. In addition to these is the hazard from tectonic fault displacement, which represents rupture and offset across the fault that caused the earthquake.

Although it is well understood that strong ground shaking, landsliding, liquefaction, and fault displacement can all result in damage to natural gas pipelines, wells, and other infrastructure, the relative importance of these phenomena to the overall seismic risks to infrastructure has not been examined in detail. The software tool *OpenSRA*, which is being developed as the focal point of this research grant award, will examine the seismic risks to California's natural gas infrastructure by combining information about the expected occurrence of earthquakes in California, the locations and intensities of deformation caused by the earthquakes, and the extent of damage to natural gas infrastructure resulting from earthquake-related deformations.

This report presents one aspect of the overall *OpenSRA* project—the assessment of fault displacement hazard. Information contained in this report will feed into the *OpenSRA* tool so that the contribution to seismic risk of California's natural gas infrastructure from tectonic fault rupture may be adequately captured and quantified.

1.2 Project Purpose

The purpose of this work is to provide fault displacement hazard input for seismic risk assessment. There are a variety of methodologies that may be used to quantify fault displacement hazard that range from extremely simple to complex; the purpose of this project is to provide an appropriately scaled methodology that accomplishes the following goals:

- Can be completed within the timeframe and budget of the grant on a state-wide scale;
- Is appropriately accurate relative to natural gas infrastructure such that it provides useful information for engineering assessment;
- Provides a quantitative measure of hazard in a probabilistic framework that satisfies requirements of *OpenSRA*; and
- Describes displacement hazard parameters that are required for the engineering assessment of infrastructure vulnerability, such that the hazard and vulnerability assessments can be combined to compute risk; and
- Is complete enough to be applicable to surface-and near-surface infrastructure (e.g., shallowly buried natural gas transmission pipelines) and deeper infrastructure (e.g., oil and gas wells used for natural underground storage facilities).

- Allows for a sensitivity analysis to determine what parts of the model are most important for understanding hazard uncertainty, and where future model improvements may have the greatest impact on the seismic risk assessment.
- Provides a quantitative measure of the model (epistemic) uncertainty that will be used in *OpenSRA* to model the uncertainties associated with the total risk.

CHAPTER 2: Project Approach

2.1 General OpenSRA Project Approach

One aspect of the overall *OpenSRA* approach is to develop risk models at a variety of *Levels* with different degrees of sophistication (as measured by input model precision or resolution). This general approach allows for implementation of the tool at a variety of scales ranging from state-wide to site-specific within the timeframe and resources of this study. The *Levels* approach also allows for both analysis at the state-wide system scale where only general information is available and detailed analysis of a specific component of a natural gas infrastructure system where better, more precise data are available, and perhaps where there is a more pressing need to quantify seismic risk and the factors that dominate the risk. The three levels and their general objectives are as follows:

> *Level 1*: Model input provides complete coverage of the state-wide system on a uniform basis, and accordingly has coarse resolution and relatively low degree of accuracy and/or precision. The *Level 1* models using these inputs are likewise simple with few explanatory variables and have large epistemic uncertainties. *Level 1* models are useful for developing and testing *OpenSRA*, and they may be appropriate for state-wide to regional-scale risk analysis. These models may provide insights into big-picture factors that contribute to overall seismic risk. *Level 1* analyses generally are not sufficiently sophisticated to provide reliable results or insights to smaller parts of a system or to specific facilities.
>
> *Level 2*: Model input provides uniform coverage of significant regions within the state's natural gas infrastructure system, but may fall short of state-wide coverage. Compared to *Level 1* input, *Level 2* input generally has higher spatial resolution and a greater degree of accuracy and/or precision. The *Level 2* input, however, lacks detailed information and input parameters may not be constrained by site-specific data. The *Level 2* models using these improved inputs are generally more sophisticated than *Level 1* models as they use a greater number of explanatory variables and have lower uncertainties. *Level 2* models are useful for regional assessments to local assessments of parts of gas storage and/or transportation systems, and should provide useful insights to factors controlling seismic risk.
>
> *Level 3*: Model input is of a specific study area where site-specific data have been collected with greater resolution, accuracy, and precision and a much higher reliability (lower epistemic uncertainty) than *Level 1* or *Level 2* input. Geotechnical test data and/or geological survey data are generally collected and provided by users so as to provide additional measurements to describe material properties. *Level 3* models using these high-quality inputs have a relatively high level of sophistication. *Level 3* models in *OpenSRA* would be applicable to site-specific risk assessment and provide insight for further engineering analysis and decision-making.

As the *OpenSRA* project is designed to analyze seismic risk at multiple spatial scales, from a state-wide "portfolio" assessment to analysis of local parts of a system, there are multiple input datasets and models proposed for use in the fault displacement hazard characterization. Each progressive *level*, from *Level 1* to *Level 3*, utilizes either the same or progressively more detailed and refined input, and modeling of displacement hazard relies on the same or progressively more detailed displacement models. The higher-level models provide more reliable estimates (lower epistemic uncertainty), but require more detailed data from the user to achieve these reliable estimates.

In order to better understand how the *Levels* approach was implemented for fault displacement hazard, it is helpful to separate fault displacement hazard into its various elements. The fault displacement hazard model for *OpenSRA* has five basic elements:

1. Locations where active tectonic faults intersect California's natural gas infrastructure;
2. Description of the earthquake magnitudes and rates that are expected to occur on the intersecting faults;
3. Relationships between the earthquakes that occur and the resulting amount of fault displacement at a given location;
4. The expected direction of fault displacement; and,
5. Additional geotechnical parameters that may be utilized by *OpenSRA* for fragility assessment – these include a description of the rupture width (width over which the fault displacement will occur) and strength properties of the soil or rock surrounding buried facilities.

For the first two model elements—fault locations and earthquake sizes and rates—our approach relies on publicly available datasets developed by the California Geological Survey (CGS) and US Geological Survey (USGS) for *Level 1* and *Level 2* analyses. These include the Unified California Earthquake Rupture Forecast, Version 3 (UCERF3) (Field et al., 2013) and the latest version of the U. S. Quaternary Fault and Fold Database (Q-faults) (USGS and CGS, 2019). An exception to this is our approach for the Honor Rancho demonstration site, where a *Level 2* analysis is being developed based on models and information presented at professional society meetings. For *Level 3* analyses, site-specific information is integrated into the model calculation to refine fault locations and reduce epistemic uncertainties. For the third model element—fault displacement amount—our approach relies on simple, published models for *Level 1* and *Level 2* analyses, and more sophisticated published models for *Level 3* analysis. The fourth element, displacement direction, has a simple geometric approach for *Levels 1* and *2* and relies on site-specific information for *Level 3* analyses. The fifth model element will be developed in collaboration with *OpenSRA*'s fragility working group to ensure provided information is relevant and useful for developing infrastructure response to fault displacement hazard. No new datasets or modeling were performed as part of the fault displacement hazard component of this project.

2.2 Probabilistic Fault Displacement Hazard Methodology

The *OpenSRA* tool uses a probabilistic formulation; accordingly the fault displacement hazard methodology developed for the project is based on the current state-of-practice formulation for probabilistic fault displacement hazard analysis (PFDHA). The following is a condensed explanation that provides the basic equations and introduces the main terms of the equations. We discuss the applicability of the terms to the *OpenSRA* project in Chapter 3.

2.2.1 General Hazard Formulation

Current PFDHA practice attempts to calculate the relationship between fault displacement amount and the annualized frequency (probability) of it being exceeded at a given site. This is expressed as:

$$\nu(D > D_0) = \alpha P(D > D_0) \tag{1}$$

where

$\nu(D > D_0)$ represents the annual exceedance frequency that a fault displacement *D* in an earthquake exceeds a test value D_0,

α is the rate of displacement occurrences on a fault at the site, and

$P(D > D_0)$ is the probability that *D* exceeds D_0.

Two alternative approaches to solving Equation (1) are available: the magnitude approach, whereby fault displacements at a specific location are calculated as a function of the earthquake magnitudes and rates modeled to occur on the faults (plus other explanatory variables), and the displacement (or direct) approach, whereby site-specific geological information is collected on the rate of displacement events and their amounts. For the *OpenSRA* project we are concerned with the magnitude approach only, as there are insufficient data available at the vast majority of locations where active faults cross natural gas infrastructure to make the displacement approach possible to implement. The magnitude approach, in contrast, is straightforward to implement in *OpenSRA* and has the advantage of sharing a common earthquake magnitude-rate distribution used as input for multiple seismic hazards including ground shaking, earthquake-induced landsliding and liquefaction.

In addition to the two methodologies, current PFDHA practice distinguishes between principal (or primary) fault displacement and distributed (or secondary) fault displacement. Principal fault displacement occurs on principal faults, which are faults identified to be continuous through the seismogenic crust and capable of generating earthquakes of engineering significance. Distributed fault displacement occurs on secondary faults and as distributed deformation across minor faults and shears. These secondary faults and shears are generally located near principal faults (within, for example, approximately 1-3 km of a principal strike-slip fault). Secondary fault displacements are typically on the order of about 10% of the average principal fault displacement, with 90 percent of secondary displacements being less than 25% of the average principal fault displacement (Petersen et al., 2011). Although distributed deformation may account for approximately 40% of the total fault displacement observed at the surface (Milliner et al., 2016), the *OpenSRA* project currently only considers principal fault displacement hazard. This is based on several lines of reasoning, including:

- Limiting the hazard assessment to principal faulting results in a simpler model that is more straightforward to implement and more appropriate given the more system-wide risk assessment objectives of *OpenSRA*;

- Distributed displacement hazard is generally much lower than principal displacement hazard owing to its comparatively lower probability of occurrence and smaller displacements; and
- Thick-walled welded steel pipelines used in natural gas transmission, which represent most of the fault-infrastructure crossings in California, can, in general, better withstand secondary displacements or distributed deformation than principal displacements due to the lower displacement amounts and/or greater widths over which the deformation occurs. Thus, risk is far more likely to be controlled in a general case by principal displacement hazard than distributed deformation hazard.

We recognize that there are likely instances where distributed deformation hazard is important to seismic risk of natural gas infrastructure. These cases, presumably, can be explored using *OpenSRA* in a site-specific *Level 3* analysis, and/or in a detailed structural analysis outside of the seismic risk framework. In addition, our methodology for fault displacement hazard to buried infrastructure (i.e., intersections of active faults and oil and gas wells at 1-2 km depth) explicitly accounts for off-fault distributed deformation observed at Earth's surface that may be localized on principal faults at depth.

The magnitude approach is based on the methodology for probabilistic seismic hazard analysis (PSHA) (Cornell, 1968). The general form of the magnitude approach for principal fault rupture (following Petersen et al., 2011) is an expansion of Equation (1) as follows:

$$\nu(D > D_0) = \alpha(M_{min}) \int_{M,S} f_{M,S}(M,S)\, P[SR \neq 0|M]$$

$$\times \int_R f_R(R)\, P[D \neq 0|Z,R,SR \neq 0]\, P[D > D_0|SOF,M,L^*,D \neq 0] dRdMdS \qquad (2)$$

where

$\alpha(M_{min})$ is the rate of all earthquakes on the intersecting fault source above a minimum magnitude, M_{min};

$f_{M,S}(M,S)$ is the probability density function (PDF) characterizing earthquake magnitudes (M) and locations (S) of ruptures on a fault (with integration over the range of magnitudes and locations that source can produce);

$P[SR \neq 0|M]$ is a conditional probability that earthquakes on the source of magnitude M will produce surface rupture (SR);

$f_R(R)$ is the PDF characterizing the distance from the site R to all potential ruptures (with integration over the range of distances considered);

$P[D \neq 0|Z,R,SR \neq 0]$ is a conditional probability that, given an earthquake that ruptures the surface a distance R from a site of area $Z \times Z$, there will be non-zero principal displacement at the site; and

$P[D > D_0|SOF,M,L^*,D \neq 0]$ is the conditional probability of displacement exceedance at a site given non-zero principal displacement. The displacement exceedance term is commonly a complementary cumulative distribution function fit to empirical data of displacements of a specific style of faulting (SOF) and following a lognormal distribution (Youngs et al., 2003; Petersen et al., 2011) or Weibull or Beta distributions (Moss and Ross, 2011). These fault displacement exceedance models show that displacement generally scales with earthquake magnitude M and normalized location along the length of the rupture L^*.

As will be discussed in Chapter 3, application of PFDHA for linear structures common to natural gas infrastructure (such as transmission pipelines and wells in natural gas storage facilities) allows for some simplification and modification of Equation (2). Further simplification of the PDFHDA formulation is appropriate for *Level 1* and *Level 2* analysis, particularly during the developemnt and testing of *OpenSRA*.

2.2.2 Additional Information Needed for Engineering Analysis

The results of a PFDHA following implementation of Equation (2) consist of hazard curves showing annual exceedance frequency versus displacement amplitude for a particular intersection of a fault with a structural element (pipeline, well, etc.). For developing fragility curves of structural response to the ground deformation, additional hazard information is needed. Such information typically includes the following:

- Fault-facility intersection location uncertainty;
- Displacement direction (e.g., horizontal and vertical displacement components, or an orthogonal three-component description of displacement);
- Width of deformation (e.g., localized, “knife-edge” displacement on a plane or distributed deformation across a several meter-wide shear band); and
- Strength properties of rock or soil surrounding the structural element.

The model approach for developing these additional elements for the *OpenSRA* project for surface and near-surface environments and for subsurface environments are discussed in Chapter 3.

CHAPTER 3: Project Results

Based on the project approach, the fault displacement hazard model for *OpenSRA* follows strategies suitable for *Level 1*, *Level 2*, and *Level 3* analysis. These strategies are summarized in a Fault Displacement Hazard Matrix (Section 3.1). The recommended methodology for calculating fault displacement hazard for surface and near-surface natural gas infrastructure is presented in Section 3.2, and fault displacement hazard for infrastructure at depth is presented in Section 3.3.

3.1 Fault Displacement Hazard Matrix

Guidance for implementing the fault displacement hazard element to *OpenSRA* for the various levels is captured in matrix form in Table 1. Rows in the matrix follow the scheme in Section 2.1, which break down the fault displacement hazard into fault location, earthquake magnitude-rate relationship, fault displacement model, fault displacement direction method, and "other" parameters including fault rupture width and soil or rock strength (for buried infrastructure). Matrix columns show strategies for *Levels 1, 2*, and *3*.

Table 1: Fault Displacement Hazard Matrix

Model Component	Level 1	Level 2	Level 3
Fault location (intersections with natural gas infrastructure)	Set of fault locations based on UCERF3 rupture sources (Field et al., 2013). Will use same set of ruptures used by *OpenSRA* for ground motion calculation.	Set of faults and fault locations derived from Q-fault database (USGS and CGS, 2019).	Fault locations and geometry based on site-specific information.
Earthquake magnitude-rate distribution	*OpenSRA* will use a subset of the UCERF3 event set (Field et al., 2013) that provides rupture locations, magnitudes, and rates.	Distribution will be the full UCERF3 mean solution event set. Will link UCERF3 ruptures to Q-faults database traces.	Faults to be linked to ruptures in the seismic source model (project event set) so that the magnitude-rate distribution can be assigned. Site-specific consideration of uncertainties.
Fault Displacement Exceedance Models	A simple fault displacement exceedance model based on Wells and Coppersmith (1994) will be used for estimating fault displacement exceedance.	Published fault displacement exceedance models for normal, strike-slip, and reverse faults will be used for surface and near-surface crossings. Modified versions adopting information about the "shallow slip deficit" will be adopted for fault displacement hazard at depth (at well intersections).	Will use published PFDHA models with adjustments as needed depending on the specific fault crossing.
Fault Displacement Direction	Normalized N, E, Z displacement components calculated based on strike, dip, and rake of fault source section as provided in UCERF3 event set.	Same as *Level 1*.	Normalized displacement components developed based on site-specific information as available on fault strike, tectonic transport direction, dip, and any direct measurements of fault rake.

Model Component	Level 1	Level 2	Level 3
Rupture width and soil/rock strength	Assume localized displacement or distributed deformation across a 2-m fault zone width. Soil/rock strength information to be based on datasets developed by the *OpenSRA* landslide and liquefaction group for consistency.	Same as *Level 1*; details will be based on approach of the *OpenSRA* fragilities group.	Width of faulting, soil and rock strength data, and other inputs will be addressed using site-specific data, as available, in coordination with the *OpenSRA* fragility group.

Table 1 summarizes in matrix form the approaches for *OpenSRA* to compute probabilistic fault displacement hazard for *Level 1, Level 2,* and *Level 3* analyses. The task of computing fault displacement hazard for California's natural gas infrastructure is broken down into four main elements: fault location, earthquake magnitude-rate relationship, fault displacement model, and fault displacement direction and width.

3.2 Fault Displacement Hazard for Surface and Near-Surface Facilities

This description of the approach to PFDHA for surface and near-surface facilities focuses on the approaches for *Level 1* and *Level 2* analyses and application to pipeline-fault crossings, which make up the vast majority of intersections between active faults and natural gas infrastructure in California. Following a description for *Level 1* and *Level 2* analyses we discuss variations that may be appropriate for *Level 3* analyses.

3.2.1 Locations of Fault-Infrastructure Intersection

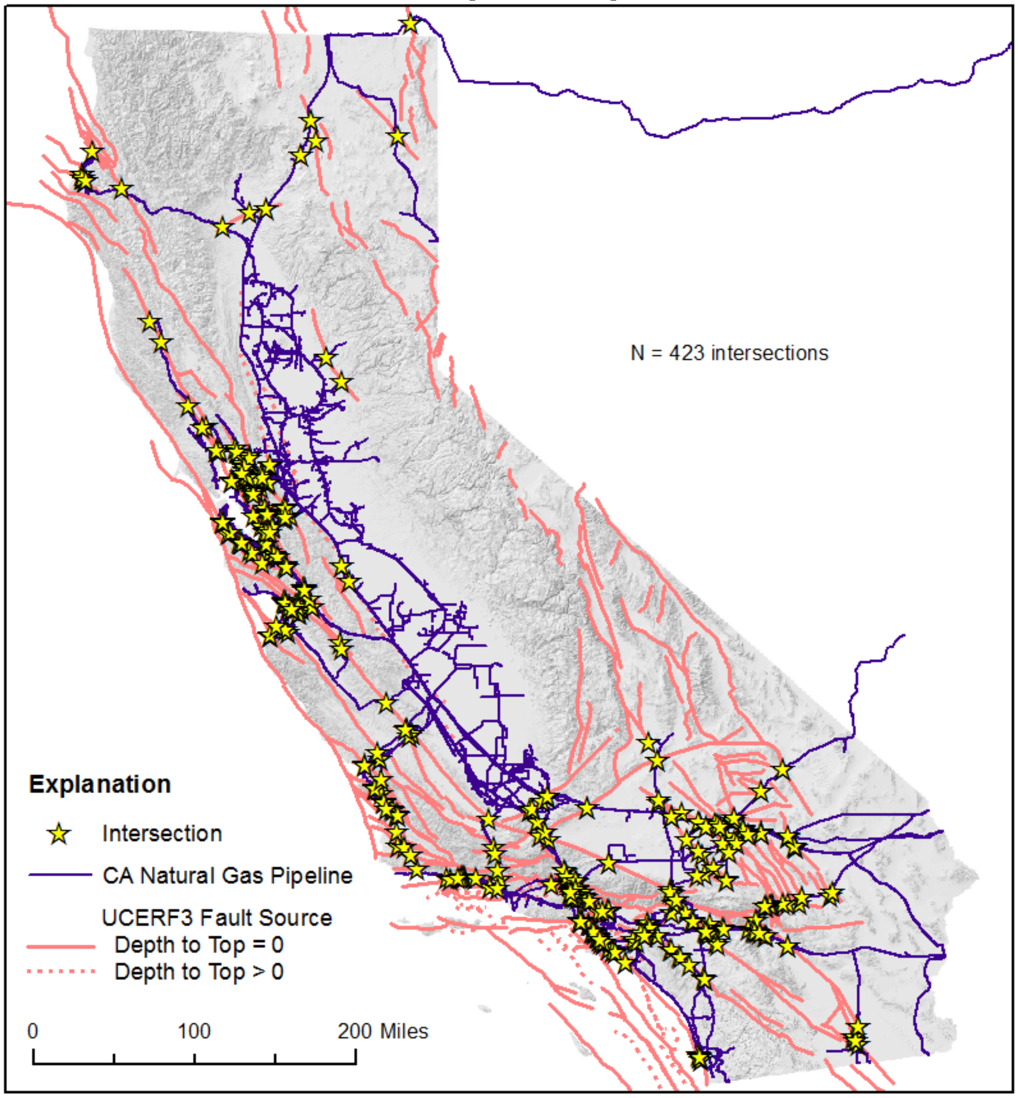
California's active fault traces are generally well understood, particularly along the San Andreas fault system that crosses through the densely populated greater Los Angeles and San Francisco Bay regions. Although recent large earthquakes such as the July 2019 moment magnitude (M_w) 7.1 Ridgecrest earthquake and its M_w 6.4 foreshock (DuRoss et al., 2020) remind us that state-wide map databases of active faults are incomplete, the earthquake hazards community generally agrees that the active faults representing the greatest hazard and risk to Californians have been identified and mapped; particularly those that have the potential to rupture the surface.

For the *Level 1 OpenSRA* analysis, the locations of active faults and their intersections with surface and near-surface natural gas infrastructure are defined based on the fault source traces of the state-wide UCERF3 model (Field et al., 2013). A map of the publicly available database of California's natural gas pipelines with the UCERF3 faults that intersect the surface (Figure 1) shows that there are 423 intersections state-wide. The use of this set of intersections has advantages and disadvantages both, including:

- Advantages –
    - Directly compatible with the earthquake event set used by *OpenSRA* for the seismic hazards of strong ground shaking and shaking-induced landsliding and liquefaction;
    - Efficient to implement state-wide and useful for building and testing the *OpenSRA* tool;

- Likely adequate for state-wide risk assessments designed to evaluate relative risk of different seismic hazards.
- Disadvantages –
  - Relies on fault source line work, which is a simplified representation of an actual fault trace (resulting in a loss of precision of actual fault-pipeline intersections);
  - May represent a gross over-simplification of the true extent and nature of fault-pipeline intersections, as actual fault zones commonly contain multiple parallel or stepping strands.

Figure 1: Intersections of Natural Gas Pipelines in California with Fault Traces from the Uniform California Earthquake Rupture Forecast, Version 3

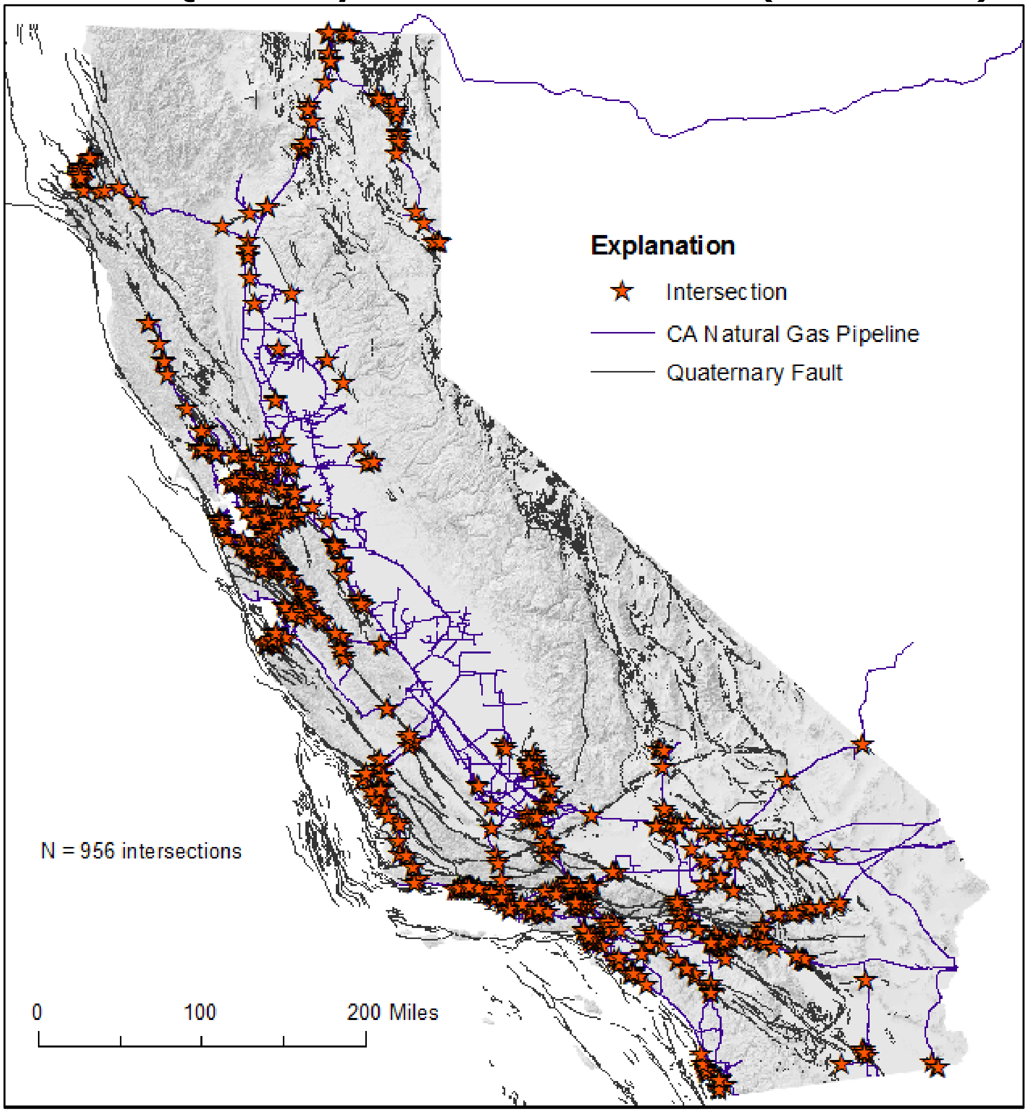


Map of California showing natural gas pipelines (in blue) and fault sources (in pink) from the Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3) model. The yellow stars show the 423 intersections of the pipelines with fault sources that intersect the surface.

Sources: Pipeline database from CEC. Fault source traces from Field et al. (2013).

For the *Level 2* analysis, *OpenSRA* plans to use a set of faults and fault locations derived from the U.S. Quaternary Fault and Fold Database (Q-faults; USGS and CGS, 2019). This publicly available database provides statewide coverage with reasonable accuracy and completeness, especially compared to the UCERF3 fault traces. Our initial geospatial analysis shows there are 956 intersections between fault traces in the database and the set of publicly available natural gas pipelines (Figure 2).

Figure 2: Intersections of Natural Gas Pipelines in California with Fault Traces from the U.S. Quaternary Fault and Fold Database (2019 edition)



Map of California showing natural gas pipelines (in blue) and fault traces from the U.S. Quaternary Fault and Fold Database (in gray). The 956 intersections of these two linear datasets are indicated by red stars.

Sources: Pipeline database from CEC. Fault source traces from USGS and CGS (2019).

As with the set of intersections based on UCERF3 traces, the set of intersections based on Q-fault traces also has advantages and disadvantages. Important ones include:

- Advantages –
  - Best publicly available state-wide representation of the known inventory of active fault traces; commonly used by the community
  - Provides a relatively precise and complete depiction of active fault locations, especially in higher population density parts of California

    - Includes a database with general documentation of recency of activity, style of faulting, location accuracy, and fault dip
- Disadvantages –
    - To implement, the Q-fault traces need to be linked to the UCERF3 fault sources so that the earthquake location-magnitude-rate distribution from the UCERF3 model can be assigned to Q-fault traces. This requires considerable effort and judgment
    - Unless the Q-fault – UCERF3 source linking is done carefully, there could be an overconfidence in the results. Though this represents an improvement in precision over *Level 1* methodology, capturing uncertainty using this method will not be straightforward.
    - Q-fault database is not complete and contains known and unknown errors.

The effort to associate Q-fault map traces that intersect gas pipelines with the UCERF3 fault sources (specifically, the UCERF3 fault subsections) has been ongoing, and the methodology for addressing complexities continues to be developed. Examples of complexities include:

- Instances of multiple Q-fault traces are represented by a single UCERF3 trace
- Instances where Q-fault traces do not have a UCERF3 trace counterpart
- Instances where UCERF3 traces do not have a corresponding Q-fault trace near the pipeline
- Instances where Q-fault traces are associated with a UCERF3 trace through UCERF3 "fault polygons", but these traces are farther from the UCERF3 trace than others or are short and apparently discontinuous.

For cases where there is not a clear and simple relationship between a Q-fault trace and a UCERF3 subsection trace, there are alternative methods that may be used in the hazard modeling. Possible treatments of Q-fault-pipeline intersections include:

- Not including the crossing in the hazard assessment due to a low fault activity criteria and/or no UCERF3 association
- Having the displacement hazard scale as a "distributed" displacement hazard rather than a principal displacement hazard (Youngs et al., 2003; Petersen et al., 2011; Nurminen et al., 2020)
- Partitioning the principal displacement among multiple Q-fault traces across fault strike (e.g., Chen and Petersen, 2011)
- Partitioning the rupture occurrence rate among multiple Q-fault traces across fault strike
- Randomizing the number and selection of alternative Q-fault traces across fault strike that rupture along with the UCERF3 rupture sources.

Because the activity of associating Q-fault traces with UCERF3 faults is a common aspect of fault source characterization and fault displacement hazard that needs to be resolved for both the PEER and parallel UCLA CEC studies, and because LCI is providing support to both teams for fault displacement hazard issues, we are developing our methodology with input from geologists and engineers from both teams, and plan on releasing a fault source characterization that may be used by both groups in developing their fault displacement hazard elements to the seismic risk assessment.

For a *Level 3* analysis, site-specific fault mapping that either confirms or improves on the Q-fault mapping will be input to the fault displacement hazard model by the user. Uncertainties in a *Level 3* analysis in fault location may be quantified based on the constraints provided by mapping and any subsurface exploration.

3.2.2 Earthquake Magnitude and Rate

The earthquake magnitude and rate relationship for the *OpenSRA* project will rely on the state-wide UCERF3 model (Field et al., 2013). The ruptures in the UCERF3 model contain information on (1) rupture location along the set of UCERF3 fault sources, (2) rupture magnitude, and (3) rate.

For *Level 1* and *Level 2* analysis, and possibly for *Level 3* analysis, this magnitude-rate relationship will be adopted for the magnitude-approach PFDHA to satisfy the portion of Equation 2: $\alpha(M_{min}) \int_{M,S} f_{M,S}(M,S)\, dMdS$.

As discussed in Section 3.2.1, the *Level 1* analysis will adopt the UCERF3 fault source locations as the basis for pipeline-fault crossings (Figure 1). For the *Level 2* analysis, the Q-fault intersection locations will be linked to UCERF3 fault source subsections in order for the magnitude-recurrence and location information to be useable.

3.2.3 Fault Displacement Model

Fault displacement models for displacement hazard must satisfy the following terms (from Equation 2 in Section 2.2.1 above):

- Conditional probability of surface rupture: $P[SR \neq 0|M]$
- Rupture location probability density function: $\int_R f_R(R)\, dR$
- Conditional probability of rupture at the crossing site: $P[D \neq 0|Z, R, SR \neq 0]$
- Displacement exceedance probability density function: $P[D > D_0|SOF, M, L^*, D \neq 0]$

3.2.3.1 Conditional probability of surface rupture

Level 1 analysis in the PFDHA will utilize a conditional probability of surface rupture, $P[SR \neq 0|M] = 1$. This model is appropriate for *Level 1* analyses given that the UCERF3 event subset consists of ruptures that are generally $M_w > 6.2$, and strike-slip and normal focal mechanism earthquakes in California of $M_w > 6$ are very likely to rupture the surface based on historical observations and the typical widths of seismogenic crust.

For *Level 2* analyses, the PFDHA will implement a logic-tree approach that adopts one or more models for conditional probability of surface rupture based on style of faulting. Published models commonly use global or regional empirical data on earthquakes that do and do not rupture the ground surface, and fit these data to a logistic regression of the form:

$$P[SR \neq 0|M] = \frac{e^{a+bM}}{1+e^{a+bM}} \quad (3)$$

For strike-slip and normal focal mechanism events, we recommend *a* and *b* parameters from Wells and Coppersmith (1993) as adopted by Petersen et al. (2011) and the parameter pairs developed based on normal focal mechanism earthquakes by Youngs et al. (2003), respectively. For reverse and thrust faults, we recommend consideration of parameters based on the work of Moss et al. (2013; 2018). Historical examples of reverse faults that produced surface rupture include the 1952 M_w 7.3 Kern County earthquake on the White Wolf fault (Buwalda and St. Amand, 1955) and the 1971 M_w 6.6 San Fernando earthquake on the San Fernando fault (Allen et al., 1975). In the case of the 1952 Kern County earthquake, most of the western portion of the rupture did not rupture the ground surface, including where the White Wolf fault crossed the PG&E natural gas transmission line L-300 near Arvin, California (Lind, 1954). In the areas where no surface-fault rupture was documented following the 1952 earthquake the geomorphic expression of the fault was poor. Examples of reverse fault earthquakes in California that did not produce surface-fault rupture are the 1983 Coalinga, 1994 Northridge, and 2003 San Simeon earthquakes (Moss and Ross, 2011). In the first two cases the earthquakes occurred on blind faults and thus the conditional probability of surface rupture would be 0; in the case of the 2003 San Simeon earthquake, the causative Oceanic-West Huasna fault is mapped at the ground surface and locally has some geomorphic expression of recent activity.

For a *Level 3* analysis, the conditional probability of surface rupture should consider available paleoseismic information, geomorphic expression, and local seismological information on crustal thickness. From this information, site-specific conditional probability of rupture relations may be developed that can provide alternative logic-tree branch values in addition to applicable empirical equations. This information and the development of site-specific models should be provided by the user.

3.2.3.3 Rupture location probability density function

The rupture location probability density function, $\int_R f_R(R)\,dR$, captures uncertainty in where the rupture will be located relative to the mapped fault (and where rupture is expected to occur). Petersen et al. (2011) reviewed a few cases where this could be quantified, and estimated rupture location uncertainties that varied from 27 m (one standard deviation) for a fault that was mapped as well located to rupture uncertainties of 116 m (one standard deviation) for a fault that was mapped as concealed or inferred in an area of fault-zone complexity.

For *Level 1* analysis, the rupture location probability density function will not be used or will be used very simply for testing. This is appropriate given the linear nature of natural gas pipelines, as a non-parallel fault-pipeline geometry will result in a crossing at some location. For L*evel 2* analysis, fault location uncertainty polygons will be created with a representative uncertainty distance (e.g., 100 m) that can be applied simply and uniformly across the state. These location uncertainty polygons will capture some of the fault location and rupture location uncertainties, and provide greater assurance that fault-pipeline intersections will be identified and evaluated.

For *Level 3* analysis, the location uncertainty will be incorporated based on site-specific information; such information will be provided by the user.

3.2.3.2 Conditional probability of rupture at the crossing site

The conditional probability of rupture at the crossing site: $P[D \neq 0|Z, R, SR \neq 0]$, is part of the complete formulation of the PFDHA but it is seldom used in practice. This is partly because the probability is relatively close to 1 given available empirical data (Petersen et al., 2011). For the *Level 1* and *Level 2* analyses, we recommend following standard PFDHA practice and adopting a probability = 1.

For *Level 3* analyses, this conditional probability should be considered for inclusion based on the specifics of the study area. Maps of surface-fault ruptures (e.g., as compiled by Wesnousky, 2008) show that there are gaps and steps in a rupture such that a large, surface-rupturing earthquake has some probability of not rupturing at or near a fault intersection with a gas pipeline. As stated in the above section, the 1952 Kern County earthquake provides an example of this, as the PG&E natural gas line L-300 crossed the White Wolf fault at the time of the earthquake (Lind, 1954). The earthquake did not damage the pipeline at the fault crossing, and there is no indication of ground rupture across the pipe, despite clear surface-fault ruptures along strike to the southwest and northeast (Buwalda and St. Amand, 1955). Earthquakes such as the 1992 M_w 7.2 Suusamyr, Kyrgyzstan earthquake ruptured the surface but had gaps in the surface rupture trace that were much greater than the ~4 km of total surface breaks (Ghose et al., 1997). Petersen et al. (2011) quantify the probability of a "gap" in primary surface rupturing as a function of site dimension, z, for the several strike-slip earthquakes in their analysis. For the largest site dimension of 200 m x 200 m, the probability of primary surface rupture through the site was calculated to be 92.5%; this probability drops to 74.5% for a 25 x 25 m cell size.

3.2.3.3 Displacement Exceedance Equation

For the *OpenSRA Level 1* analyses, the fault displacement exceedance term, $P[D > D_0|SOF, M, L^*, D \neq 0]$, is simplified from this standard form (Youngs et al., 2003; Petersen et al., 2011; Moss and Ross, 2011) to remove dependence on style of faulting (SOF) and normalized location along the rupture length (L^*). The recommended form has M as the only predictor variable and is applicable to all styles of faulting, all along-strike locations, and has a clear separation of an aleatory term (expressing the component of hazard uncertainty due to natural event-to-event rupture variability at a given site) from an epistemic term (expressing the component of hazard uncertainty due to lack of scientific knowledge about the rupture process and/or ignorance). This simple exceedance equation has the form:

$$P[D > D_0|M, D \neq 0] = 1 - \Phi(\varepsilon_D^*) \tag{4}$$

where $\Phi(x)$ is the standard normal cumulative distribution function. Epsilon star ε_D^* is the number of standard deviations from the median predicted displacement at the crossing site, and is given by:

$$\varepsilon_D^* = \frac{\ln(D_0) - \ln(D_{med,site})}{\sigma_{SS}} \tag{5}$$

where $D_{med,site}$ is the median displacement at the crossing site and σ_{SS} is the standard deviation representing the aleatory variability for displacement at a single site.

The median displacement is given by:

$$\ln(D_{med,site}) = a + bM \tag{6}$$

where *D* is in meters, *M* is in moment magnitude, and *a* and *b* are fitting parameters. Equation (6) has a standard deviation representing epistemic uncertainty of $\sigma_{Dmed,site}$. Published values for *a* and *b* (or their equivalent values using $\log_{10}$) are based on fitting the log-linear equation to available empirical data (Wells and Coppersmith, 1994; Moss and Ross, 2011; Hecker et al., 2013). Table 2 provides the recommended values for a, b, $\sigma_{Dmed,site}$, and σ_{SS} for use in the *Level 1* analyses. The *a* and *b* values are based on averaging three published models that are fit to average surface displacement (AD) data of all styles of faulting: Wells and Coppersmith (1994; their all slip types M_W-log(AD) relation), Hecker et al. (2013; values fit to a dataset from Wesnousky, 2008), and Wells and Youngs (2015; their all slip types M_W-log(AD) relation).

Table 2: Parameters for *Level 1* Fault Displacement Exceedance Equation

Parameter (Eq. 5 and 6)	Level 1 Value	Notes
$\boldsymbol{a}$	-10.181	Parameters in Equation (6) based on the average of three empirical equations: Wells and Coppersmith (1994); Hecker et al. (2013); Wells and Youngs (2015)
$\boldsymbol{b}$	1.464	Parameters in Equation (6) based on the average of three empirical equations: Wells and Coppersmith (1994); Hecker et al. (2013); Wells and Youngs (2015)
$\boldsymbol{\sigma_T}$	0.943	Based on average of three empirical equations (above)
$\boldsymbol{\sigma_{Dmed,site}}$	0.800	Epistemic uncertainty in median displacement at a site estimated based on removing σ_{SS} (below) from σ_T (Equation 7).
$\boldsymbol{\sigma_{SS}}$	0.498	"Single site" aleatory standard deviation based on Hecker et al. (2013) coefficient of variation of 0.53 estimated for all slip types.

Table 2 provides recommended values to use for the fault displacement exceedance equations (5) and (6) for *Level 1* analyses.

For *OpenSRA* development, Equation (5) will be implemented as shown with the value for aleatory single site standard deviation and epistemic uncertainty in Table 2. This allows us to estimate the total epistemic uncertainty of the risk estimates.

The derivation of the epistemic and aleatory uncertainties in Table 2 follows the simple method described in Abrahamson (2008) and Thompson et al. (2018). This method estimates the total standard deviation of estimating displacement at a given point along a rupture as the square root of the sum of the squares of the regression standard deviation of an empirical relation between log of average displacement (*AD*) of a rupture, σ_{AD} as a function of magnitude and the standard deviation of the along strike variability of any one point along a rupture, σ_{AS}. This same total standard deviation can be considered to be composed of a site-specific aleatory term, σ_{SS}, and a site-specific epistemic term, $\sigma_{Dmed,site}$, or:

$$\sigma_T = \sqrt{\sigma_{AD}{}^2 + \sigma_{AS}{}^2} = \sqrt{\sigma_{SS}{}^2 + \sigma_{Dmed,site}{}^2}. \quad (7)$$

The value of σ_{AS} is estimated to be approximately 0.555 (in natural log; or 0.24 in $\log_{10}$ units) based on an along-strike displacement coefficient of variation of approximately 0.6 from data compiled by Wesnousky (2008); Values of σ_{AD} range from approximately 0.691 to 0.829 (in natural log; or approximately 0.30 to 0.36 in $\log_{10}$ units).

The advantage of using the *Level 1* fault displacement model is that it is very simple, applicable to all styles of faulting, and is independent of other parameters such as normalized location along strike that may be difficult to justify in a simple representation of hazard. The proposed *Level 1* model also has a simple method of isolating epistemic uncertainty that will facilitate the exploration of the contribution of fault displacement hazard uncertainty to overall seismic hazard and risk uncertainty.

The disadvantage of using the above formulation is that it is a known over-simplification of fault displacement models. The recommended procedures described above for a *Level 1* analysis greatly simplify the various terms in Equation (2) and by doing so overlook aspects of fault rupture behavior known to occur. The simplifications should be recognized by the *OpenSRA* team and considered in the development of fragility functions.

For the *OpenSRA Level 2* analyses, the fault displacement exceedance term, $P[D > D_0|SOF, M, L^*, D \neq 0]$, will be based on published empirical models developed specifically for PFDHA (Youngs et al., 2003; Petersen et al., 2011; Moss and Ross, 2011). These models are developed for a specific style of faulting (SOF) and use normalized location along the rupture length (L^*) as an explanatory variable in addition to M. Implementation of the L^* term with the *Level 2* fault source characterization will require some simplifications that will be based on the UCERF3 rupture model.

The PFDHA publications include alternative functional forms of the exceedance term, which represent a limited amount of epistemic uncertainty within each model. Each displacement exceedance equation has a published standard deviation that represents a total uncertainty in the fit of the model to empirical data. For *OpenSRA*, this "total" empirical model sigma, σ_T, is assumed to consist of a combination of site-specific aleatory variability (σ_{SS}) and additional epistemic uncertainty in the site-specific median displacement ($\sigma_{Dmed,site}$), as noted in Equation (7). Although there is epistemic uncertainty in the correct aleatory variability term at any given location, for simplicity we plan to use a current best-estimate value of σ_{SS} based on Hecker et al. (2013) as listed in Table 2.

For *Level 3* analyses, we plan to use appropriate published models based on site-specific conditions. For example, for the Cordelia Junction demonstration site, the fault displacement hazard is the intersection of a PG&E gas transmission line with the southern Green Valley strike-slip fault. Trench data across the fault zone have identified two parallel principal faults. These data will be reviewed and a fault displacement exceedance formulation based on Petersen et al. (2011) will be adopted, with adjustments based on information available to constrain how displacement may be partitioned between the two identified principal faults. In addition to existing models, emerging PFDHA models (e.g., Lavrentiadis and Abrahamson, 2019) will be considered as well.

3.2.4 Displacement Direction

Fault displacement models for displacement direction (normalized displacement components as easting, northing, and vertical) will be developed based on fault strike, dip, and rake. For *Level 1* and *Level 2* analyses, these parameters will be based on fault dip, dip direction, and rake information in the UCERF3 event set. As these parameters are defined in UCERF3 as averages for the entire rupture section through seismogenic depth, there is considerable uncertainty in these values given the very specific locations of the fault crossings at the near-surface, and the possible differences in both dip and rake in the near surface versus averaged over the seismogenic crust. The exact methodology for incorporating uncertainty in displacement direction will be determined during discussions with the fragility working group and as *OpenSRA* continues to be developed and tested.

For *Level 3* analyses, calculating displacement direction is more straightforward as it will rely on site-specific field data. Using direct observations will allow for more reliable estimations of preferred values and uncertainties.

3.2.5 Width of Faulting and Soil or Rock Strength for Buried Infrastructure

Items such as width of faulting at the pipe scale, soil strength data for backfill and trench walls needed to estimate soil springs, etc. will be addressed in coordination with the fragility group.

3.3 Fault Displacement Hazard for Facilities at Depth

There are twelve operational underground natural gas storage facilities in California in 2020 (CalGEM, 2020). These facilities hold reserves of natural gas within permeable sandstone layers that historically were drilled for oil and gas extraction. Wells serve to exchange gas between the natural reservoirs and surface facilities including above-ground storage tanks, pump stations, and natural gas transmission lines. These natural reservoirs consist of permeable strata that provide the reservoir volume and overlying impermeable "caprock" that retards the migration of gas out of the reservoir to higher stratigraphic levels and possibly the ground surface. The geometric and geologic configurations of these reservoirs are the result of prior tectonic activity that folded and/or faulted the strata. In some instances, such as at the Honor Rancho Underground Gas Storage Facility (Honor Rancho) near Valencia, California, ongoing tectonic activity may have resulted in one or more active faults within or above the caprock. Such a fault or faults may intersect the set of wells used to inject or extract the gas. The intersection of such faults with the wells would represent a fault displacement hazard at depth, whereby fault displacement may have the potential to rupture the wells and result in uncontrolled release of gas from the reservoir (which may, in turn, be captured within the caprock or escape to the surface).

For the *OpenSRA* project, we are addressing the fault displacement hazard to underground storage facilities by building on the geological hazard screening study conducted as part of the Long-Term Viability of Underground Natural Gas Storage in California study report published in 2018 by the California Council on Science and Technology (CCST, 2018). In Chapter 1.2 of that study, a possible fault displacement hazard was identified at four facilities: Kirby Hill, Los Medanos, Aliso Canyon, and La Goleta. The potential fault displacement hazard at the Honor Rancho facility was not identified based on their screening analysis methodology. As part of the *OpenSRA* project, the PEER team is working with the Southern California Gas (SoCalGas) company, the owner and operator of the Honor Rancho natural gas storage facility, to develop a demonstration study assessing the seismic risk at Honor Rancho, including the risk associated with fault displacement hazard.

Our work on characterizing the fault displacement hazard to underground storage facilities to date has consisted of literature review and the development of structure contours at the Kirby Hill, Los Medanos, Aliso Canyon, and La Goleta facilities, plus a review of available information about the geologic and tectonic setting of the Honor Rancho storage facility. For the Honor Rancho demonstration, we are assessing proposed models of faulting that may intersect the facility, and exploring possible relationships between the proposed faults and active fault sources capable of generating large earthquakes. This initial work builds on information developed by LCI as part of a risk assessment of the Honor Rancho gas storage facility led by Lawrence Berkeley Natural Labs (LBNL) and funded by the CEC (Agreement PIR-16-027). This work has documented the probable geologic setting of the Honor Rancho reservoir as bounded by faults on the north, south, and east sides that do not cut the caprock directly overlying the reservoir (Jeanne et al., 2020). We recognize that, in addition to these faults, there is a "proponent" geologic model of the site that includes a moderately dipping fault that cuts the caprock above the reservoir. This fault is interpreted to intersect the wellfield used to operate the facility and regulate pressures and exchange of gas. We deliberately use the term "proponent" to underscore our interpretation that this moderately dipping fault is not clearly demonstrated to exist based on the currently available data, but likewise it cannot be precluded. As such, it represents a viable hypothesis for faulting at the reservoir site that, if present, may represent a seismic hazard. For the purposes of the demonstration study, we presume this fault exists as described by the proponent. Furthermore, we are examining the potential activity of this fault given the current thrust faulting stress regime (Jeanne et al., 2020) and the possible geometric and kinematic connections of this fault with regional active fault sources that are represented in the UCERF3 model used by *OpenSRA*. Additional details about the *Level 3* PFDHA at Honor Rancho will be presented in the Validation Report in 2021/2022.

The sections below describe the work that will be performed and documented; this information is preliminary.

3.3.1 Locations of Fault-Well Intersection

The suspected natural gas storage facilities where active faults may intersect the wellfield used for reservoir operation are the Kirby Hill and Los Medanos facilities in Northern California, and the La Goleta, Aliso Canyon, and Honor Rancho facilities in Southern California (CCST, 2018). Wellhead locations from the CalGEM site and well attribute data collected by P. Jordan of LBNL provide a preliminary database for the wellfield locations. Based on literature review and available maps, preliminary fault structure contours have been generated for all sites but the Honor Rancho location. Structure contours for the Santa Susana fault intersecting the Aliso Canyon facility are based on the PFHDA for the Aliso Canyon site documented by Thio and Somerville (2019). The structure contour/fault geometry information will be input to OpenSRA. For locations of fault-well intersection to these four facilities, we will assume vertical well orientations for the *Level 1* and *Level 2* analyses. This simplification will allow the OpenSRA tool to compute intersection locations and provide a first-order view of hazard locations. *Level 3* analysis should incorporate well-specific information about well depth and drill-hole direction.

For the Honor Rancho demonstration study, the fault location information will be based on available information, which to date consists of the proponent model mentioned above. As the quality of the available information is poor, we are reluctant to classify it as a *Level 3* study; however, because following the *Level 1* and *Level 2* procedures described above for surface faulting would result in no principal faulting at the Honor Rancho site, we will consider the Honor Rancho PFHDA as a *Level 3* effort. As part of this effort, the wells that may intersect the active fault, and the depth intervals where the intersections may occur, will be documented as part of the final effort. Initial estimates are that the fault will intersect the majority of operating wells in the Honor Rancho wellfield at depths of approximately 1-2 km.

3.3.2 Earthquake Magnitude and Rate

The earthquake magnitude and rate relationship for the faults intersecting the gas storage facilities will follow the *Level 2* procedure described above for surface faulting. The work required will be to identify the possible relationships between faults and the UCERF3 fault subsections. For the Honor Rancho study, this will include identifying an appropriate UCERF3 source to associate with the "proponent" fault.

3.3.3 Fault Displacement Model

The fault displacement model to be used for the underground storage facilities will implement a logic tree approach in coordination with the *OpenSRA* model team and fragility team. For the conditional probability of rupture, the displacement model will consider the general methodology of Thio and Somerville (2019) that was developed for Aliso Canyon, where a site-specific conditional probability was developed based on fault width, earthquake nucleation depths, and the depths of fault-well intersections. The concern with implementing such a model for the Honor Rancho site (and possibly the Kirby Hill site) is that the fault representing the hazard does not appear to be a principal earthquake source, but rather a secondary fault that branches from a principal source. This geometric relationship suggests that alternative conditional probabilities may need to be explored.

For the fault displacement exceedance equations, it is likely that the reverse fault PFHDA model of Moss and Ross (2011) will be adopted along with secondary displacement scaling from Petersen et al. (2011) and Nurminen et al. (2020). These models may include modifications that account for localization of faulting at depth, as quantified based on research of the shallow slip deficit (Fialko et al., 2005; Dolan and Haravitch, 2014; Xu et al., 2016). The shallow slip deficit is an observation that the average displacements of earthquake ruptures at seismogenic depths are greater than the corresponding average displacements measured at the ground surface. The difference in displacement observed at the surface relative to the displacement at seismogenic depths is the shallow slip deficit. One proposed explanation for this phenomenon is that earthquake displacements are localized on a principal slip surface and narrow fault damage zone at seismogenic depths (e.g., Savage and Brodsky, 2011), but the localized displacements become distributed across a broad zone as ruptures approach the ground surface (Dolan and Haravitch, 2014). Only some of the fault slip at depth, therefore, is expressed at the ground surface as localized principal fault displacement. Estimates of the ratio of surface principal displacement to principal displacement at depth are on the order of 0.7 ± 0.2 (Xu et al., 2016). The remainder of the displacement is distributed onto secondary faults or as distributed shear of the ground that is difficult to recognize using traditional field methods, but is now quantifiable using remote sensing techniques (Xu et al., 2016). For the *OpenSRA* project, our approach to displacements at depth will likely assume a ratio of ~0.7 ± 0.2 for the shallow slip deficit, and postulate that at the 1-2 km depth range of fault intersections at Honor Rancho the fault displacement is more localized. In addition to adjusting the median models, consideration will be given to adequately adjust epistemic and aleatory uncertainties for displacement at depth.

3.3.4 Displacement Direction

Displacement direction for intersecting wells at depth should follow a combination of *Level 2* and *Level 3* procedures whereby consideration should be given to available site-specific information. In the case of Honor Rancho, preferred estimates and uncertainties of fault strike, dip, and rake at the intersections will be used to develop model uncertainties in displacement direction. Any specific methods of reporting results will be developed in coordination with the fragility group.

3.3.3 Width of Faulting and Rock Strength

It is generally considered that displacement at depth (~3 km) is more localized than at the ground surface (Thio and Somerville, 2019), but fault damage zones consisting of a principal fault and secondary faults and shears probably continue to operate (Savage and Brodsky, 2011). Given the ~1-2 km depth of the well intersections, we will consider uncertainty in the width of faulting but will likely emphasize localized (knife edge; or mm- to cm-scale) displacements of principal faulting in any modeling by the fragility group for pipeline response. Rock strength information will be developed by LBNL project team members that are familiar with caprock data and who are involved in modeling pipeline response and fragilities.

CHAPTER 4: Discussion and Conclusions

The recommended inputs and models presented in this report for fault displacement hazard assessment developed under this work are suitable for developing the *OpenSRA* tool, for portfolio-level seismic risk assessment from the hazard of fault displacement (for *Levels 1* and *2*), and for conducting site-specific seismic risk assessments (for *Level 3*, subject to requirements discussed in that section). As the project is still in the developing stages, the recommendations herein will be periodically reviewed and updated based on feedback from initial modeling efforts, development of approaches for fragilities, details that will be revealed as the project conducts the site-specific case studies, and initial hazard results.

4.1 Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

The *OpenSRA* tool is the objective for a technology that would be shared with California's utility owners and regulators and ideally be suitable for other owners, regulators, researchers, and practitioners interested in understanding seismic risks to lifelines or other critical installations in a probabilistic framework. The fault displacement hazard component, at least in this stage, is crude and is applicable to the overall objectives of the seismic risk software. The fault displacement hazard tools are not intended to represent a sophisticated, state of the practice hazard analysis methodologies, but rather appropriately simplified methodologies that are useful for quantifying seismic risk at the portfolio and regional scales.

4.2 Benefits to California

The *OpenSRA* project benefits California by providing a tool for natural gas utility owners, regulators, stakeholders, and the public to assess the seismic risks to the natural gas infrastructure. As large earthquakes are relatively rare natural phenomena and their occurrence cannot be predicted with sufficient accuracy for routine mitigation, developing a risk analysis tool that is based on sound scientific information and engineering evaluation provides a useful and practical means for evaluating and discussing these seismic risks and the potential harm they may cause to people and the environment. The *OpenSRA* project represents an initial effort to bring together models for a variety of types of seismic hazards that threaten natural gas infrastructure (hazard models) and models for structural response of infrastructure to the hazards (vulnerability models) so that the risk of failure may be estimated. To ensure the risks are being compared on an equal footing, hazard, vulnerability, and risk are measured using a probabilistic framework that includes both the aleatory variability, or intrinsic variability of natural phenomena (e.g., the amount of fault displacement at a pipeline crossing that may occur in the next earthquake) and the epistemic uncertainty in the models and parameters used as input to the tool. This probabilistic frameworks provides value to California by allowing engineers, decision-makers, and stakeholders to assess the hazards, vulnerabilities, and parts of the modeling that are most important to the seismic risk. Furthermore, this assessment may be performed at various spatial scales (state-wide, city-wide, or by facility) so that policy, funding, and/or engineering decisions may be made at various scales using scale-appropriate information. The *OpenSRA* project represents an innovative start to the long-term objective of quantifying seismic risk to California's natural gas infrastructure; only by continued investment by the state and utilities in applied research and engineering analysis will the models improve along with our ability to mitigate risks of damage to people and the environment.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
AD	average displacement (principal faulting, at the surface)
CalGEM	California Geologic Energy Management Division
CCST	California Council on Science & Technology
CGS	California Geological Survey
d	secondary fault displacement
D	principal fault displacement
LBNL	Lawrence Berkeley National Labs
LCI	Lettis Consultants International
M_W	moment magnitude
PEER	Pacific Earthquake Engineering Research Center
PFDHA	probabilistic fault displacement hazard analysis
PG&E	Pacific Gas and Electric
PSHA	probabilistic seismic hazard analysis
Q-faults	faults in the U.S. Quaternary Fault and Fold Database
Slate	Slate Geotechnical Consultants
SoCalGas	Southern California Gas
UCERF3	Uniform California Earthquake Rupture Forecast, Version 3
USGS	U.S. Geological Survey

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