Aliso Canyon Gas Storage Field Geologic, Seismologic, and Geomechanical Studies: Scope of Work

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Scope of Work

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BACKGROUND

On July 29, 2016, Southern California Gas Company (SoCalGas) submitted a Storage Risk Management Plan (SRMP) pursuant to DOGGR's Emergency Regulations Section 1724.9(g) of Title 14 of the California Code of Regulations, DOGGR Order No. 1109. On October 11, 2016, SoCalGas supplemented the SRMP pursuant to a request by DOGGR dated October 5, 2016, identifying potential geologic, seismologic and geotechnical hazards to the Company's Aliso Canyon Natural Gas Storage Field (Storage Field). In the supplement, SoCalGas identified additional geologic studies that could be undertaken to further assess those hazards.

By letter dated January 17, 2017, DOGGR concluded that SoCalGas' SRMP and supplement were in compliance with DOGGR's regulations "conditioned upon further study as recommended by subject matter experts at Lawrence Berkeley, Lawrence Livermore, and Sandia National Laboratories" (collectively, the National Labs), and in conjunction with those laboratories.

Pursuant to DOGGR Order No. 1118, SoCalGas committed, by letter dated July 31, 2017, to provide DOGGR with a "workplan for completing the seismic risk study to the satisfaction of DOGGR using a third-party consultant approved by the Division and National Laboratories." The study will include a Probabilistic Seismic Hazard Analysis, a Probabilistic Fault Displacement Hazard Analysis, and the evaluation of potential mitigation measures.

GENERAL SCOPE OF WORK

The tasks outlined below will more fully identify and assess any potential geologic, seismologic, and geomechanical hazards to SoCalGas' Storage Field. Consultants for and employees of SoCalGas (collectively the "Work Team") will perform the following tasks:

Task 1: Petrophysical Model

Create a geomechanical earth model that will represent the structural and stratigraphic framework of the Storage Field, including the gas storage zone, the oil and gas zones, and the overlying geologic units. The three-dimensional earth model will include structural features such as faults, petrophysical and stratigraphic properties in and around the Storage Field, and the geological connection to wellbore conditions. These features will provide the basis for other technical analyses of the field such as fault seal analysis and other geomechanical modeling.

Task 2: **Seal Analyses**

Compile and analyze the relative stratigraphic offsets for the faults affecting the reservoir. Use rock properties to calculate shale gouge ratios and to assess the sealing capacities of these structures, including faults transecting wellbores in the Storage Field, oil reservoirs, and overlying geologic units. Assess the caprock/top-seal properties of the Mohnian shale caprock directly above the gas storage reservoir and the caprocks of the overlying oil and gas reservoirs.

Task 3: **Probabilistic Seismic Hazard Analysis**

Perform a quantitative Probabilistic Seismic Hazard Analysis (PSHA) that considers potential significant earthquake sources within and near the Storage Field. This activity will assess the probability of key ground and subsurface shaking intensity measures for future seismic event in the Storage Field region, including specific components of these hazards contributed by the Santa Susana and other regional faults. The goal of this analysis is to define the ground and subsurface shaking hazards present at the Storage Field.

Task 4: **Probabilistic Fault Displacement Hazard Analysis**

Perform a quantitative probabilistic fault displacement hazard analysis (PFDHA) for the faults within the Storage Field by assessing the potential for surface and subsurface fault rupture, with an effort to estimate the magnitudes and patterns of displacement on the Santa Susana fault and other structures. The goal of this analysis is to define the fault displacement hazards present at the Storage Field. This will involve assessment of how tectonic fault displacements may impact fault seal and gas containment.

Task 5: **Landslide Hazard Analysis**

Examine the extent of landslides and debris flows (natural hazards; mass-wasting processes) in the Storage Field. Analyze the character, nature and relative hazard of mass-wasting phenomena for their potential impact on the continued and safe operation of the Storage Field.

Task 6: **Mitigation Evaluation**

SoCalGas, after consultation with its Work Team, will evaluate potential mitigation actions. The Company will determine what measures may be used to mitigate identified hazards, including modification of SoCalGas' current risk management plans. SoCalGas will implement the measures in accordance with current regulations, risk priorities, available resources, timing considerations, and costs.

SoCalGas will provide updates of the Work Team's efforts to DOGGR on a monthly basis.

DELIVERABLES

The deliverables for these tasks will include the following:

Task 1: **Petrophysical Model Outputs**

Outputs from a petrophysical model, based on Petrel software, and a report that will define all known trap and fault geometries, as well as reservoir and caprock properties, including the caprock top seal properties above the oil and gas storage reservoirs. These data will be used to calculate the stresses and fluid pressures acting on the reservoir, caprock, and faults. The formal documentation will show:

- 3-D geometries of faults and stratigraphic horizons
- Reservoir and caprock properties
- Reservoir seal integrity analysis
- Fault displacement maps
- Fault seal integrity analysis
- Wellbore conditions as they relate to petrophysical properties

Task 2: **Seal Analyses**

A technical report that will determine the current status of fault and top seal integrity and will estimate mechanical and fluid resistance of overlying stratigraphy as related to the stress state. There will be a qualitative identification of at-risk areas within the gas storage reservoir and overlying caprock, and a determination of quantitative limits on injection pressures (if in-situ stress data are available). Further, there will be an assessment of how tectonic fault displacements may impact fault seals and gas in storage.

The Petrel model will be used to correlate cement tops to stratigraphy and structure. These correlations will show presence of a cement barrier to flow path through the top seal.

Task 3: **Probabilistic Seismic Hazard Analysis**

A technical report that provides comprehensive probabilities of exceedance or spectral accelerations and other ground and subsurface motion intensity measures at the Storage Field. This analysis will incorporate earthquake sources defined in the California Uniform Earthquake Rupture Forecast (UCERF3), as well as refined representations of the Santa Susana fault and other local sources based on data from the Storage Field. This report will include:

- an Earthquake Rupture Forecast (ERF) describing possible earthquake sources that may impact the Storage Field, the distribution of potential earthquake magnitudes, and the distribution of source-to-site distances;
- prediction of distribution of ground and subsurface motion intensity measures resulting from the ERF based on established attenuation relationships;
- full distribution of levels of ground and subsurface shaking intensity and their associated rates of exceedance that incorporates uncertainties in earthquake size, location, and ground motion intensity; and
- a full description of the data and methods used in the analysis.

A separate technical report summarizing the structural analysis of the various well casing systems under applicable seismic loading conditions will be provided. The report will document the methodology and approach for the structural analysis and summarize the load distribution along the well casing.

Task 4: Probabilistic Fault Displacement Hazard Analysis

A technical report that provides comprehensive probabilities of fault displacement magnitudes for faults transecting the Storage Field wellbores. This study will build on the PSHA analysis, augmented with measurement of past fault displacements at the site obtained through geomorphic and/or paleoseismic analysis, including:

- an assessment of fault displacement magnitudes based on rupture scenarios defined by the ERF that are part of the PSHA. Event magnitudes will be translated to mean and maximum fault displacements using standard regressions and fault displacement attenuation functions;
- an assessment of these regressions and fault displacement attenuation functions based on empirical constraints on displacement patterns in past thrust fault earthquakes in southern California and similar tectonic settings. Revised displacement attenuation functions will be developed and incorporated in the analysis if warranted;
- a full distribution of plausible fault displacement patterns, and their associated rates of occurrence that incorporates uncertainties in earthquake size, location, and magnitude-to-displacement scaling; and
- a full description of the data and methods used in this analysis.

A separate technical report summarizing the structural analysis of the various well casing systems under applicable seismic loading conditions will be provided. The report will document the methodology and approach for the structural analysis and summarize the load distribution along the well casing.

Task 5: Landslide Hazard Analysis

A technical document that gathers and provides field and remote sensing data, supplemented with field investigations ("ground truth") and related interpretations within the Storage Field. The formal documentation will:

- identify the area, magnitude, and possible age of previous, large-scale mass-wasting events;
- determine and rank mass-wasting locations and factors that might trigger future deleterious landslides and debris flows; and
- delineate the most vulnerable areas and describe potential effects on the Storage Field.

Task 6: Mitigation Evaluation

A report that identifies the hazards, rank orders them, and identifies potential measures to mitigate the hazards. To the extent possible, the timing and cost of mitigation measures will be identified as part of comprehensive implementation plans.

To date, SoCalGas has addressed these hazards in a number of earlier submissions to DOGGR. In its SRMP dated July 29, 2016, SoCalGas identified a number of preventative and mitigative efforts to reduce risks to its underground storage facility assets. Those efforts include data collection and management, continual threat identification and risk analyses, ongoing verification and demonstration of the mechanical integrity of each asset, and diligent implementation of preventative and mitigative measures. The measures are conducted to reduce the likelihood of events related to threats listed in API RP 1171, and consist of performing routine condition monitoring and analysis for threats to wells, reservoir and well laterals. SoCalGas also identified the teams responsible for the preventative and mitigative measures, the work flow processes, and specific measures to address the potential threats.

In its supplement to its SRMP dated October 11, 2016, SoCalGas further identified protocols to mitigate potential geologic and geotechnical risks. Those efforts include: (i) prepositioning materials and equipment; (ii) real-time pressure monitoring; (iii) surface safety systems; (iv) auxiliary wellsite kill piping; (v) slope stabilization; (vi) surface and subsurface subsidence measures; (vii) tubing flow only; and (viii) leak patrols and methane monitoring.

In July 2017, SoCalGas updated its Gas Storage Emergency Binder to utilize in the event of a "Limited Scale Event" or a "Major Incident," which includes an earthquake. The 700-page binder includes field service emergency plans, transmission command post guidelines, and a gas emergency response plan.

Schedule:

The Company proposes the following schedule:

Anticipated Dates to Submit Draft Reports to DOGGR:

Petrophysical Model	February 1, 2018
Seal Analyses	February 1, 2018
Probabilistic Seismic Hazard Analysis	February 1, 2018
Probabilistic Fault Displacement Hazard Analysis	February 1, 2018
Landslide Hazard Analysis	January 1, 2018
Mechanical Stress Analysis	February 1, 2018

Anticipated DOGGR Comments:

All Reports	April 1, 2018

Anticipated Final Reports:[1]

All Reports	June 1, 2018

Monthly Reports:

The Company will provide monthly progress reports to DOGGR on the tasks.

ACCESS, DATA SHARING, AND PRIVACY CONCERNS

SoCalGas will: (i) provide access to the Storage Field; (ii) identify and provide existing reports, maps, imagery, and other pertinent data in its possession; (iii) share this data with the Work Team and other designated parties as appropriate; and (iv) perform any other work that SoCalGas deems appropriate.

The Work Team will establish and follow strict protocols on the use and public release of

[1] These deadlines assume that DOGGR will provide its comments to the specific reports by April 1, 2017.

data to protect the release of sensitive or confidential information. Additional privacy concerns will be addressed as they arise.

DESCRIPTION OF ANALYSIS/METHODOLOGY

Task 1: Petrophysical Model

Review key well data including drilling and completion records, well logs, and core data along with structure contour maps and existing geologic models. Integrate these data in a 3-D modeling environment and develop refined representations of the reservoir and seal units, as well as faults in the region, including top seal properties of caprock above the oil and gas producing reservoirs and above the gas storage reservoir. Formalize methodology based on available data to specify the properties of the caprock and reservoir facies. Clay content (Vclay) will be modeled as it is a key control of ductility, porosity, permeability, and mechanical rock properties.

Task 2: Seal Analyses

To evaluate the ability of faults that transect the Storage Facility wellbores and the Mohnian shale caprock above the reservoir, to contain injected gas, the following analysis may be performed:

- stratigraphic separation (triangle) diagrams showing juxtaposition of reservoir and overlying strata across faults;
- calculating shale gouge ratio (SGR) along faults for incorporation into the stratigraphic-separation (triangle) diagrams and for use in obtaining potentially heterogeneous values of cohesion and friction at various points on the fault surfaces;
- plotting of estimated friction and cohesion values along faults by using a relationship between SGR and fault strength;
- plotting of relative seal integrity along and within fault zones using the results of the above analysis; and
- estimating regional and localized stresses using available data.

Task 3: Probabilistic Seismic Hazard Analysis

The Storage Field lies within a region of southern California where extensive, state-of-the-art PSHA studies have been performed that utilize comprehensive descriptions of regional seismic sources, seismicity patterns, and site conditions. Thus, there will be a two-phase study that leverages these resources.

Phase 1 will involve a comprehensive evaluation of seismic hazard maps produced by the California Geological Survey and U.S. Geological Survey, combined with UCERF3. This ERF and deterministic model will define the contributions of various regional earthquake sources to the ground and subsurface motion hazards at the Storage Field.

Phase 2 will involve an extension of this ERF and deterministic seismic hazard analysis that utilizes additional data at the Storage Field. This will include refinement of the source characterization for key regional faults, such as Santa Susana; the addition of local faults, such as Northridge Hills, not included in the regional studies; and consideration of local conditions that will influence site amplification and other wave propagation phenomena. The precise scope of Phase 2 will be dependent upon the results from Phase 1. For example, possible field investigations of the Santa Susana fault will be motivated by the need to reduce epistemic uncertainty in the source characterization that has a significant impact on the PSHA results.

Together the results of Phase 1 and 2 will be employed in a PSHA analysis that incorporates a range of established attenuation relations and deterministic ground and subsurface motion intensity forecasts. This analysis will employ a standard total probability theorem to determine a full distribution of ground and subsurface shaking intensity levels and their associated rates of exceedance. If ground motion histories are required to represent the probabilistic ground motions or to represent deterministic scenario events, they will be generated using the Southern California Earthquake Center Broadband Strong Ground Motion Simulation Pattern.

The ground motion and subsurface intensity forecast information derived from the PSHA will be incorporated as input to global structural modeling of the well casing system. The resulting structural analysis will provide the magnitudes and locations of the maximum loads and resulting stress distribution along the length to the well casing due to applicable seismic loading conditions.

Task 4: Probabilistic Fault Displacement Hazard Analysis

The Storage Field lies within a region of southern California where extensive, state-of-the-art PSHA and PFDHA studies have been performed that take advantage of comprehensive descriptions of regional seismic sources, seismicity patterns, and site conditions. There will be a two-phase study that leverages these resources, with additional contributions from local measures of displacement patterns on the Santa Susana fault. This follows a standard methodology for PFDHA analysis (*e.g.,* Youngs *et al.*, 2003; Abrahamson, 2008).

Phase 1 will involve a natural extension of the PSHA study conducted for the site. This PSHA will incorporate UCERF3, augmented with refinement of the source characterization for key regional faults (*e.g.,* Santa Susana), and addition of local faults not included in the regional studies. For the PFDHA study, the ground-motion attenuation functions used in PSHA will be replaced by fault displacement attenuation functions. These fault displacement attenuation functions are based on published regressions of earthquake magnitude to fault displacement. This analysis will employ a standard total probability theorem to determine a full distribution of fault displacement magnitudes and their associated rates of exceedance.

Phase 2 will involve an evaluation of the regressions between fault displacement and earthquake magnitude used in Phase 1 for thrust faults in southern California and other tectonic settings that are most analogous to the Santa Susana fault at the Storage Field. Datasets will include mapped surface rupture patterns and/or seismic source inversions for thrust fault events, including the 1971 San Fernando and 1994 Northridge earthquakes. In addition, investigations will be conducted of patterns of displacement on the Santa Susana fault from past earthquakes at the study site through geomorphic and/or paleoseismic methods. If these data warrant, the displacement-to-magnitude regressions and associated fault displacement attenuation functions will be revised.

The PFDHA results will be used to assess ground rupture hazards and the risks to surface infrastructure at the site. Specifically, the results will be used as shear/displacement inputs for global and local structural modeling of the well casing system. The resulting structural analysis will provide information on the local response of the well and casing systems in the region where the faults transect the wellbore/casing. A parametric assessment will be performed with several input parameters, including material properties and imposed ovality, to estimate the stress state of the casing when subject to fault displacement activity. The global modeling methodology will be consistent with that used for structural analysis with PSHA results.

Task 5: Landslide Hazard Analysis

The landslide hazard study will be carried out in three phases, and the scope of each will be dependent on the results from the preceding phase.

Phase 1 will identify and obtain maps and relevant ground and aerial imagery needed to identify existing, on-site, large-scale landslides and mudflows. The information may include, to the extent it exists, is readily available and is not restricted for security reasons: sequential aerial photography of the site and immediate region (stereographic vertical and possibly oblique; B&W/color/IR), LIDAR and DEM imagery as available, GIS base maps showing (a) property boundaries, (b) topography, (c) location and identification of pertinent infrastructure (e.g., wells, pumping stations). These phenomena are then portrayed on pertinent maps or aerial photographs and preliminarily ranked as to their potential impact on existing infrastructure.

Phase 2 entails field verification of previously mapped or interpreted mass-wasting phenomena through selected trenching and coring and related interpretations.

Phase 3 formally documents the investigation's findings; namely, the data obtained, the technical interpretations, and the conclusions. Included will be a fully integrated graphical interface system (GIS) data set and a prioritized listing of landslide hazard areas and potential impacts.

Task 6: Mitigation Evaluation

SoCalGas, after consultation with its Work Team, will evaluate potential mitigation steps. The Company will determine what measures may be used to mitigate identified hazards, including modification to SoCalGas' current seismic response plans. SoCalGas will implement the measures in accordance with DOGGR recommendations, risk priorities, available resources, timing considerations, and costs.

CONSULTANTS

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John Shaw is the Harry C. Dudley Professor of Structural & Economic Geology, Department Chair of the Department of Earth & Planetary Sciences, and Professor of Environmental Science and Engineering at Harvard University. He specializes in active faulting and earthquake hazards assessment, hydrocarbon exploration and production methods, and structural geology and tectonics. He is a member of the Southern California Earthquake Center and has published extensively on the tectonics and earthquake hazards of southern California. Dr. Shaw has a B.Sc. from the University of Massachusetts, a M.S. from Princeton University, a M.A. (honorary) from Harvard University, and a Ph.D. from Princeton University.

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John Harris is the principal of Numeric Solutions LLC of Ventura, CA. Mr. Harris is a consulting geoscientist specializing in oil and gas reservoir characterization/modeling, asset evaluation, reserves estimation, and risk management. He has over 20 years' experience in domestic and international hydrocarbon exploration and production. He has a B.S. in Geology from the University of New Hampshire and a M.S. in Geology from the University of Michigan.

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Roy Shlemon is the principal of Roy J. Shlemon & Associates, Inc. of Newport Beach, CA. He is a consulting geologist specializing in Quaternary geology, geomorphology, geoarcheology, soil stratigraphy and erosion and sedimentation control. Among other matters, he performs fault-activity investigations (neotectonics/paleoseismicity); and landslide, ground-fissure and differential settlement evaluations. Dr. Shlemon has a B.A. from Fresno State, a M.S. from the University of Wyoming, and a Ph.D. from the University of California Berkeley. He has been published in approximately 275 professional journal publications.

Dr. Paul Somerville – PSHA/PFDHA Lead
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Paul Somerville is the principal seismologist of AECOM in Los Angeles. He has worked on many aspects of seismic hazards and has been involved in the development of innovative seismological methods for specifying seismic design ground motions in earthquake and engineering practice. He has a B.Sc. in geophysics from the University of New England (Australia); a M.Sc. in geophysics from the University of British Columbia and a Ph.D. in geophysics from University of British Columbia. He has published extensively on seismological issues.