Independent Peer Review Panel

A multi-agency panel of seismic hazard specialists
established by the California Public Utilities Commission
CALIFORNIA GEOLOGICAL SURVEY, CALIFORNIA COASTAL COMMISSION, CALIFORNIA ENERGY COMMISSION, CALIFORNIA SEISMIC SAFETY COMMISSION, CALIFORNIA PUBLIC UTILITIES COMMISSION, COUNTY OF SAN LUIS OBISPO, CALIFORNIA OFFICE OF EMERGENCY SERVICES

IPRP Report No. 16

Initial Review of the PG&E "Updated Seismic Assessment, February 2024" by the Independent Peer Review Panel for Seismic Hazard Studies of the Diablo Canyon Nuclear Power Plant

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Executive Summary

- The Hosgri fault is the primary seismic source for the Diablo Canyon Power Plant (DCPP), and it's slip rate has been increased in the hazard model based on several peer-reviewed studies of the Cross-Hosgri slope (CHS) that now provide a high degree of confidence in a 2.6 mm/yr rate. We agree with PG&E that this rate best represents the hazard. However, because other slip rate sites along the Hosgri fault are unrepresentative of current rates of tectonic deformation, it is our opinion that the CHS slip rate should receive full (100%) weight in seismic hazard models.
- Though PG&E reduced the estimated rate of uplift for the Irish Hills, the fault geometry models for the faults that bound the Irish Hills remain uncertain and warrants further geologic investigation to characterize these seismic sources.
- New data that was not addressed in the PG&E Update: A 2021 study concluded that the slip rate for the Casmalia fault, is a magnitude higher than previously assessed in 2015, at 5.6 to 6.7 mm/yr. This has important implications for onshore deformation models as the nearby Casmalia Hills may represent an analog to the Irish Hills in addition to a seismic source and potential kinematic connections with the Hosgri fault and other faults in the vicinity of DCPP. Additionally, a Nuclear Regulatory Commission (NRC)-commissioned study based on offshore seismic data reports Hosgri fault slip rates have increased during the past million years, suggesting that rates older than Holocene are not representative of the current seismic hazard.
- The IPRP requests that PG&E conduct a comprehensive review that includes all fault studies in the region since the previous assessment (PG&E, 2015). That review should address the

implications for the seismic hazard at the DCPP, including newly developed slip rates on faults in the region that may inform deformation rates of faults in the vicinity of Diablo Canyon.

- Our review of the methodologies used to estimate ground motions for the DCPP site indicates those methods are appropriate. We also find PG&E's evaluation of new data and new ground motion models adequate. However, the results of site-specific ground motion hazard should be recalculated with recommended changes to the seismic source characterization inputs.
- We continue to encourage efforts to improve the characterization of site condition in terms of V_S profile and kappa estimate. We suggest the more traditional approach of site response analysis be carried out to supplement existing analyses. We further encourage PG&E's continuing effort to reduce uncertainty in empirical site factors, including further improving the non-ergodic ground motion modeling approach and data.
- Finally, we would like to see an updated analysis of seismic hazard model inputs ranking sensitivity of ground motion hazards to uncertainties in revised input parameters.
- This report is intended to share the Independent Peer Review Panel's (IPRP) initial findings with the public, PG&E, and the Diablo Canyon Independent Safety Committee. PG&E is expected to submit a written response addressing our findings. The IPRP will subsequently submit a second report addressing PG&E's response along with the IPRP's updated conclusions and recommendations.

Introduction

On February 1, 2024, Pacific Gas and Electric Company (PG&E) issued a report, “Diablo Canyon Updated Seismic Assessment” (PG&E, 2024, referred to as “the Update”), that updates their previous seismic assessment (PG&E, 2015) for the Diablo Canyon Power Plant (DCPP), located along the southwest margin of the Irish Hills along the coast of San Luis Obispo County, California. The purpose of the report was to present new technical data that has been acquired since the PG&E (2015a) report regarding nearby faults that could potentially generate strong seismic ground motions at the power plant and to revise and update specific elements of the seismic hazard analysis to reflect this new information. In this initial report, the Independent Peer Review Panel (IPRP) provides a technical peer review of the seismic source characterization and ground motion characterization contained in PG&E's Update report. The intent of the IPRP’s report is to share its initial findings with the public, PG&E, and the Diablo Canyon Independent Safety Committee (DCISC). As with past IPRP reports, PG&E is expected to submit a written response addressing our findings (which will be made available on the CPUC’s website). The IPRP will subsequently submit a second report addressing PG&E’s response along with the IPRP’s updated conclusions and recommendations.

The IPRP presented preliminary assessments of the PG&E Seismic Update at the May 30, 2024, IPRP meeting and the June 20-21, 2024, DCISC meeting. Three members of the IPRP attended the public meeting of the DCISC and presented findings regarding the PG&E (2024) update report. After the presentation, we answered questions posed by the committee members and the public. Gordon Seitz (CGS) presented an overview of the IPRP Update review with a focus on the most pertinent change from 2015, which is a significant increase in the Hosgri fault slip rate. We emphasized that we agree with PG&E that the cross-Hosgri-Slope slip rate, documented by three peer-reviewed articles published since the PG&E (2015a) Seismic Source Characterization (SSC), is the most representative slip rate estimate and, that given the unrepresentative age-range of other slip rate estimates, that it should be fully adopted at a 100% weight. Philip Johnson (CA Coastal Commission) presented an overview of the onshore seismic source characterization that is related to the deformation and uplift of the Irish Hills. PG&E has lowered the slip rate of the Los Osos fault because a newer regional paleo sea-level curve has been published and they adopted those results. Since the 2015 assessment PG&E has not revised their SSC for the Irish Hills.

Previous investigations of the region surrounding the DCPP identified the Hosgri fault as the most significant source of strong seismic ground motions for the DCPP site (PG&E, 2015). In addition, the faults that bound the Irish Hills (the Los Osos fault, Shoreline fault, San Luis Bay fault, San Luis Range fault, and Wilmar Avenue fault) are considered potential seismic sources. The PG&E (2024) report includes an update to the slip rate analysis for the Hosgri fault as well as revision of the tectonic uplift rate for the Irish Hills.

Ground motion (GM) related subjects addressed by PG&E (2024) include evaluation of: new GM data, GM characterization for reference rock site condition (including the performance of previous GM models (GMMs) against the new data and new GMM), vertical GM, site characterization and site-specific adjustments (including analytical and empirical approach), and hazard calculations for the reference and control point site conditions to incorporate changes in slip rates for the Hosgri and Los Osos faults.

The Update was prepared in response to Senate Bill 846, which was passed in September 2022 to extend operation of DCPP five years beyond the original scheduled closure date of 2025. The 2024 Update followed the process for a Senior Seismic Hazard Analysis Committee (SSHAC) Level 1 study. In contrast, the 2015 study was conducted as a SSHAC Level 3 study. The SSHAC levels indicate how extensive the studies are, with the higher levels being more extensive (NUREG, 2018). The IPRP was present at the SSHAC workshops of the 2015 study; however, we were not included in the workshops of the 2024 update study. The 2024 study reports:

"*The project was planned and executed with oversight from Diablo Canyon Independent Safety Committee (DCISC) and the California Department of Water Resources (DWR), which managed the project for the State of California. The DCISC and DWR participated in technical workshops addressing review of previous studies, new information and models, impact evaluation and analyses results*."

In section 3.1 it also states: "*After development of an initial project plan, it was presented to both DCISC and DWR for their input.*" In contrast to the procedural and contractual focus of the DCISC and DWR participation during the development of the Update, IPRP review occurred after the Update was finalized.

This technical review will focus on issues that the IPRP has been actively engaged with since the inception of the IPRP, namely the seismic source characterization and ground motion characterization of the earthquake hazard at DCPP. We will discuss PG&E's revisions to the seismic source model. We will also comment on additional data and studies that may influence the SSC model that were not considered in the Update. We follow this with a summary of the ground motion data and analyses presented in the Update. Our conclusions will follow each of the three issues reviewed: Hosgri fault slip rate, Los Osos fault/Irish Hills Tectonic Model, and Ground Motions. Since the ground motions are based on SSC documented in the Update (PG&E, 2024) and the IPRP has open questions about the SCC, our ground motion review is limited to the methods and not on the final hazard results. We are aware of comments from Dr. Peter Bird concerning the PG&E (2024) update report. At this time we have elected to not review Dr. Bird's comments, PG&E's responses (Chapter 6 of the Update), and Dr. Bird's subsequent submissions as this dialog appears to be ongoing, with a Nuclear Regulatory Commission (NRC) meeting scheduled for July 17, 2024 regarding Dr. Bird's petition. We expect to take up the matter, with possible requests for additional information and documentation at a future date.

Review of Seismic Source Characterization (Chapter 5)

The 2024 Update consists of a site-specific Probabilistic Seismic Hazard Assessment (PSHA), including a SSC, which aims to accurately characterize all significant seismic sources that impact the seismic hazard of a site. This update should include all relevant new data and methods, particularly those that have become available since the last assessment in 2015.

The SSC for the DCPP focuses on characterizing seismic source parameters and parameter uncertainties for a handful of sources that contribute most to the total hazard at annual hazard levels of 10^{-4} to 10^{-6} yr-1.

The SSC model considers three different types of seismic sources:

- *Primary Fault Source*: A fault source that has been shown to contribute significantly to the seismic hazard at the DCPP. There are four Primary fault sources (Hosgri, Los Osos, Shoreline, and San Luis Bay fault sources), all within 12 km of the DCPP at their closest source-site distance.
- *Connected Fault Source*: A fault source that connects to a Primary fault source in the SSC model.
- *Regional Fault Sources*: Fault sources within the DCPP site region other than the Primary and Connected fault sources. Types of regional fault sources include the San Andreas fault source, UCERF3 regional fault sources, and non-UCERF3 regional fault sources.

The sources from the 2015 SSC model that contribute most to the total hazard are the following, ranked in order of significance:

- Hosgri fault source
- Los Osos fault source
- Shoreline fault source
- San Luis Bay fault source
- Local seismic source zone

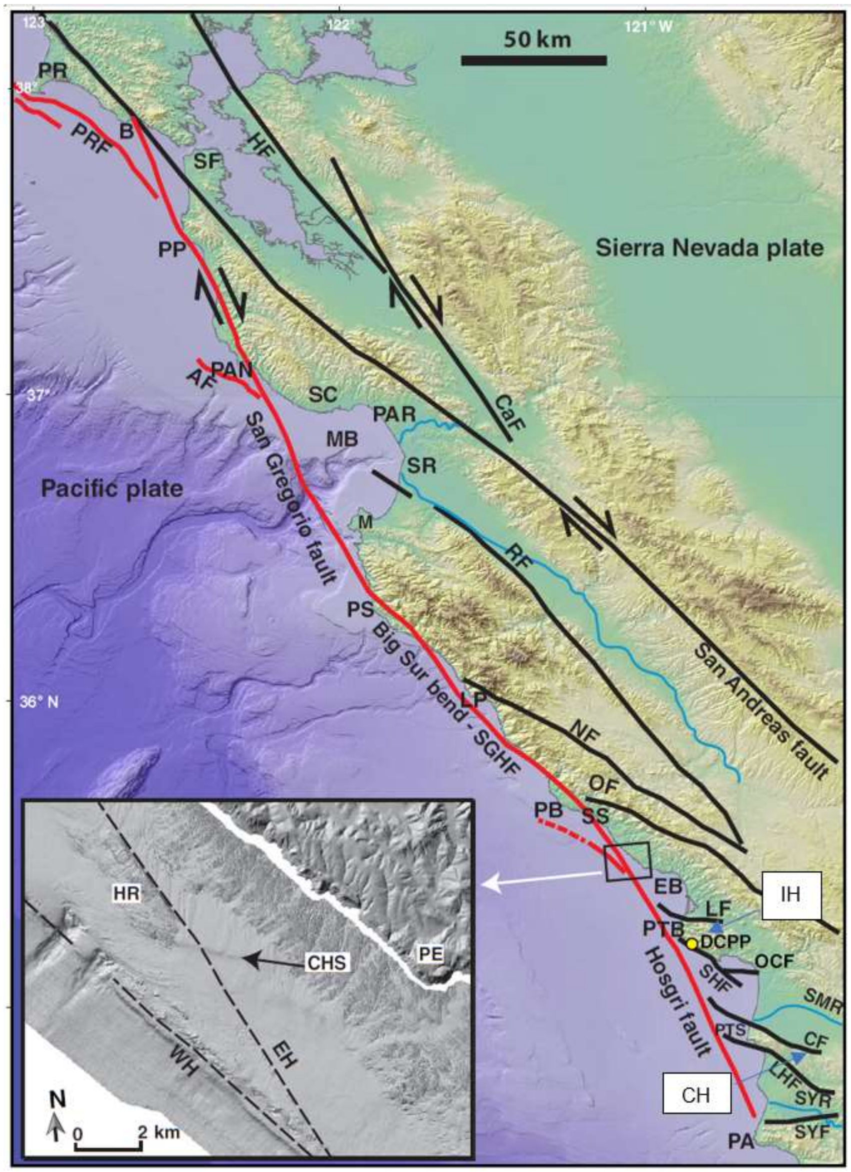
The Update (PG&E, 2024) revised the slip rates of two Primary Fault seismic sources:

- Hosgri fault source
- Los Osos fault source

The revisions were based on new data relevant to hazard-significant faults and parameters in the 2015 SSC model. New information regarding the Hosgri fault slip rate is available at the offshore cross-Hosgri slope (Kluesner et al., 2023; Medri et al., 2023), and a new model of coastal uplift rates and paleo-sea levels by Simms et al. (2016) impacts the vertical uplift rate component of the net slip rate for the Los Osos fault.

Slip Rate Estimation Methods

Fault slip rates cannot be measured directly, but rather are calculated using two parameters: the distance that a geologic feature has been offset and the amount of time that the offset has taken to occur. It is useful to consider these parameters separately because this allows assessment of the uncertainty of the slip rate estimate.



Regional map showing the main fault structures that are part of the Pacific–North American plate boundary along central California. The San Gregorio–Hosgri fault (SGHF) system is predominantly located near the coastline and highlighted in red. Inset map shows the focus region of this study where the Cross-Hosgri slope (CHS) is located. Inset bathymetry is from the California Seafloor Mapping Program (Johnson et al., 2014). The four slip rate sites used by PG&E are:

SS—San Simeon

CHS- Point Estero indicated by the inset box

PTB—Southern Estero Bay

PTS—Point Sal

With white boxes we indicate :

IH- Irish Hills

CH- Casmalia Hills

AF—Ascension fault; B—Bolinas; CaF—Calaveras fault; CF—Casmalia fault; DCPP—Diablo Canyon Power Plant; EB—Estero Bay; EH—eastern strand of Hosgri fault; HF—Hayward fault; HR— Hosgri Ridge; LF—Los Osos fault; LHF—Lions Head fault; LP—Lopez Point; M—Monterey; MB—Monterey Bay; NF— Nacimiento fault; OF—Oceanic fault; OCF—Oceano fault; PA—Point Arguello; PAN—Point Año Nuevo; PAR—Pajaro River; PB—Piedras Blancas; PE—Point Estero; PP—Pillar Point; PR—Point Reyes; PRF—Point Reyes fault; PS—Point Sur;RF—Rinconada fault; SC—Santa Cruz; SF—San Francisco; SHF—Shoreline fault; SR—Salinas River; SMR—Santa Maria River;; SYF—Santa Ynez fault; SYR—Santa Ynez River; WH—western strand of Hosgri fault.

Figure 1. Regional Location Map with Faults. Features discussed in this review. Slip Rate Sites: San Simeon, Point Estero: Inset detail, Cross Hosgri Slope (CHS) most representative slip rate estimate for the Hosgri fault (Kluesner et al., 2023), Southern Estero Bay, Point Sal. Also shown IH- Irish Hills, CH- Casmalia Hills. Relevant data not addressed in the Update (PG&E, 2024) includes: Casmalia Fault (McGregor, I.S., and Onderdonk, 2021); Hosgri fault CNWRA, 2016). Figure modified from Kluesner et al. (2023).

Hosgri Fault Slip Rate: Cross-Hosgri Slope Point Estero

Offshore of Point Estero (Fig.1), Johnson et al. (2014) investigated a southwest-facing bathymetric slope which crosses the northwest trending eastern main trace of the Hosgri fault. They documented 30.3 ± 9.4 m of right-lateral offset of the lower slope break of the Cross-Hosgri slope (CHS) by using high-resolution bathymetry. They estimated the age of the CHS using global sea-level curves at 11.5 to 7.0 ka B.P., which resulted in a slip rate of 2.6 ±0.9 mm/yr. The 2015 SSC model (PG&E, 2015) considered the slip rate from this site, one of four Hosgri fault slip rate sites, and assigned it a relatively low weight of 0.2 in the SSC model. The IPRP (2014, IPRP Report No. 7) evaluated this slip rate estimate, based on offset of a Holocene feature, and preferred it over the other two offshore slip rate estimates on the Hosgri fault (Southern Estero Bay and Point Sal) (Fig. 1). They considered the Holocene age to be more representative of current rates of tectonic deformation for seismic hazard assessment than the other estimates, which were less certain and older, and thus less applicable (Fig.2 in IPRP Report No. 7).

Since 2015, the CHS was further investigated with additional offshore data collection including seismic profiling and sediment coring. Medri et al. (2023) investigated the sedimentology of the CHS using Chirp seismic profiles collected in a water depth of 30 to 200 m in conjunction with vibracores collected in a transect across the CHS. Chirp seismic profiling images to sediment depths of tens of meters with about 10 cm-scale resolutions. The sediment cores provided valuable chronological samples for radiocarbon (C-14) and Optically Stimulated Luminescence (OSL) age dating, in addition to the sedimentologic data. The study demonstrated the depositional history of the CHS which was a primary shoreface deposit that constructed the bathymetric feature, and an additional thinner blanketing finer grain deposit.

Johnson et al. (2014) included an estimate of uncertainty in the CHS offset measurement, and Kluesner et al. (2023) report that the previously unrecognized blanketing layer does not appear to impact the offset measurement significantly: "…*we do not think it compromises this distinct geomorphic feature as a piercing point*". Their measurements have defined uncertainties, based on documented best matching of piercing lines , they published their method, and have gone through two peer reviews (2014, 2023). However, PG&E (2024) used this near-surface layer and speculative interpretations of the slope morphology to modify the offset measurement probability density function (PDF) from that presented by Kluesner et al. (2023) (Fig.3 a). PG&E stated: "…*there is no good basis for a preferred offset within this range…* " in support of their decisions to apply a trapezoidal PDF to the reported offset data, "… *as there are several remaining uncertainties related to the approach used to define the lower slope break*".

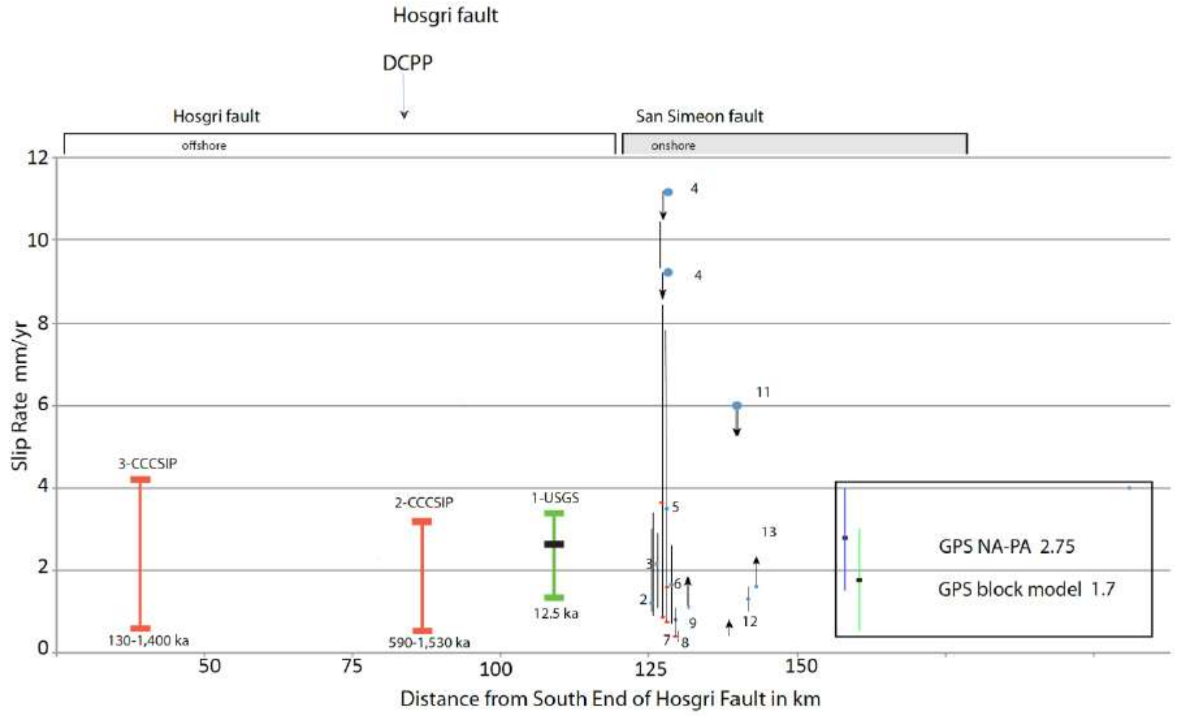


Figure 2, Hosgri – Fault Slip Rates. Geologic fault slip rates are shown with vertical bars. The three new offshore slip rate estimates are shown on the left side of the figure with red and green vertical bars. For the new offshore rate estimates the green indicates a highly suitable age range for seismic hazard assessments, whereas the red indicates a less suitable age range due to the increasing uncertainty of fault zone evolution and behavior changes over time. Modes are indicated by a tick mark, when absent no basis for a preferred choice was recognized, blue dots and associated errors. Downward pointing black arrows indicate a maximum rate whereas upward pointing black arrows indicate minimum rates. Red half dots indicate offset terrace slip rates inferred from vertical separations and slickensides from a fault exposure. The geodetic slip rates are representative of a region, and are indicated with broad color bands spanning the ranges, with central point estimate and error bars. GPS NA-PA: 2.75 mm/yr; geodetic slip rate constraint west of the West Huasna fault (DeMets, 2012). GPS block model: 1.7 mm/yr (Murray et al. 2012).

Figure 2. Hosgri Fault Slip Rate Sites. From IPRP report No. 7. This plot shows the range of slip rate estimates along the Hosgri fault. The Cross Hosgri Slope estimate (labeled USGS, green) of 2.6 mm/yr lies in the center of all estimates and is not an outlier. Note: We plotted the full uncertainty of the PG&E offshore Hosgri fault slip rate estimates based of channel offsets, as opposed to the preferred rates used by PG&E based on speculative correlations.

The IPRP considers that these uncertainties, although not perfectly characterized, appear to be captured well by the method used by Johnson et al. (2014). In the 2024 Update, however, PG&E increased the offset measurement range from that reported by Kluesner et al. (2023) by an additional 10 m, concluding: "…*the new full uncertainty range (10 to 50 m) also captures the interpreted offsets of the upper slope break and slope face by Johnson et al. (2014)*." As all (Johnson et al., 2014, Kluesner et al., 2023, PG&E, 2024) assessments of the CHS agree that the lower slope break is the most reliable offset feature to measure, the modification of values to account for less reliable features does not appear well supported. From the data presented in

Johnson et al. (2014) and Kluesner et al. (2024), their estimates with uncertainties appear justified as-is with no additional modifications.

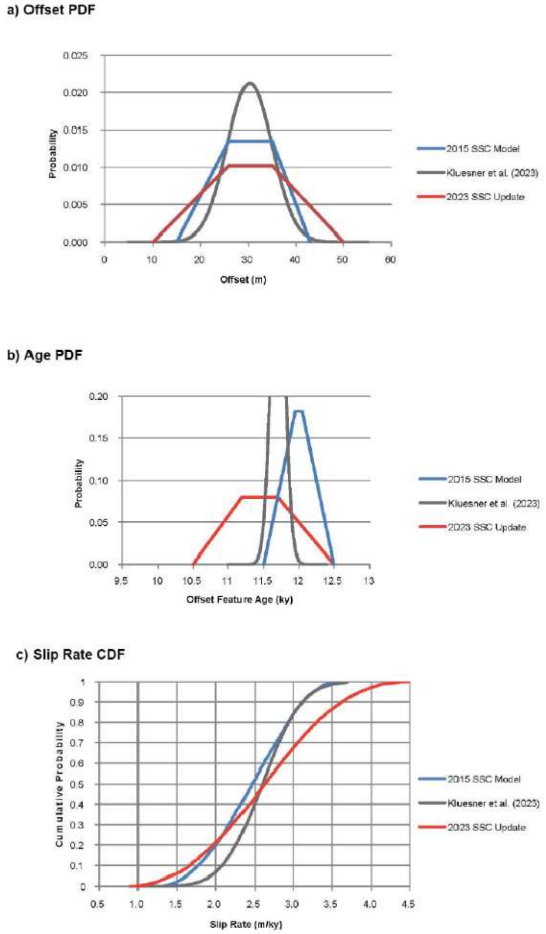


Figure 5-40. Comparison of 2015 SSC Model (Blue), Kluesner et al. (2023) Model (Grey), and SSC Model Update (Red) Input PDFs and Slip Rate CDFs for the Point Estero (Cross-Hosgri Slope) Slip Rate Site on the Hosgri Fault:
a) Offset PDFs; b) Age PDFs; c) Slip Rate CDFs

Figure 3. Hosgri Fault Slip Rate Calculations from the PG&E Update (2024)

IPRP Conclusions Regarding CHS Slip Rate

The PG&E Update (2024) recalculated the slip rate of Kluesner et al. (2023) using the input parameters shown in Figure 3. PG&E made changes to the chronology, although these revisions are not documented sufficiently for a full evaluation. PG&E should explain their decisions to broaden the uncertainties and by how much. These changes increased the CHS slip rate from a mean of 2.5 to 2.6 mm/yr. The Kluesner et al. (2023) results are peer-reviewed and well documented. If PG&E chooses to reinterpret the data and develop an independent slip rate estimate, rather than simply integrate what has been published into the SSC, this should be carefully documented, published formally, and peer-reviewed independently as a new stand-alone model. In particular, the choice of Offset PDF in the 2023 SSC Update for the CHS is a significant departure from the published Kluesner et al. (2023) model and should be further vetted and if pursued should be documented at a peer-review level.

Weighting of the Four Slip Rate Sites used by PG&E for the Hosgri fault

PG&E has used three criteria to develop a weighting method to calculate the Hosgri slip rate from data obtained at four sites along the fault:

- The age of the offset feature
- The location of the slip rate site along the Hosgri fault and its proximity to the DCPP
- The confidence that the interpretation of the site data provides a reliable result

These three criteria cover different aspects of the applicability of a calculated slip rate for the purpose of defining the center, body, and range of technically defensible interpretations for the Hosgri fault slip rate applicable to the DCPP.

Weighting is used to combine multiple measurements in a systematic and relevant way to develop a weighted mean slip rate and to evaluate uncertainties. The weighting for the Hosgri fault is shown in Table 1.

Study Site	Applicability of Offset Feature Age	Applicability of Slip Rate Site Location	Confidence in Site Location	PG&E 2015 Weight	PG&E 2024 Weight	Slip Rate mm/yr.
San Simeon	High (200 ka)	Moderate	Moderate	0.3	0.25	1.8
Point Estero - CHS	**High** **(12 ka)**	**Moderate**	**High**	**0.2**	**0.5**	**2.6**
Southern Estero Bay	Low (700 ka)	High	Low	0.3	0.2	1.7
Point Sal	Low (700 ka)	Low	Moderate	0.2	0.05	0.8

Table 1. Hosgri Slip Rate Weighting Summary. Includes data taken from Table 5-6 PG&E 2024 Update.

The appropriateness of the age criteria is critical, as we are interested in the present seismic hazard and not that of the distant past, as rates on any given fault system may evolve through time. The Holocene age range (11.7 ka) has been established to be most representative for seismic hazards on high slip rate faults like the Hosgri fault because it includes enough earthquake recurrence intervals for a robust average, yet avoids the uncertainties associated with much older, several hundred thousand year, rates. In the absence of Holocene-age slip rates, Late Quaternary-age rates are often used but Holocene-age slip rates are more likely to be representative of current conditions. While well-constrained slip rates over several time frames (e.g. Holocene, Late Quaternary, and Quaternary) would be ideal to demonstrate the stationarity or variability of fault slip rates through time, in the absence of such data, the use of faster, shorter term rates is more conservative, unless there are serious and demonstrated concerns regarding the reliability of the shorter term slip rates. We agree with PG&E's statement: "*Given the complicated, multi-stage structural evolution of the central coast of California over the last 5 Ma, a slip rate over this time frame may not be applicable to the current tectonic framework*". However, we would qualify their statement: "*The relevant time frame of interest for site-specific seismic studies is the Late Quaternary*". (Section 6.3.2, PG&E, 2024), as there is evidence that the most representative time frame for PSHA is the Holocene, especially when there is evidence that the slip rates have increased from the Quaternary to the Holocene time periods.

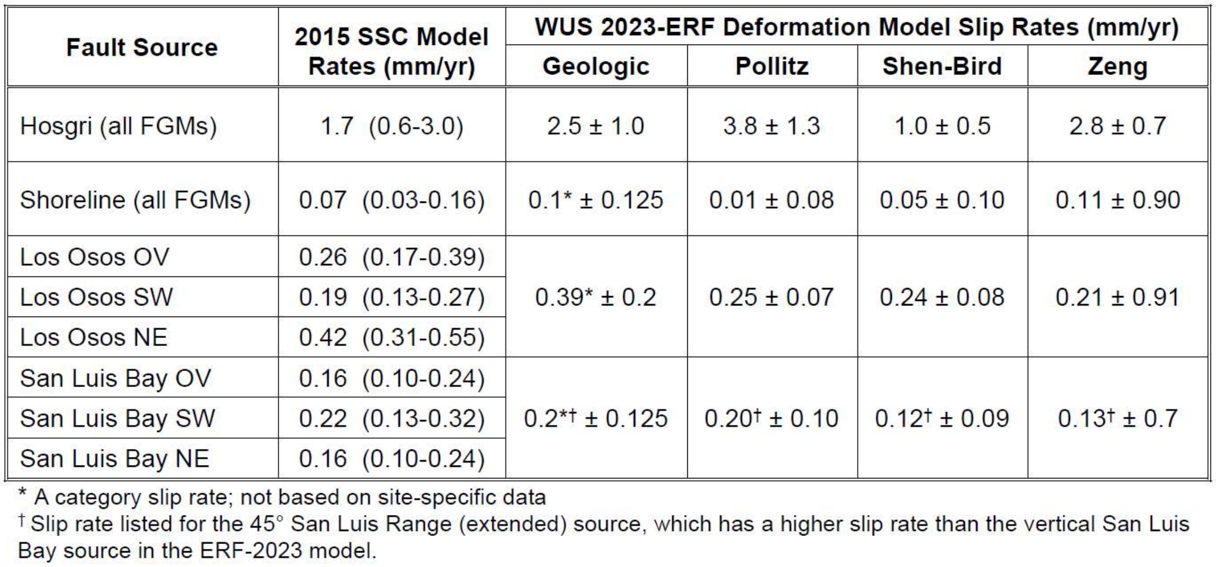
Only the CHS slip rate site has the optimal age range that we would consider having high applicability of offset feature age. The San Simeon site offset is an order of magnitude older than the CHS site offset, yet PG&E assigned it the same age applicability weight, suggesting that their ranking is defined in terms of age thresholds. We would weight a mid-late Quaternary slip rate much lower than a Holocene rate.

In Figure 2, we plot the full age ranges obtained at the different slip rate sites. The full age uncertainties could be factored into these rankings, and only the CHS has an age with a relatively low uncertainty. In 2015, when the CHS had no direct age control, the age weighting of the CHS was more defendable. Now, with a fully documented and much more certain age determination, it may be more appropriate to use the age criteria as a screening criterion. Further, if a site is ranked low in age applicability (e.g. Southern Estero Bay and Point Sal), why is it being considered for inclusion at all? In the IPRP report No. 7 (2014), we conducted a thorough review of the offshore sites and concluded their value when compared to the CHS site slip rate was too low to be useful for improving the slip rate used to assess present seismic hazard at the DCPP. Now that the CHS site has been improved by additional published studies, diluting the quality of the final weighted slip rate estimate by including less relevant site data is less defendable. We therefore agree with PG&E (5.3.1.2., 2024): "*Due to the more thorough documentation of the CHS age and stratigraphy (Kluesner et al., 2023, Medri et al., 2023), there is greater confidence now than in 2015 that the geological interpretation of the site is correct and that the slip rate estimated from the site is a reliable estimate of slip rate for the Hosgri fault source near the DCPP*."

We also question the utility of the slip rate site location criterion, given that all sites are within an anticipated rupture length distance from the DCPP. Because we only have confidence in the San

Simeon and CHS sites, and the CHS is much closer, we would rank it higher. In addition, in the data presented, we find no evidence for decrease in the Hosgri fault slip rate from San Simeon to Point Sal in the Holocene. There appears to be very little well-constrained data, such as rates on other structures, that indicates slip rates are changing along strike of the Hosgri fault.

The confidence in site location refers to the overall confidence in the slip rate estimate at the site. Again, only the CHS provides results in which we have high confidence. It is challenging determining a Hosgri fault slip rate that is most representative for hazard at DCPP because we do not have multiple high quality geologic sites. Instead, we have a single high quality site, and all other sites are of questionable value as we have reported in IPRP reports Nos. 5 and 7. We think it is best practice to use all data for overall screening, but it is not appropriate to include flawed data to calculate slip rate, and dilute the significance of the highest quality, most applicable slip rate determination for seismic hazards. If poor quality site data is included in determining the weighted slip rate on this section of the Hosgri fault, one may underestimate the hazard because all the poor quality sites have much lower rates and, if overweighted, may bias the slip rate and hazard estimate too low. Also, in Figure 2 the full uncertainty range of the Point Sal and Estero Bay sites are provided, and these rates confirm that the CHS slip rate of 2.5 mm/yr is within the range of technically defensible slip rates. Because all the lower slip rates are associated with older features, this may be evidence that the rates were actually slower in the past and hence are not representative of current rates. An alternative explanation is that these should be considered as minimum rates as the time of initiation on the individual fault strands may be significantly later than the age of the features. In either case, including them may yield an unrealistically low preferred and weighted slip rate.



Fault Source	2015 SSC Model Rates (mm/yr)	WUS 2023-ERF Deformation Model Slip Rates (mm/yr)			
		Geologic	Pollitz	Shen-Bird	Zeng
Hosgri (all FGMs)	1.7 (0.6-3.0)	2.5 ± 1.0	3.8 ± 1.3	1.0 ± 0.5	2.8 ± 0.7
Shoreline (all FGMs)	0.07 (0.03-0.16)	0.1* ± 0.125	0.01 ± 0.08	0.05 ± 0.10	0.11 ± 0.90
Los Osos OV	0.26 (0.17-0.39)	0.39* ± 0.2	0.25 ± 0.07	0.24 ± 0.08	0.21 ± 0.91
Los Osos SW	0.19 (0.13-0.27)				
Los Osos NE	0.42 (0.31-0.55)				
San Luis Bay OV	0.16 (0.10-0.24)	0.2*† ± 0.125	0.20† ± 0.10	0.12† ± 0.09	0.13† ± 0.7
San Luis Bay SW	0.22 (0.13-0.32)				
San Luis Bay NE	0.16 (0.10-0.24)				

* A category slip rate; not based on site-specific data

† Slip rate listed for the 45° San Luis Range (extended) source, which has a higher slip rate than the vertical San Luis Bay source in the ERF-2023 model.

Table 2. Geodetic and Geologic Deformation Model Results. From PG&E (2024), Table 5-11.

The geodetic and geologic deformation model results are consistent with the site-specific rate determined for the CHS. Three of the four models indicate a slip rate above 2.5 mm/yr (Table 2).

These models emphasize that a slip rate in the 2.6 mm/yr range appears most representative of the current tectonic regime and that significantly lower slip rate determinations should be treated as outliers.

Data that was not considered in the Update

A 2016 (CNWRA, 2016) study prepared for the NRC titled: "*Independent Evaluation of the Hosgri Fault Slip Rate Based on a Structural Analysis of the Pull-Apart basin linking the Hosgri and San Simeon Fault Systems*" reports slip rates that have increased significantly in the past 1 million years and are now in the 1.5 to 2.5 mm/yr. range. If true, these results further indicate that slip rates based on Pleistocene-age features are not representative of the present seismic hazard. PG&E should address these findings. The recent work by McGregor and Onderdonk (2021) reports a slip rate on the Casmalia fault that is a magnitude higher than previous estimates. The interaction of the Casmalia fault with the Hosgri fault offshore should be revisited, as it was considered by PG&E (2015a) to affect the Hosgri slip rate.

IPRP Conclusions Regarding Hosgri Fault Slip Rate

The IPRP recommends using the published CHS slip rate as the Hosgri fault mean slip rate. It falls well within the range of all determinations along the fault (Fig.2) and we agree with PG&E that it is the highest-quality value and most representative of the current hazard at DCPP. It is our opinion that the ranking of slip rate sites by *Applicability of Site Location* is not defendable, based on available data and a general lack of supporting evidence that there is a significant change of slip rates along strike of the Hosgri fault between the CHS and DCPP. There appears to be evidence that slip rates are accelerating through time based on the modeled slip rates of deformed unconformities by CNWRA, (2016), and PG&E's own preferred interpretations of the Southern Estero Bay and Point Sal sites. This suggests that older slip rates are not representative of the current seismic hazard, because they are lower than Holocene-age slip rates and thus should not be averaged with high quality data such as the CHS (Kluesner et al., 2023), diluting their effective value (Fig.4). Therefore, it is our opinion that the CHS slip rate of 2.6 mm/yr for the Hosgri fault should receive a weight of 100% in the SSC model, which would result in a doubling of the scale factor from 1.26 to 1.53 as presented in Table 10-1 (PG&E, 2024)

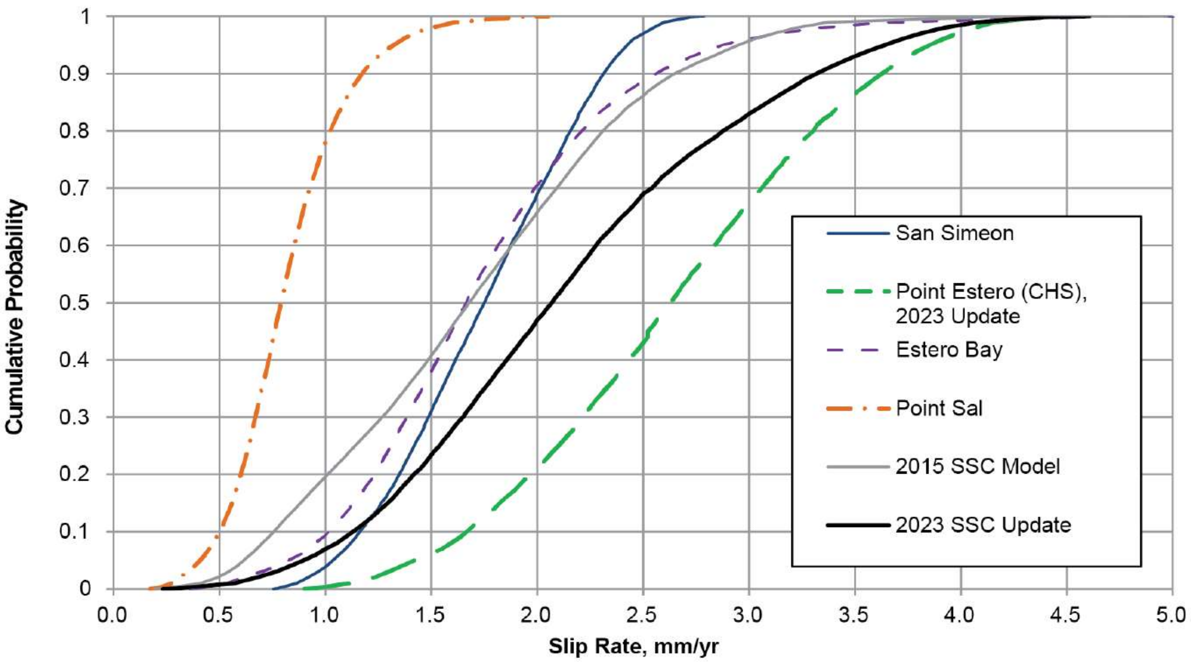


Figure 4. Hosgri Fault Source Slip Rate CDFs for the SSC Model Update. These cumulative probability curves illustrate the lower slip rate bias that has resulted from combining poor quality data with the only high quality data at Point Estero (CHS). Although the IPRP agrees with PG&E that the CHS site provides the highest quality and most hazard representative Hosgri slip rate, it has not been used as effectively as warranted. Our figure 3, c) includes the peer-reviewed slip rate curve that we have evaluated as the slip rate that should be used. Above, the increase at 0.5 cumulative probability from 2.1 to 2.6 mm/yr is indicated by the shift from the black to the green curves. (Figure 5-41, PG&E, 2024).

Irish Hills-Los Osos Fault Tectonic Model

The Irish Hills lie within the southwestern portion of the Coast Ranges (Fig. 5). The southwestern Coast Ranges region is separated from the central Coast Ranges by the West Huasna fault/Oceanic fault. The central portion of the Coast Ranges is characterized by northwest-trending (approximately N30W to N40W) folds and right lateral and reverse faults; overall, the topography in the central Coast Ranges is higher. By contrast, the southwest portion of the Coast Ranges is characterized by west-northwest trending (approximately N60W to N70W) reverse and thrust faults with possible oblique slip. The southwestern Coast Ranges region is bordered on the south by the east-west trending Transverse Ranges region that is characterized by east-west trending, north-vergent reverse and thrust faults formed by north-south shortening associated with clockwise rotation of the Transverse Ranges during opening of the Los Angeles Basin beginning in Miocene time. The boundary between the Transverse and Coast Ranges is a north-vergent reverse fault, the Santa Ynez River fault. The Hosgri fault forms the western boundary of the southwestern Coast Ranges. Looking at the geologic structure of the southwestern Coast Ranges from a broad, regional view, the orientation of the Irish Hills (and the Casmalia Hills, located farther south) as well as the faults that bound those uplifts is clearly different from the rest of the Coast Ranges and seem to be intermediate in orientation between the northwest-striking folds and faults farther east in the Coast Ranges and the east-west trending folds and faults of the Transverse Ranges. Structures in this region are more westerly than central Coast Ranges structures and more northerly than Transverse Ranges structures. In that sense, the geologic structures in this region appear to be transitional between the central Coast Ranges to the east and the Transverse Ranges to the south (Lettis, et al., 1994). This implies that the southwestern Coast Ranges are deformed by an element of north-vergent shortening that is not present in the central Coast Ranges. PG&E (2015a) recognized the unique geologic structure of this region and described it as the Los Osos crustal domain.

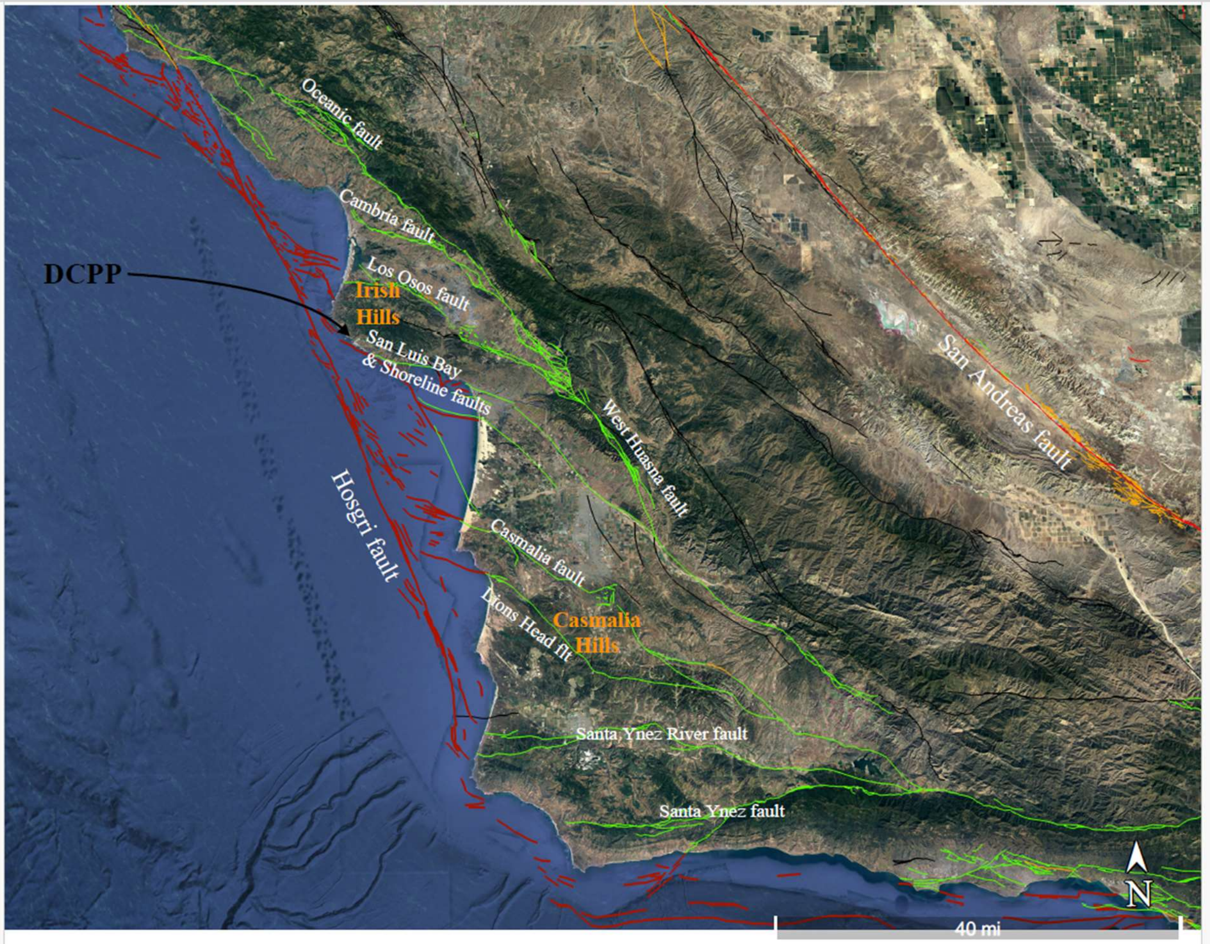


Figure 5. Map of Faults and Uplifts in the Southwestern Coast Ranges (Fault source: USGS Quaternary Fault and Fold Database).

Irish Hills Uplift- Los Osos Fault

The seismic hazard analysis in the PG&E (2015a) report included characterization of potential seismic sources in the Irish Hills region. Those potential sources included the Los Osos fault at the northern margin of the Irish Hills and a group of faults described as the Southwest Boundary Zone (including the San Luis Bay, Wilmar Avenue, and San Luis Range faults) at the southern margin of the Irish Hills. With these faults bounding the Irish Hills (labeled the San Luis-Pismo Block), PG&E

(2015a) identified three potential fault block geometry models. The first is the Outward-Vergent (OV) model that posits oblique reverse-dextral slip on the Los Osos fault with uplift of the Irish Hills the result of reverse slip on both the south-dipping Los Osos fault and the north-dipping San Luis Bay fault. This reverse slip would be accompanied by strike slip motion along the Los Osos fault and San Luis Bay fault. The Southwest-Vergent (SW) model calls for uplift of the Irish Hills by thrust/reverse slip on the San Luis Bay fault and other Southwest Boundary Zone faults. With this model, these faults dip approximately 45° northeast. The Northeast Vergent (NE) model calls for uplift of the Irish Hills by northeast-vergent reverse slip on the Los Osos fault that dips approximately 50° to the southwest. Based on their review of the available data, the PG&E team decided to give the OV and SW fault block geometry models 40% weight (each) and the NE model 20% weight in their logic tree. The PG&E (2024) report did not revise the fault block geometry models first described in the PG&E (2015a) report.

However, the PG&E (2024) Update report revised the uplift model for the Irish Hills. In their previous report, PG&E (2015a) adopted the model of Hanson, et al. (1994) for marine terrace stratigraphy that used global average paleosea levels and gave it a weight of 80%; an alternate model by Muhs, et al. (2012) received a weight of 20%. The update report also used data from a regional study of glacio-isostatic adjustment (Simms et al., 2016). It appears that the PG&E team was convinced that the data supporting the Simms et al. (2016) study was sufficiently robust, and they chose to give the Simms et al. (2016) model 40% weight, the Hanson, et al. (1994) model 40% weight, and the Muhs, et al. (2012) model 20% weight. This resulted in a reduction of the estimated tectonic uplift rate. In PG&E's model the Irish Hills uplift rate is considered a proxy for the Los Osos fault, so reducing the reported uplift rate implies a reduced slip rate for the Los Osos fault.

The PG&E (2024) update report also included a discussion of transpression along the Hosgri fault as modeled by McConnell and Turner (2023). This study concluded that the uplift of the western portion of the Irish Hills could be explained by transpression alone, and the study demonstrated that the modeled uplift is compatible with the uplift rate determined for a marine terrace along the western edge of the Irish Hills. However, the McConnell and Turner (2023) model also indicates that uplift should diminish with distance from the Hosgri fault. Ongoing research by the U.S. Geological Survey Irish Hills Working Group may answer questions about the uplift rate in the central and eastern portion of the Irish Hills where uplift related to transpression along the Hosgri fault should diminish to zero. The PG&E team decided not to adopt the McConnell and Turner (2023) model for uplift of the Irish Hills or use it to revise the model weighting.

The understanding of the three competing fault geometry models (OV, SV, and NE) remains unchanged from the 2015 report. We still don't know whether the Los Osos fault is a reverse-oblique fault or purely thrust-reverse. We don't know whether the Los Osos fault or San Luis Bay fault is responsible for uplift of the Irish Hills. This unresolved issue of fault geometry highlights the need for improved geologic characterization of the Irish Hills and the bounding faults. Without a single geologic model for the Irish Hills that is clearly supported by hard data, there is greater (perhaps unrecognized) uncertainty regarding the seismic hazard model. Given that the DCPP is located in the Irish Hills, the lack of fundamental understanding of fault geometry and the mechanism responsible for the uplift appears to limit the potential for meaningful seismic hazard analysis.

There are potential options to improve the characterization of the faults that bound the Irish Hills. For instance, offshore seismic reflection profiling has been very successful at determining slip rates for the Hosgri fault and the Shoreline fault. That method could also be used to investigate other faults. Limited offshore seismic reflection profiling by the U.S. Geological Survey indicates that the Los Osos fault is a broad fault zone characterized by local vertical faults and flower structures, indicating strike slip faulting. If this preliminary work can be followed up with more detailed low energy seismic reflection profiling of the offshore Los Osos fault (such as can be accomplished using Chirp or sub-bottom profiler equipment capable of high-resolution imaging extending tens of meters below the ground surface), it may become easier to evaluate the three competing models and identify a single fault geometry model supported by geologic data. It is our opinion that additional geologic investigation along the Los Osos fault and South Boundary faults, both onshore and offshore, is warranted to resolve the fault geometry issue.

Previous efforts to characterize the Los Osos fault on land using vibroseis methods resulted in seismic images that were inconclusive (IPRP report #8). It appears that other tools to characterize fault geometry are worth consideration. Other options for investigation of the Irish Hills faults (on land) include trenching across mapped faults and fault scarps. Another option would be a transect of deep core borings or bucket auger borings across the mapped faults. We recommend that PG&E consider a range of surface and subsurface investigation methods to improve the geologic characterization of faults that bound the Irish Hills.

Data that was not considered in the Update: Implications of recent studies related to the Casmalia Fault

The Casmalia Hills, located southeast of DCPP, are an elongate uplift characterized by a series of folds trending approximately N60W. This uplift is cored by a north-vergent blind thrust fault, as demonstrated in a recent paper by McGregor and Onderdonk (2021). In the Casmalia Hills, a Pleistocene fluvial deposit, the Orcutt Formation, is folded into a series of anticlines that formed by a combination of fault bend and fault propagation folding that root into thrust faults. The authors of that study used post-infrared-infrared stimulated luminescence (pIR-IRSL) dating to determine that the age of the deposit is between 119 ± 8 ka and 85 ± 6 ka. By reconstructing the base of the Orcutt Formation and forward modeling the folds, they determined that slip rates on the blind thrust system range from 5.6 to 6.7 mm/yr.

These findings are relevant to seismic source characterization, because the Casmalia fault is located approximately 27 km south of the DCPP (at the closest point), and the slip rate for this fault is higher than many other faults within 40 km of the site. The updated seismic hazard analysis for the DCPP should consider the Casmalia fault as a potential seismic source.

The most important implication of the Casmalia fault study is as a possible analog and implications for slip rates on neighboring and linked faults. The Casmalia Hills and Irish Hills uplifts are similarly shaped, display a distinct parallel orientation, and are bounded by faults along the north and south flanks. Additionally, these bounding faults all merge into or are truncated by the high slip offshore Hosgri fault. Based on these clear similarities, the geologic structure of the Casmalia Hills might prove to be a useful analog for the Irish Hills.

Though recent work by McGregor and Onderdonk (2021) clarified the origin and timing of uplift of the Casmalia Hills, the significance of oblique slip is not well understood. The slip rate determined by forward modeling of an anticline at the Casmalia Hills is purely a dip slip rate based on a thrust fault interpretation. If there is a strike slip component of fault slip in the Casmalia Hills, that would not be apparent from this model. Considerable progress has been made in the offshore zone using Chirp seismic reflection profiling along the Hosgri fault, and this approach may prove useful to evaluate potential oblique slip along faults that extend westward from the Casmalia Hills. Furthermore, kinematically high slip rates in the Casmalia Hills may contribute to the slip rate budget of more poorly understood faults closer to DCPP that lack well-constrained slip rates. Thus, while structures underlying the Casmalia Hills may be less significant for the ground motion hazard at DCPP, the slip rate determined for the Casmalia fault should be considered in a regional model of structures related to faults in the Diablo Canyon vicinity.

IPRP Onshore Tectonic Model Conclusions

The three fault geometry models used in the PG&E (2015a) report have not changed. This lack of progress appears to result from a lack of geologic characterization of the Irish Hills. Offshore seismic imaging shows the Los Osos fault zone consisting of near-vertical faults with strike-slip characteristics. The linkage of this offshore fault zone with the mapped onshore Los Osos fault remains unclear, though additional detailed seismic imaging of the offshore fault zone should clarify that linkage. Given that the fault kinematics are better defined with offshore imaging methods, improved offshore data may inform the selection of fault models for the onshore Los Osos fault. Additional investigation, both onshore and offshore, is warranted to improve our understanding of the faults that surround the Irish Hills and contribute to the seismic hazard at the DCPP.

New data concerning the Casmalia Hills uplift indicates a need to evaluate this secondary seismic source as an analogue for the Irish Hills uplift. The McGregor and Onderdonk (2021) paper was not addressed in the PG&E (2024) update report. The slip rate used for the Casmalia fault in the PG&E (2015a) report was 0.5 mm/yr, but the slip rate determined by McGregor and Onderdonk (2021) is approximately an order of magnitude greater at 6 mm/yr. It is our opinion that this potential seismic source should be included in the seismic hazard model for the DCPP. Perhaps more importantly, this study of the Casmalia fault may provide a useful analogue for the kinematics and style of deformation in the region, especially given that uplift of the Irish Hills is poorly understood, as evidenced by multiple fault geometry models for the Irish Hills.

It is important to consider lateral slip on the Los Osos fault and faults in the Casmalia Hills. Additional offshore seismic reflection data focusing in detail on the Los Osos fault and the Casmalia Hills faults may identify piercing features that could yield rates of lateral slip. This methodology has proved effective in studies of the Hosgri fault and could be applied to the Los Osos fault and faults in the Casmalia Hills where they extend offshore and cross late Pleistocene and Holocene marine sediments.

REVIEW OF GROUND MOTIONS

Ground motion related subjects addressed by PG&E included (chapter numbers are those in PG&E, 2024): new ground motion data (Chapter 4), ground motion characterization for reference rock site condition (Chapter 7), vertical ground motions (Chapter 8), site characterization and site-specific adjustments (Chapter 9), hazard calculation and results (Chapter 10), and control-point hazard for risk assessment (Chapter 11). Our review follows the same structure as PG&E (2024). For each part, we start with a brief summary of PG&E's evaluation, followed by IPRP's comments on PG&E's evaluation, statement of remaining issues, and IPRP's suggestions and questions. A summary of IPRP review on ground motion related subjects is given at the end of this section. It should be understood that our review of the ground motion hazard calculation is for the input parameters from the seismic source characterization presented in PG&E (2024). The results of site-specific ground motions are likely to change with refinement of the seismic source characterization.

New Ground Motion Data (Chapter 4)

New data evaluated by PG&E (2024) include new globally and regionally recorded ground motion data. It is indicated that there are no new earthquakes in the immediate vicinity of the DCPP site, nor are there any new ground-motion recordings from the two stations at the DCPP site. Instead, PG&E evaluated three new regional and global ground motion datasets:

- A preliminary dataset from three large earthquakes occurred in Turkey in 2023 (Table 4-1 of PG&E, 2024, also see Figure 6),
- A dataset searched and selected specifically for DCPP that includes 7 earthquakes with magnitude from 5.0 to 5.8 and rupture distance from 15 to 201 km (Table 4-2 of PG&E, 2024),
- A subset of the preliminary NGA-West3 data (working flatfile dated July 28, 2023) considered hazard-significant for DCPP. The subset includes 14 events with magnitude ranging from 5.01 to 7.06, rupture distance 2 to 346 km (Table 4-3 of PG&E, 2024).

In addition, PG&E briefly discussed simulated data, including simulations performed using the Southern California Earthquake Center (SCEC) broadband platform (BBP) and SCEC regional 3D simulation program (CyberShake) for calculating probabilistic seismic hazard curves for sites in California. It was concluded that there are no new BBP simulation results applicable to DCPP. There are new CyberShake hazard curves and ground motions. However, those were precluded for further evaluation because of limited 3D velocity structure, large regional scale, and limited frequency range in which the CyberShake results are regarded as being valid. PG&E, however, noted that the ground motions computed from the CyberShake platform were used to evaluate and inform the potential path effect.

IPRP comments on new ground motion data

We found PG&E's search and evaluation for new ground motion data complete and agree with their assessment that simulated data are either not new or not appropriate for the DCPP except for informing specific components of ground motion characterization. There are no new ground motion data to refine empirical site term. In fact, there are no new ground motion recordings within 50 km of the DCPP site as shown in Figure 6.

Issues noted in previous IPRP reports regarding site condition and site amplification remain (see IPRP comments on Site Characterization and Site-Specific Adjustments). These, however, do not invalidate PG&E's updated seismic hazard given broad uncertainty ranges considered in input parameters for the hazard evaluation. However, future effort to reduce uncertainty or improve its quantification would be worthwhile when new data become available.

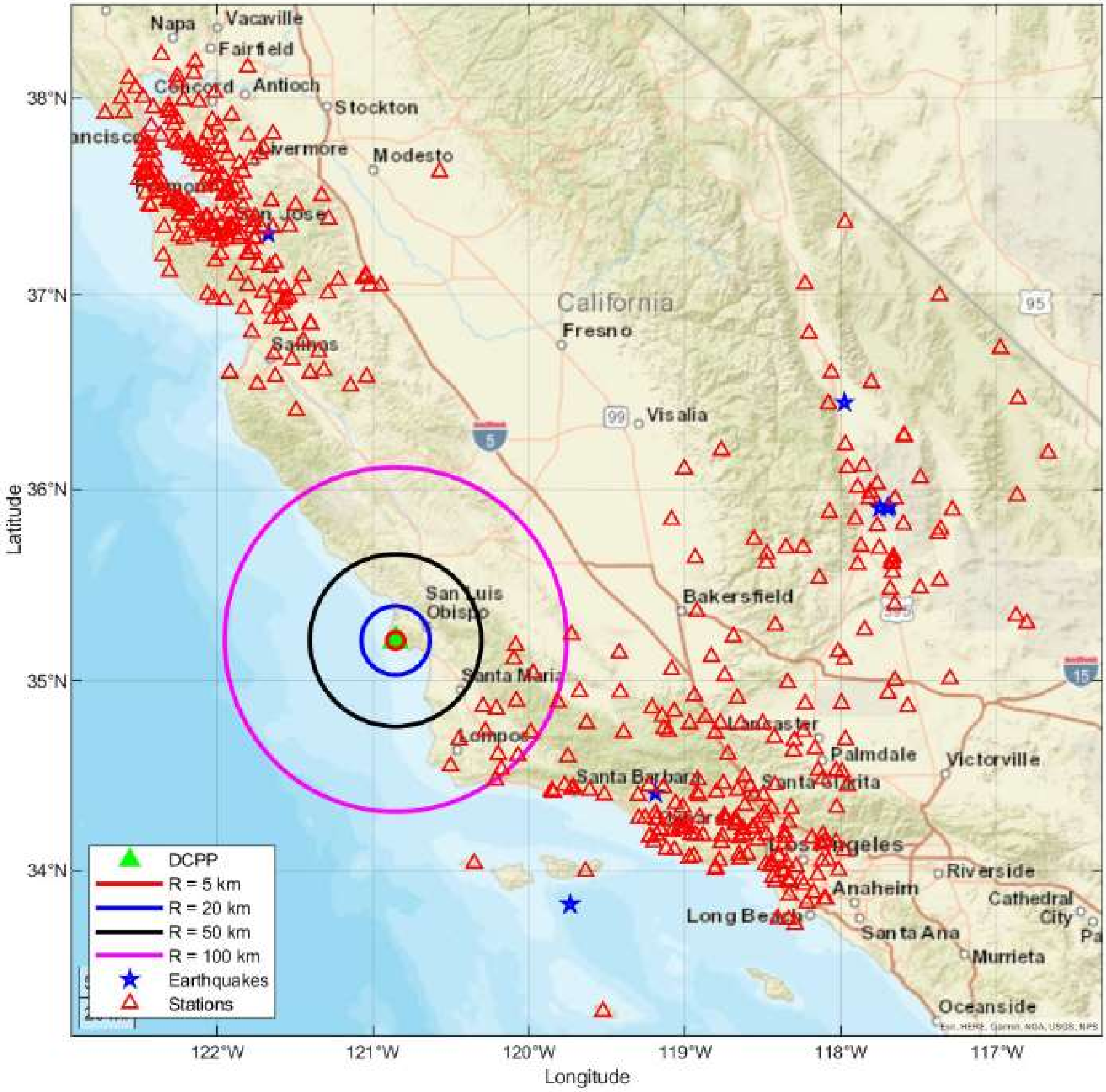


Figure 6. Earthquake epicenters (blue stars) and ground-motion recording station locations (open red triangles) for the supplemental DCPP California empirical catalog (from PG&E 2024, Figure 4-2).

Ground Motion Characterization for Reference Rock Site Condition (Chapter 7)

PG&E's seismic hazard re-evaluation started from the comprehensive ground motion characterization for the DCPP reference rock site condition in 2015 as part of the SSHAC Level 3 study for the nuclear power plants in southwest United States (SWUS) (GeoPentech, 2015). The reference rock condition was defined as having V_{S30} of 760 m/sec and a kappa value of 0.041 sec, which was selected based on the upper range in site conditions that are well constrained by available empirical ground-motion data. PG&E's evaluation of the 2015 SWUS study included two components: 1) assessment of the performance of the ground motion models (GMMs) in the 2015 study, referred to as the SWUS models, against new ground motion data, and 2) evaluation of new models that became available since the conclusion of the 2015 study. The SWUS models include median and aleatory variability models, which were assessed separately.

A few noteworthy aspects for the 2015 SWUS ground motion data and models (GMMs) are recapped here to aid the understanding of PG&E's evaluation and IPRP's review comments:

Median model

- Both empirical (recorded) and simulation-based ground-motion data were used, with simulated data used to supplement the empirical data in the evaluation of splay and complex ruptures and Hanging wall (HW) effects.
- NGA-West2 models were used without their HW effect, models from Sammon's mapping methodology were used for local source and the NGA-West2 GMMs were used for distance sources.
- Five HW models were developed specifically as part of the SWUS study based on limited empirical and simulated data (Donahue and Abrahamson, 2014).
- The 2015 SWUS Technical Integration (TI) team decided not to include rupture directivity effect.
- Earthquakes from splay and complex ruptures in the seismic source characterization (SSC) model for DCPP have relatively low occurrence rate. They do not contribute significantly to the total hazard at the DCPP. Ground motions from the two separate seismic sources that make up the splay and complex ruptures were estimated separately, and the final ground motions were a combination of the ground motions from each source using the square-root-of-the-sum-of-the-squares approach.

Aleatory variability model

- The 2015 study used a partially non-ergodic approach, specifically, it relies on single-station sigma models that quantify and remove the site-to-site variability from the ergodic ground motion variability.
- The use of single-station sigma requires: (1) adjustment of the median ground motion to site-specific conditions, (2) quantification of the epistemic uncertainty in the site adjustment, and (3) quantification of the epistemic uncertainty in single station sigma. These were satisfied in the 2015 study and the subsequent site response analysis for DCPP.
- Single station sigma was combined from individual models for the between event variability and the single-station within-event variability.

The median model was evaluated in PG&E (2024) in terms of residuals obtained by applying the model to the new datasets, including assessment of hanging wall (HW) effect, directivity effect, and applicability to splay and complex ruptures. Comparison was also made with the new non-ergodic ground motion models for California developed after the 2015 study.

PG&E's evaluation started with an overview of new information, followed by evaluations of key aspects of the median model. It was noted that more empirical data will be compiled in the near future as part of the on-going NGA-West3 study and can be used to supplement the current evaluation of the SWUS median model.

PG&E found no new GMMs for active crustal regions that can be added to the suite of seed models selected in the 2015 study as input models into the framework of Sammon's mapping methodology. They concluded that the 2015 seed models still represent the range of models that are currently applicable.

PG&E further concluded that Sammon's mapping methodology for selecting candidate GMMs by modeling and sampling the GMM space is still current and acceptable partly because this approach or its variation has: 1) been used by other influential projects, e.g., the NGA East project (Goulet et al., 2018); and 2) become the standard practice for high-level (e.g., SSHAC Level 3) studies for nuclear installations (such as PNNL, 2014; INL, 2022; and Bommer et al., 2015).

PG&E performed multiple analyses on residuals for several spectral periods obtained by applying the central model in the 2015 suite of models to the new datasets. These include residual analyses of three groups: 1) residuals from preliminary NGA-West3 and Turkish data, 2) residuals from the DCPP-specific data, and 3) total residuals for events with rupture distances less than or equal to 15 km. The analysis results do not show any trends in the residuals between the new empirical ground motions adjusted for the reference V_{S30} value of 760 m/sec and the SWUS median ground-motion model, hence the SWUS median ground motion model is applicable to the new data.

The aleatory variability model was evaluated in PG&E (2024) in terms of between-event variability, single-station within-event variability, and single-station sigma. A discussion of recent updates to each component was presented. PG&E stated that the new datasets are not sufficient and do not allow for a revision or an update of the aleatory variability models for DCPP due to their limited magnitude and distance ranges and preliminary nature. It was noted that new between-event and single-station within-event standard deviation models will be available as part of the NGA West3 project, but these models will not be available until the end of 2024.

PG&E's evaluation of aleatory variability model, therefore, focused on published models since the completion of the 2015 study in terms of their applicability to the DCPP site and their differences compared to the SWUS model. The new models are global models developed as part of the NGA-East project (Al Atik, 2015), including a model for between-event variability (τ), a model for single-station within event variability (φ_{ss}), and a model for single-station sigma. These new models were adopted in the SSHAC Level 3 studies for the Idaho National Laboratory (INL, 2022) and in the Natrium Demonstration Project in Wyoming (Natrium, 2024).

The SWUS and the global between-event variability (τ) models are similar in that both models are based on the NGA-West2 τ. Both are magnitude-dependent, period independent, and similar in their characterization of epistemic uncertainty. τ as a function of magnitude from these two models is compared and shown to be mostly consistent for magnitude range important to DCPP.

Based on this comparison and the stated similarities, PG&E concluded that the SWUS τ model is consistent with new τ models adopted in other, newer SSHAC Level 3 studies.

There are many similarities between the three SWUS φ_{ss} models and the global φ_{ss} model, including magnitude-dependence, period-dependence, NGA West2 based, and the way uncertainty is characterized. Comparison of φ_{ss} from the three SWUS models with φ_{ss} from the global model for PGA and 1.0-s spectral acceleration show reasonable consistency.

The SWUS single-station sigma approach combined the between-event and within-event standard deviation models for the distribution of ground motion residuals and the impact of the spatial correlation of residuals on the components of the aleatory variability. This approach was adopted by later SSHAC Level 3 studies; therefore, it is still current. PG&E noted, the impact of the spatial correlation of ground-motion residuals can be evaluated and updated in future following the completion of NGA-West3 study.

IPRP Comments on Ground Motion Characterization for Reference Rock Site Condition

The IPRP finds PG&E's search for new ground motion data and models thorough. We agree with their conclusion that the SWUS seed GMMs and the Sammon's mapping methodology for GMM sampling are still current and applicable. PG&E's comprehensive residual analyses demonstrated that the SWUS models fit the new datasets and, therefore, are still appropriate for DCPP.

PG&E's evaluation of directivity, HW effects, and the treatment of splay and complex ruptures are also reasonable. IPRP agrees with PG&E's conclusion that there are no significant differences between the DCPP ground-motion model and the more recent data and models with respect to directivity, HW effect, and the treatment of complex ruptures. Comparisons of the median predictions from the DCPP model with available non-ergodic ground-motion models also indicates consistent results. PG&E, therefore, concludes that no changes are warranted for the median model at this time, which IPRP agrees with.

IPRP further concurs with PG&E's conclusions regarding the SWUS aleatory variability models. These include: i) available preliminary datasets do not allow for an update to the aleatory variability model for the large-magnitude and short-distance ranges that are important for the DCPP (e.g., M > 5 and rupture distance < 50 km); and ii) components of the DCPP aleatory variability model indicated consistency in the approach, elements of the logic tree, and results in the magnitude and distance ranges of interest. Therefore, the SWUS aleatory variability model developed for DCPP is considered valid and no updates are recommended at the time of this evaluation.

Vertical Ground Motions (Chapter 8)

PG&E developed vertical ground motions (PG&E, 2017a, b) after the 2015 study (horizontal only) for structural analyses that require three-component ground motion time histories. Their approach in developing vertical ground motions is applying a vertical to horizontal ground motion spectral r (V/H) ratio to the horizontal Foundation Input Response Spectra (FIRS) (PG&E, 2017a).

The V/H ratio approach is the standard of practice in earthquake engineering. PG&E stated that one advantage of this approach is that it prevents potential mismatch of scenario events that controls ground motion hazards. Controlling scenarios are used to guide selection of ground motion time histories for structural analysis.

PG&E (2017a) utilized the scenario-based empirical approach of Gülerce and Abrahamson (2011) to develop vertical ground motions for the control point horizon with V_{S30} of 967 m/s. The controlling scenario was selected to be an M7 earthquake at 5 km. Given these scenario parameters, V/H ratios were calculated and applied to the horizontal spectrum to obtain vertical spectrum.

A few newer ground motion V/H ratio models were mentioned but were judged not applicable to the DCPP site given its tectonic environment and controlling scenario event. One exception is the Bozorgnia and Campbell (2016) model. PG&E compared the PG&E (2017a) V/H ratios with ratios obtained using the new V/H ratio model of Bozorgnia and Campbell (2016) for the same scenario and found that the PG&E V/H ratios envelope the Bozorgnia and Campbell (2016) ratios at all frequencies. PG&E does not recommend using lower ratios, because the Bozorgnia and Campbell (2016) V/H ratio model is dependent on one particularly GMM for horizontal ground motion, namely the Campbell and Bozorgnia (2014) GMM that predicts larger high-frequency horizontal ground motions than other NGA-West 2 GMMs.

IPRP Comments on Evaluation of Vertical Ground Motions

We agree with PG&E's evaluation that V/H ratio approach is more appropriate than using GMMs developed specifically for vertical ground motion. We believe the main reason is because there are fewer GMMs for vertical ground motion than for horizontal ground motion so using Sammon's mapping approach would be questionable. It would also require a full PSHA analyses for vertical ground motion similar to the SSHAC level 3 approach used in the 2015 study for horizontal ground motion. As for controlling scenarios, it should be determined by what ground motion parameter the structures in question are sensitive to. One could get different controlling scenarios at different spectral periods even for just horizontal ground motions.

IPRP finds it reasonable not to recommend the new V/H ratio model that relies on one particular horizontal GMM and yields lower V/H ratios. It is never a good idea to rely on one particular model given large epistemic uncertainty in ground motion characterization. We further agree that the other newer V/H models are for other tectonic settings and are not appropriate for the DCPP site.

Site Characterization and Site-Specific Adjustments (Chapter 9)

Site characterization, site-specific adjustments, and the site-specific ground-motion response spectrum (GMRS) at a control point for the DCPP were discussed in PG&E (2015b, 2015c, and 2017b) following the 2015 SSHAC Level 3 study. The control point was selected as a hypothetical location at an elevation of 85 ft (25.9 m) and a best estimate V_{S30} of 968 m/s. Probabilistic ground motion hazards were calculated for the reference rock site condition as part of the 2015 SSHAC

Level 3 study. Site- specific adjustments were then developed and applied to the ground motion spectrum at the reference site condition to obtain GMRS at the control point.

PG&E (2024) provided an overview of the previous studies, discussed the DCPP inputs and methods in site response study considering new information, and evaluated potential changes to and impact on the established GMRS. PG&E methodology to develop adjustment factors for the DCPP control point relative to the reference rock site condition included an analytical approach and an empirical approach.

Analytical Approach

The analytical approach is a 1-D site response analysis. It was carried out by Pacific Engineering and Analysis (PE&A) and documented in PE&A (2015). The input motions were assumed to be from the controlling scenario earthquake (M7 at a depth of 8 km) with a range of point source distances to generate a range of input ground-motion levels. Response spectra from the M7 scenario were computed for the reference (host) rock site condition and for the control point (target) site condition. For both the host and target rock sites, nonlinearity was allowed only for the top 500 ft (152.4 m). The methodology requires characterization of both host site and target site conditions in terms of their V_S profiles and other values.

This approach requires V_S profiles for both the host and target site conditions. For the host site, the V_S profile was a generic profile developed by Kamai et al. (2013) that yielded a V_{S30} of 760 m/s and a kappa of 0.03 s based on inversion of NGA-West2 GMMs.

For the target site, inputs were defined by a logic tree that accommodates uncertainties in 3 inputs: shallow V_S profile, kappa value, and nonlinearity. The shallow V_S profile extended to 125 m depth with three logic tree branches defining a central, an upper, and a lower V_S profile. These profiles were extracted from the 3D velocity model developed by Fugro (2015a) at locations defined by a grid over the power block and the turbine building footprint. The central profile is based on the geometric mean of the grid point profiles, and the upper and lower profiles correspond to ±1.6 standard deviation from the central profile. For each of these three base-case profiles, 30 random profiles were generated and analyzed. The 1D site response model extends to a depth of 8 km. From 125 m to 3 km, the V_S profile was constructed based on the 1D V_P profile below the DCPP area determined by Fugro (2015b). From 3 to 8 km, the V_S profile was the same as for the reference rock site profile. (Note this summary is based on the text description in PG&E (2024), which is inconsistent with V_S profiles depicted in Figure 3 of the same report, see IPRP Comments below).

Analytical site adjustment factors were presented in Figure 9-8 in PG&E (2024) for 3 reference rock peak ground acceleration values. This figure shows that, in general:

- Ground motions at the target site are lower than at the reference site for frequencies higher than about 1 or 2 hz,
- The largest reductions occur at frequencies around 10 Hz, and

- Higher V_S, kappa, and PGA values result in greater reduction in ground motions.

PG&E's reevaluation of the analytical site factors included evaluation of the PE&A (2015) site factor approach, and characterizations of target and host site conditions. It was noted that the PE&A approach differs from traditional soil-over-rock site response approach. The PE&A approach uses broadband point-source stochastic simulations to develop ground motions for the entire profile depth for the host and target V_S profiles separately. The ratio of the host and target ground motions is used to define the site adjustment factors for different input ground motion levels. Even though this approach is not as widely used in geotechnical engineering community as the traditional approach, PG&E noted that it has been advocated for and used on recent SSHAC Level 3 studies such as the Idaho National Laboratory study (INL, 2022) and the Natrium study (Natrium, 2024) and is, therefore, appropriate.

The host site condition was reevaluated given the GMM-compatible V_S profiles and kappa values for the NGA-West2 GMMs developed in a recent study by Al Atik and Abrahamson (2021). It was found that the GMPE-compatible profiles and the generic profile used by PE&A (2015) differ at both the shallow and deep layers, leading to differences in the site amplifications at high and low frequencies. A sensitivity analysis was carried out, site factors from the sensitivity study were found to be within the range of the DCPP empirical site factors. Giving this finding and small weight assigned to the analytical factors, no revision was deemed necessary by PG&E.

Empirical Approach

PG&E's empirical approach relied on the evaluation of ground-motion recordings from the 2003 San Simeon and the 2004 Parkfield earthquakes at station ESTA27 and a recording from the Parkfield earthquake at station ESTA28. V_{S30} at ESTA27 and ESTA 28 was estimated to be 856 and 777 m/s, respectively, based on Fugro's (2015a) 3D velocity model. The approach involves the following steps, all calculations utilized the four NGA-West2 GMMs:

1. Evaluate the average source and path terms for each event at the distance range of interest to DCPP.
2. Calculate source-path corrected residuals by removing the average source-path term from the total residual for each of the 3 recordings at DCPP.
3. The source-path corrected residuals for DCPP recordings were further corrected for V_{S30} scaling based on different V_{S30} values at the recording stations and the control point.
4. The empirical site term was then estimated based on the weighted average of the corrected residuals.

Epistemic uncertainty in the empirical site term was quantified to account for: 1) limited number of recordings at DCPP, 2) the standard error in the estimated average source-path term, and 3) the uncertainty in the V_{S30} adjustment.

Comparison of uniform hazard spectra at the DCPP control point obtained using analytical and empirical site terms are shown to be in general agreement (Figure 9-11 in PG&E, 2024) for frequencies below 1 hz and above 8 hz. From 1 to 8 hz, spectral acceleration using the analytical approach is lower. In hazard calculations, the analytical and empirical approaches were weight 2/3 and 1/3, respectively.

PG&E's reevaluation of the empirical site factors includes evaluation of new data and methodology. The new non-ergodic ground motion approach was noted as a major development in ground motion study since the development of the 2015 DCPP site factors and was evaluated for its applicability to the DCPP site. It was also noted that the non-ergodic approach and the dataset compiled for this approach are considered preliminary.

As noted previously, even though there are new ground motion data in the vicinity of DCPP since the completion of the 2015 study, there are no new ground-motion recordings at either of the DCPP stations (ESTA27 and ESTA28) on which the empirical site term relies on. Therefore, PG&E doesn't expect the 2015 empirical site term to change.

The new non-ergodic procedure allows for the estimation of repeatable source, path, and site effects and the adjustment of ergodic ground-motion models to become site-, source-, and region-specific. The characterization of these repeatable effects requires the availability of empirical ground-motion data at the site of interest and in the region of interest.

The non-ergodic ground-motion modeling approach was implemented (as summarized in Section 9.3 and appendix F of PG&E, 2024) using the 3 DCPP recordings and the updated dataset in vicinity of the DCPP site. The total site term and its regional and uncorrelated components from this preliminary implementation are presented and compared to the 2015 DCPP site term in Figure 9-27 of PG&E (2024). Site terms from these two studies are found to be in general agreement. Minor differences are illustrated in Figure 9-28 of PG&E (2024) in which ratio of the updated empirical site term to the 2015 site term is plotted. For frequencies above 0.67 Hz, the ratio is between 0.83 and 1.15 (ratio at 5 Hz). Overall, the differences are smaller compared to the uncertainty in the empirical site term and no update to the 2015 site term is recommended. PG&E attributes the differences to the preliminary nature and potential data quality issues in the dataset used in the non-ergodic modeling approach.

IPRP Comments on Evaluation of Site Characterization and Site-Specific Adjustments

Regarding site factors, PG&E's search for new data and methodology is again thorough. Sensitivity analysis using updated host site profile yielded noticeable differences from the 2015 analytical results, but we agree that the differences are insignificant given the large uncertainty range in the empirical factors and its higher logic-tree weight as shown in Figure 7. We further agree that the results from independent analysis via preliminary implementation of the new non-ergodic ground motion modeling approach do not call on any changes to the 2015 empirical factors for the DCPP.

Previous IPRP reports (e.g., numbers 9, 10 through 13, and number 15) noted some projects and issues regarding site characterization and site factor that PG&E was to address or improve via its LTSP. Several projects noted as on-going previously and remaining issues may have significant influences on ground motion estimates at the DCPP site. These include: (1) the "3-year Kappa project" initiated in 2017 with multiple partners to better address kappa scaling for hard rock sites; (2) development of 3D site response methodologies and models, potentially augmenting the current empirical and 1D analytical approaches; (3) better understanding of the differences in the results from analytical and empirical site amplification approaches; (4) evaluation on validity of the deep 1D analytical approach given the complex 3D geologic conditions beneath the DCPP site and lack of reliable data on damping characteristics in deeper layers, (5) addressing considerable inconsistency observed between the 3D velocity model derived from tomographic and surface wave dispersion data and the downhole velocity measurements, and (6) assessment of path effects on the estimated empirical site amplification factors given that these factors were estimated from two earthquakes (2003 San Simeon and 2004 Parkfield) with limited azimuthal coverage. IPRP requests a status update regarding these issues or projects for continuity as there are no updates in PG&E (2024).

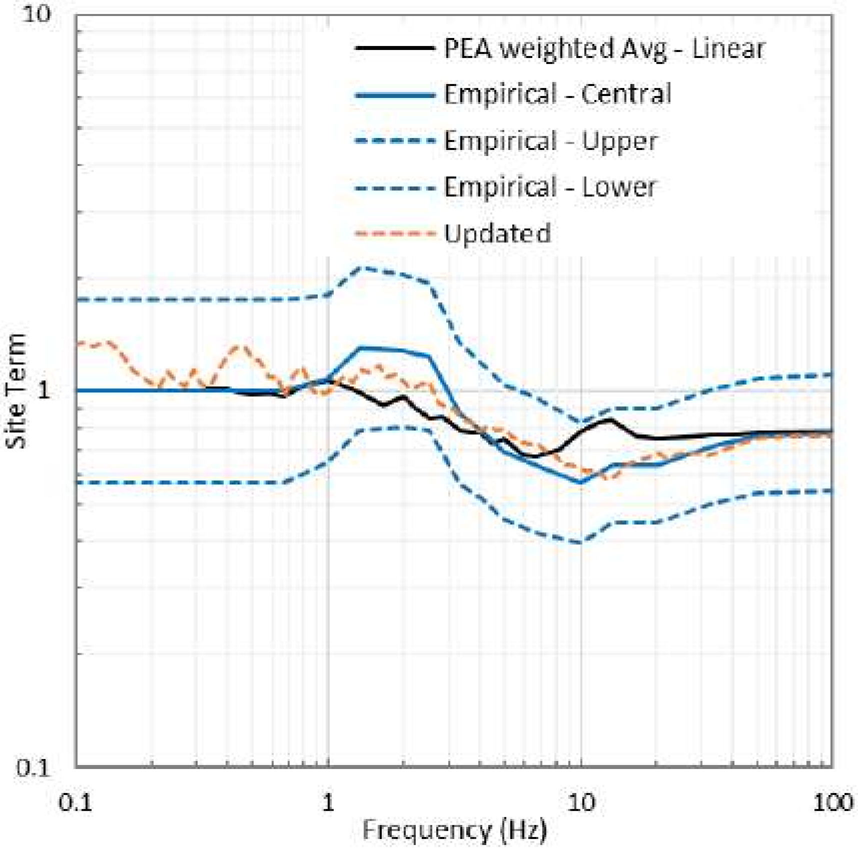


Figure 7. Comparison of the 2015 site term and its epistemic uncertainty (5th and 95th percentile labeled as lower and upper, respectively) and the updated empirical site term obtained from the non-ergodic modeling approach. The average analytical linear site term is shown in black. (from PG&E 2024, Figure 9-29)

The PG&E 1D site response analysis is sensitivity to site properties on both the host and target sites, as demonstrated by the notable differences in analytical site factors using updated, NGA-West2 GMM compatible host-site V_S profile. PG&E cited two main reasons not to update the analytical factors: 1) small logic tree weight for the analytical site factors, and 2) the fact that the change in analytical factors from sensitivity studies using the updated host-site profile is within the broad uncertainties of the empirical site factors.

Given there are no new site data, the decision not to update the analytical factors appear reasonable. However, we believe analytical site factors can be improved if the characterization for the target site can be improved by devoting resources to acquire more site-specific data, including improving V_S profile and kappa value estimates. We are dubious about PG&E's statement that the site data at the DCPP were extensive and provided a well-constrained velocity model for depths up to 3 km. We believe there is still potential to improve site data. Analytical site factors may also be improved by carrying out supplemental site response analyses using the more traditional approach of propagating acceleration time histories selected from controlling scenarios determined from hazard disaggregation through the control-point rock and soil profiles. In additional, we encourage continuing effort to reduce uncertainty in the empirical site factors in future studies.

The description of V_S profiles for the target site condition given in the 1st and 2nd paragraphs of Section 9.1 is inconsistent with profiles shown in Figure 9-3 in PG&E (2024):

1. The text says the central, upper, and lower plant region profiles extend to 125m, whereas figure 9-3 shows these profiles extend to about 4 km.
2. The text says the central, and upper and lower profiles correspond to the geomean and ±1.6 standard deviation from the central profile, whereas figure 9-3 shows only upper and lower profiles below 4 km. It is not clear whether the central profile is the same as the lower profile or is the lower profile was not used.
3. The V_S profile for target site between 125 m to 3 km descripted in the text was not shown on Figure 9-3
4. The text says the target site V_S profile below 3 km is the same as the reference site. However, Figure 13 in PG&E (2024) shows that it is the upper profile for the plant region instead.

Which version is correct? We request a revision with corrections.

Hazard Calculation and Results (Chapter 10)

PG&E's evaluation of SSC resulted in an increase in the mean slip rate and EPHR for the Hosgri fault and a slight decrease in the mean slip rate for the Los Osos fault. No changes were recommended by PG&E in fault geometry or ground motion models.

As a result, a simple scaling approach was used to incorporate changes in Hosgri and Los Osos slip rates to obtain updated hazard results. In hazard calculation, change in slip rate for a fault source leads directly to change in the event rates (for events greater than or equal to a magnitude of engineering significance) which scales the hazard curves linearly. The same scaling approach is also applicable for the recommended change in the EPHR for the Hosgri fault. This scaling approach for hazard calculation includes the following steps:

1. Extract the hazard curves from the Hosgri and Los Osos fault sources from the 2015 PSHA results,
2. Scale the Hosgri fault hazard curve based on the adjustment for the mean slip rate,
3. Scale the Hosgri fault hazard curve based on the adjustment for the EPHR,
4. Scale the Los Osos fault hazard curve based on the adjustment for the mean slip rate,
5. Combine the scaled Hosgri and Los Osos fault hazard curves with the original hazard curves (PG&E, 2015a) from the other seismic sources to compute the scaled total hazard curve.

These steps were applied to hazard curves for the reference rock condition for 17 spectra frequencies from 100 Hz (PGA) to 0.333 Hz, followed by constructions of uniform hazard spectral and the GMRS for the reference rock conditions.

The resulting change in the total hazard curve varies with ground motion and spectral frequency depending on the relative contribution from the Hosgri and the Los Osos faults to the total hazard. For lower spectral frequencies, the relative contribution from the Hosgri fault to the total hazard is larger, leading to a larger increase in the updated hazard curves when compared to the intermediate and higher spectral frequencies where the relative contribution from the Hosgri fault is smaller. For the 5 Hz case, it is observed that the ratio of updated and original hazard curves is approximately constant for hazard levels of about 10^{-4} and lower.

Uniform hazard spectra were updated for three hazard levels at 10^{-4}, 10^{-5}, and 10^{-6}. These spectra increase slightly compared to the 2015 results because the Hosgri fault source contributes more than the Los Osos fault source to the total hazard. The ratios of the UHS vary with hazard level and spectral frequency, with 5-7% increase at lowest frequency (0.333 Hz) and 4% or less for higher frequencies.

PG&E's GMRS for reference rock site condition is defined based on 10^{-4} and 10^{-5} UHS. It is the 10^{-4} scaled by a factor that is 0.6 times the spectral ratio of 10^{-4} and 10^{-5} UHS if the ratio is less than 1. If the ratio is greater than 1, GMRS is equal to the 10^{-4} UHS. Similar to UHS comparison, the updated GMRS is slightly higher than the 2015 GMRS, up to 7% increase for lower frequencies and about 3% increase for intermediate to high frequencies. PG&E (2024) noted that the increase in ground motion values is well within the epistemic uncertainty of the 2015 study. In that study, the ratio of 95th to 5th percentile ground motions has a range of 3 to 5 at 10^{-4} to 10^{-6} hazard level, which is approximate 100 times larger than the increase seen in this update due to changes in slip rates.

IPRP Comments on Hazard Recalculation and Results

The PG&E scaling approach to incorporate changes in slip rates appears appropriate. The resulting updated hazard curves, uniform hazard spectra (Figure 8), and GMRS (Figure 9) also appear reasonable. It would be good to illustrate mathematically why hazard curves can be scaled by the same factor as the mean slip rate. It would also be good to clearly state any underlying assumptions of this scaling approach and discuss why these assumptions are appropriate. It appears that the scaling approach is consistent with the moment balancing approach. It constrains the overall energy release but does constrain how deformation is accommodated over all different size events on the fault. Given that smaller earthquakes only rupture a smaller area of the fault, one would expect larger increase in the number of smaller earthquakes than larger earthquakes for a given amount of increase in moment rate which is scalable from slip rate. For the Hosgri fault, the rationale for multiplying the scaling factors for mean rate and for EPHR should be stated.

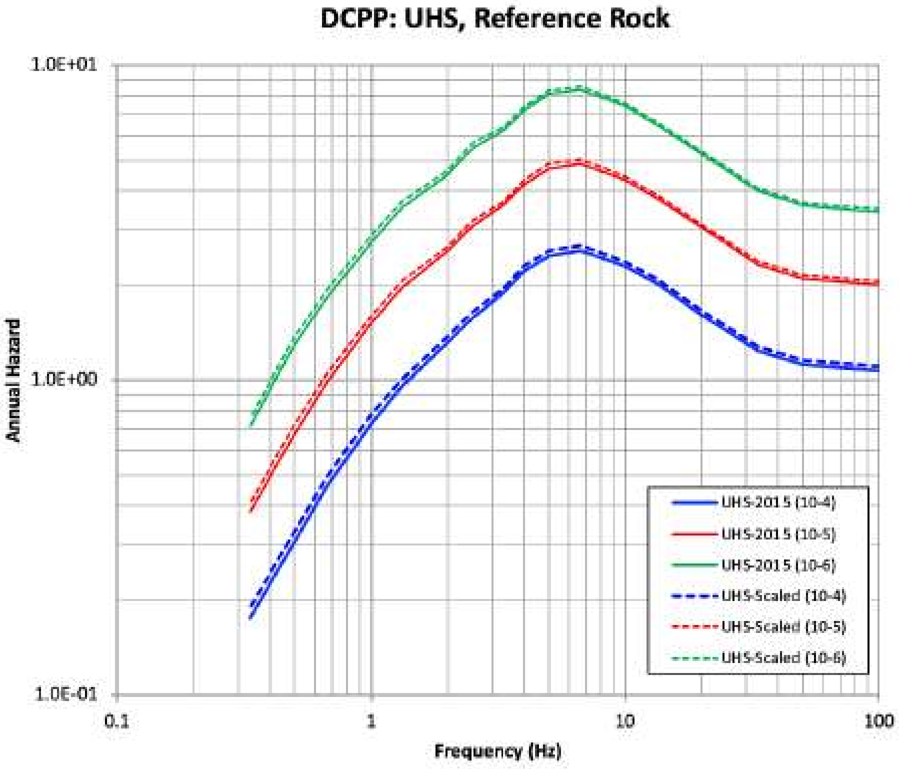


Figure 9. UHS from the 2015 study (solid lines) and the updated results (dashed lines) for hazard levels of 10^{-4} (blue lines), 10^{-5} (red lines), and 10^{-6} (green lines). (from PG&E 2024, Figure 10-18).

Equation 10-2 does not look correct. The term “0.6*AR0.8” is not defined. It looks like a typo.

Control-Point Hazard for Risk Assessment (Chapter 11)

Evaluation of ground motion characterization (Chapter 9, PG&E 2024) concluded that the site factors to adjust ground motions from the reference site condition to the control point site condition used in the 2015 study are still acceptable. Therefore, scale factors derived from hazard curves for reference rock condition to account for slip-rate change can be applied to hazard curves at the control point to obtain updated hazard curves. This is because site adjustment is a linear scaling process. Consequently, ratios of updated and 2015 hazard curves obtained at reference rock condition can be applied directly to the 2015 hazard curves at the control point to account for changes in Hosgri and Los Osos fault slip rates.

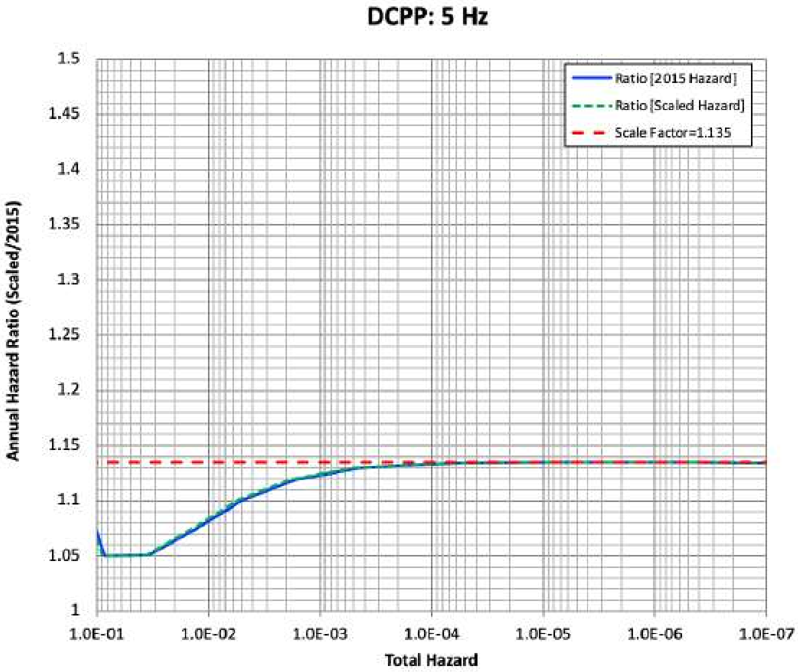


Figure 10. Hazard curve ratio (i.e., scaled hazard divided by 2015 hazard) plotted as a function of 2015 total hazard (solid blue line), scaled total hazard (dashed green line), and selected scale factor (dashed red line) for 5 Hz. (from PG&E 2024, Figure 11-4)

PG&E (2024) demonstrated that the ratio of updated hazard divided by the 2015 hazard varies by hazard level at multiple spectral frequencies. For simplicity, a constant ratio was recommended for a given spectral frequency to approximate scaling factors. The recommended ratio is the ratio at the hazard level near 10^{-5} (Figure 9).. The scaling factor is 1.135 for 5-Hz hazard curve which is what PRA study is based on. The highest factor is 1.233, which is based on the 0.5-Hz hazard curve. PG&E recommends using this highest ratio for bounding sensitivity study to be conservative.

IPRP Comments on Control-Point Hazards

The recommended hazard-level independent scaling factors for the control point hazard curves appear reasonable given overall small changes. We agree that the recommended factor of 1.233 for bounding sensitivity study is appropriate for the source models, ground motion models, and site characterization and site adjustment described in PG&E (2024). However, we note hazard results may be subject to revision if the seismic source characterization inputs are modified based on the comments in this report regarding slip rates on the Hosgri fault and models for deformation in the Irish Hills.

Ground Motion Review Summary

In summary, we found PG&E's search and evaluation for new ground motion data and new ground motion models, including the non-ergodic ground motion models and the V/H models for vertical ground motions, to be thorough and comprehensive. PG&E demonstrated that the 2015 DCPP model remains current and applicable through analyses of residuals obtained by applying it to new data. Comparisons of median predictions from the DCPP model with available non-ergodic ground motion models also indicate consistent results. PG&E concluded that the 2015 Sammon's mapping methodology for GMM sampling is still the best practice, as newer influential projects, including some SSHAC level 3 studies for nuclear installations conducted after the 2015 DCPP study, have used the same or similar methods. For vertical ground motion, we agree with PG&E's evaluation that the V/H ratio approach is more appropriate than using GMMs developed specifically for vertical ground motion. This may be due to the scarcity of published GMMs for vertical ground motion and extensive work required for a SSHAC level 3 study parallel to the 2015 DCPP study for horizontal ground motion.

Regarding site characterization and site-specific adjustments, PG&E's search for new data and methodologies is again thorough. Sensitivity analysis using the updated host site V_S profile resulted in noticeable differences compared to the 2015 analytical site factors, but we agree the differences are insignificant given the large uncertainty range in the empirical factors and their higher logic-tree weight. The IPRP further agrees that results from independent analysis via preliminary implementation of the new non-ergodic ground motion modeling approach do not necessitate any changes to the 2015 empirical factors for the DCPP. Previous IPRP reports (e.g. IPRP Report #6) raised several issues regarding site characterization and site factors; however, these issues remain unresolved due to lack of new site data. IPRP continues to encourage efforts to improve the characterization of site condition in terms of V_S profile and kappa estimate in order to improve analytical site factors. We suggest the more traditional approach of site response analysis, which propagates time histories through site soil/rock models, be carried out to supplement existing analyses. This issue ranks high on the tornado diagram (PG&E, 2015) of ground motion hazard sensitivity (Figure 11), and could be addressed with additional characterization at the site. IPRP also encourages PG&E's continuing effort to reduce uncertainty in empirical site factors, including further improving the non-ergodic ground motion modeling approach and data.

PG&E's scaling approach to incorporate changes in slip rates for the Shoreline and Los Osos faults appears appropriate and the updated hazard curves, uniform hazard spectra, and GMRS appear reasonable. The recommended hazard-level independent scaling factors for the control point hazard curves also appear plausible given the overall small changes. We agree that the recommended factor of 1.233 for the bounding sensitivity study is conservative for the source models, ground motion models, and site factors established in PG&E (2024). We note future changes in any of these input components may necessitate reevaluation of ground motion hazards.

Finally, we reiterate the importance of site characterization, site factors, and ground motion modeling approaches in a site-specific probabilistic seismic hazard assessment. Figure 11 is a tornado plot reproduced from a 2015 PG&E presentation and was cited in IPRP Report No 9 (as Figure 4 in that report). The most striking feature of this tornado plot is the six items related to ground motion calculation on the top of the tornado that have the most uncertainty and hazard sensitivity. We ask PG&E to update the tornado plots as seismic hazards are reevaluated (including for updated fault slip rates discussed in PG&E, 2024), and include the sensitivities of new models as they are developed. These kinds of diagrams help put things in perspective, illustrating the effectiveness of efforts to reduce uncertainty in input parameters, and prioritizing future research.

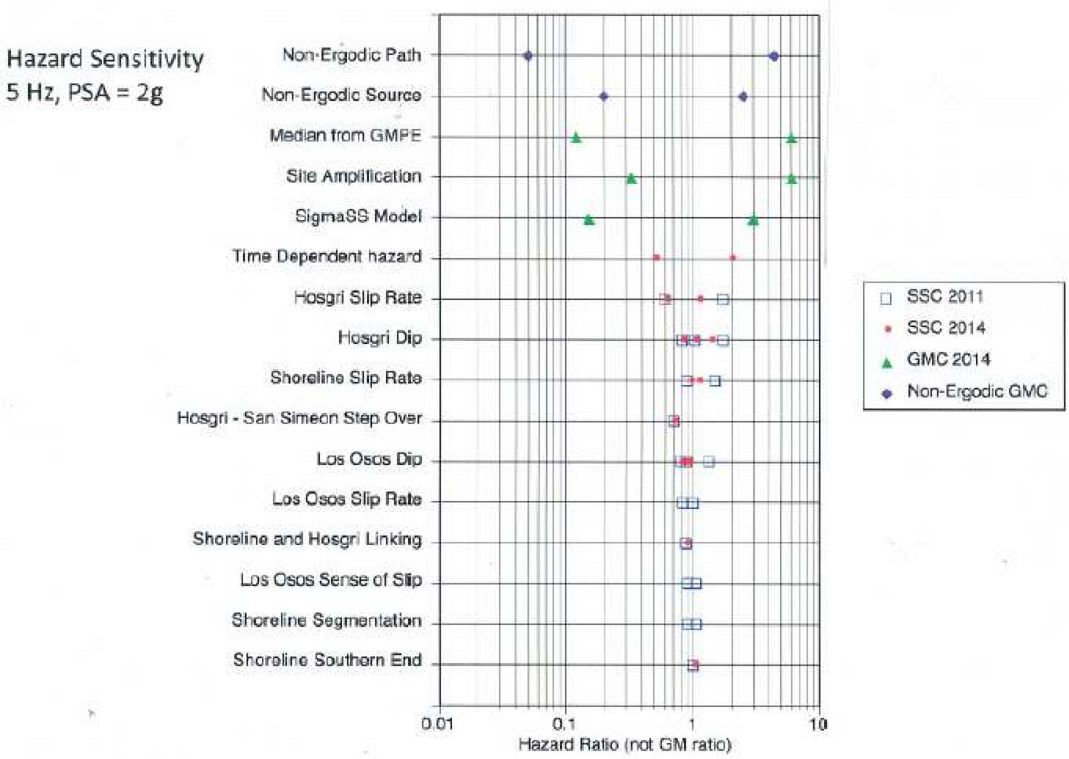


Figure 11. "Tornado Plot" ranking sensitivity of ground motion hazards to uncertainty in input parameters (included in IPRP Report #9, and originally presented by Norm Abrahamson at the January 8, 2015 IPRP public meeting).

CONCLUSIONS

The IPRP requests that PG&E conduct a comprehensive review that includes all fault studies in the region since the previous assessment (PG&E, 2015) and they address the implications for the seismic hazard at DCPP. The IPRP considers the PG&E Update (2024) report incomplete until it has been revised to fully address and clarify the issues and questions raised in this review.

The Hosgri fault is the most important seismic source for the DCPP. New data from the Point Estero area (Cross Hosgri Slope, CHS) indicate a slip rate of 2.6 +/- 0.9 mm/yr based on the offset of a shoreface deposit dated at 12.85 – 11.65 ka. The results from the CHS site provide the highest quality data of the four slip rate sites identified by PG&E along the Hosgri fault, and it is the only site that provides a Holocene-age slip rate. We judge the other slip rate sites to not to represent the current hazard due to the older age range (200 ka to 1.5 Ma) when the fault slip rates were slower than during the Holocene time period. Therefore, we recommend that PG&E give 100% weight to the published CHS slip rate in the Hosgri fault seismic hazard model.

The PG&E (2024) Update report uses the three fault geometry models for the Irish Hills that were previously described in the PG&E (2015a) report. Given the inherent uncertainty in seismic source characterization based on simply weighting multiple models, additional investigation, both onshore and offshore, is warranted to improve our understanding of the Irish Hills faults and the contribution of those faults to the seismic hazard at the DCPP. We recommend that PG&E consider a range of investigative methods, especially onshore subsurface investigation and offshore Chirp seismic reflection profiling with sediment coring.

A recent study of the Casmalia fault, not considered by PG&E, indicates a slip rate that is over 10 times higher than PG&E used in their SSC. Most importantly, this newly published geologic model for the Casmalia fault and the uplift of the Casmalia Hills may inform the style of Quaternary deformation in the region; and provide an analogue for the poorly understood deformation of the Irish Hills. It is our opinion that this new slip rate data should be included in the seismic hazard model for the DCPP. Also, additional offshore investigation of the faults in the Casmalia Hills (where they extend offshore) appears warranted.

Our review of the PG&E (2024) report indicates that the evaluation of new ground motion data and models are thorough, and the methods used to update ground motions are appropriate. It should be understood that our review of hazard calculation focused on the methodologies and not the input parameters from the seismic source characterization. An outstanding issue noted in previous IPRP reports (IPRP Report # 6) is the characterization of site conditions at DCPP. We recommend PG&E improve the characterization of site condition in terms of V_S profile and kappa estimate. We suggest the more traditional approach of site response analysis be carried out to supplement existing analyses. We further encourage PG&E's continuing efforts to reduce uncertainty in empirical site factors, including further improving the non-ergodic ground motion modeling approach and data. The results of site-specific ground motions will likely change when the revisions to the SSC model that the IPRP recommends are adopted. Finally, we would like to see an updated sensitivity analysis, typically presented by PG&E in the form of tornado diagrams, ranking ground motion hazards to uncertainties in revised input parameters.

The IPRP expects PG&E to issue a written response to this initial report within 60 days of its receipt. PG&E's response will be made available to the public on the CPUC's website.

REFERENCES

Al Atik, L., 2015. NGA-East: *Ground-motion Standard Deviation Models for Central and Eastern North America,* Report PEER 2015–07, Pacific Earthquake Engineering Research Center, University of California, Berkeley.

Al Atik, L., Abrahamson, N., Bommer, J.J., Scherbaum, F., Cotton, F., and Kuehn, N., 2010. The variability of ground-motion prediction models and its components: *Seismological Research Letters* **81** (5): 794–801.

Bommer, J.J., Coppersmith, K.J., Coppersmith, R.T., Hanson, K.T., Mangongolo, A., Neveling, J., Rathje, E.M., Rodriguez-Marek, A., Scherbaum, F., Shelembe, R., Stafford, P.J., and Strasser, F.O., 2015. A SSHAC Level 3 probabilistic seismic hazard analysis for a new-build nuclear site in South Africa: *Earthquake Spectra* **31** (2): 661–698.

CNWRA, 2016. Independent Evaluation of the Hosgri Fault Slip Rate based on a Structural Analysis of the Pull-Apart Basin Linking the Hosgri and San Simeon Fault Systems, prepared for U.S. Nuclear Regulatory Commission, Contract No. NRC-HQ;50-14-E-0001, Center for Nuclear Waste Regulatory Analyses, San Antonio, Texas.

Donahue, J., and Abrahamson, N.A., 2014. Simulation-based hanging-wall effects: *Earthquake Spectra* **30** (3): 1269–1284, doi:10.1193/071113EQS200M.

Fugro, 2015a. *Update of the Three-dimensional Velocity Model for the Diablo Canyon Power Plant (DCPP) Foundation Area*, Final Report prepared for PG&E, dated May 2015.

GeoPentech, 2015. *Southwestern United States Ground Motion Characterization SSHAC Level 3: Technical Report, Rev. 2*, Report prepared for Arizona Public Service Company and Pacific Gas and Electric Company, 10 March 2015.

Goulet, C., Bozorgnia, Y., Abrahamson, N., Kuehn, N, Al Atik, L., Youngs, R., and Graves, R., 2018. *Central and Eastern North America Ground-Motion Characterization - NGA-East Final Report*, Report PEER 2018/08, Pacific Earthquake Engineering Research Center, University of California, Berkeley.

Gülerce, Z., and Abrahamson, N.A., 2011. Site-specific design spectra for vertical ground motion: *Earthquake Spectra* **27** (4): 1023-1047.

Hanson, K. L. and Lettis, W.R., 1994, Estimated Pleistocene slip rate for the San Simeon fault zone, south-central coastal California, in, Alterman, I.B., McMullen, R.B., Cluff, L.S., and

Slemmons, D.B. (editors) *Seismotectonics of the Central California Coast Ranges*: Geological Society of America Special Paper 292, P. 133-150.

Hanson, K.L., Wesling, J.R., Lettis, W.R., Kelson, K.I., and Mezger, L., 1994. Correlation, ages,and uplift rates of Quaternary marine terraces, south-central California: in Alterman, I.B.,McMullen, R.B., Cluff, L.S., and Slemmons, D.B. (editors), *Seismotectonics of the Central California Coast Ranges*: Geological Society of America Special Paper 292, P. 45–72.

Idaho National Laboratory (INL), 2022. *Idaho National Laboratory Sitewide SSHAC Level 3 Probabilistic Seismic Hazard Analysis*, Technical Report INL/RPT-22-70233, dated November 2022, 2487 pp.

IPRP Reports No. 5, Nos. 7-13 and 15: available at: https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/electric-costs/diablo-canyon-independent-peer-review-panel

Johnson, S. Y., S. R. Hartwell, and P. Dartnell. 2014. "Offset of latest Pleistocene shoreface reveals slip rate on the hosgri strike-slip fault, offshore central California." *Seismol. Soc. Am. 104* 1650-1662.

Johnson, S.Y., Watt J.T., Hartwell S.R., Kluesner J.W. 2018. "Neotectonics of the Big Sur Bend, San Gregorio-Hosgri Fault System, Central California." *Tectonics* 1930-1953.

Kamai, R., Abrahamson, N., and Silva, W., 2013. *Nonlinear Horizontal Site Response for the NGA-West2 Project*, Report PEER 2013-12, Pacific Earthquake Engineering Research Center, University of California, Berkeley.

Kluesner, J.W., Johnson, S.Y., Nishenko,S.P., Medri, E., Simms, A.R., Greene, H.G., Gray, H.J.,Mahan, S.A., Padgett, J.S., Krolczyk, E.T., Brothers,D.S., and Conrad, J.E. 2023. "High-resolution geophysical and geochronological analysis of a relict shoreface deposit offshore central California: Implications for slip rate along the Hosgri fault." *Geosphere* v.19, no. 6, p.1788-1811.

Lettis, W. R., Kelson, K. I., Wesling, J. R„ Angell, M„ Hanson, K. L„ and Hall, N. T„ 1994, Quaternary deformation of the San Luis Range, San Luis Obispo County, California, *in* Alterman, I. B„ McMullen, R. B„ Cluff, L. S„ and Slemmons, D. B„ eds., *Seismotectonics of the Central California Coast Ranges*: Geological Society of America Special Paper 292, p. 111-132.

McGregor, I.S., and Onderdonk, N.W., 2021, Late Pleistocene rates of rock uplift and faulting at the boundary between the southern Coast Ranges and the western Transverse Ranges in California from reconstruction and luminescence dating of the Orcutt Formation: Geosphere, v. 17, no. 3, p. 932– 956, https://doi .org /10.1130/GES02274.1.

Medria, E., Simms A.R., Kluesner J., Johnson S.Y.,. 2023. "Subaqueous clinoforms created by sandy wave-supported gravity flows:." *Marine Geology* 13.

Muhs, D.R., Simmons, K.R., Schumann, R.R., Groves, L.T., Laurel, D., and Mitrovica, J.X., 2012, Sea-level history during the Last Interglacial complex on San Nicolas Island, California: Implications for glacial isostatic adjustment processes, paleozoogeography and tectonics: *Quaternary Science Reviews* v. **37**, p. 1–25.

Natrium Demonstration Project (Natrium), 2024. *Natrium SSHAC Level 3 Probabilistic Seismic Hazard Analysis*, Report under review.

NUREG. 2018. *Updated Implementation Guidelines for SSHAC Hazard Studies.* NUREG-2213, p.145, U.S. NRC.

O'Connell, D.H. Turner, J. 2023. "Hosgri Fault Transpressional Slip Rates Reproduce Observed Central California Coast Uplift Rates." *The Seismic Record 3, (3)* 182-193., doi: 10.1785/0320220047.

Pacific Engineering and Analysis (PE&A), 2015. *Development of amplification factors for the Diablo Canyon Nuclear Power Plant: Site-wide profiles*, Report to PG&E, 24 November.

Pacific Gas and Electric Company (PG&E), 2015a, Seismic Source Characterization for the Diablo Canyon Power Plant, San Luis Obispo County, California, report on the results of a SSHAC level 3 study, Rev. A, unpublished technical report, dated March, 2015.

Pacific Gas and Electric Company (PG&E), 2015b. Response to NRC request for information pursuant to 10 CFR 50.54(f) regarding the seismic aspects of recommendation 2.1 of the near term task force review of insights from the Fukushima Dai-ichi accident: in *Seismic Hazard and Screening Report, Diablo Canyon Power Plant, Units 1 and 2,* PG&E Letter DCL-15-035 to U.S. Nuclear Regulatory Commission, 11 March.

Pacific Gas and Electric Company (PG&E), 2015c. *Response to NRC request for additional information dated October 1, 2015, and November 13, 2015, regarding recommendation 2.1 of the near-term task force seismic hazard and screening report*, PG&E Letter DCL-15-154 to U.S. Nuclear Regulatory Commission, 21 December.

Pacific Gas and Electric Company (PG&E), 2017a. *Development of FIRS for Unit 1 and Unit 2 Containment Turbine Building, and AUX Building*, PG&E Geosciences Calculation No. GEO.DCPP.CAL.16.01, 14 April.

Pacific Gas and Electric Company (PG&E), 2017b. *Updated DCPP GMRS Using the Analytical and Empirical Site Term Approaches*, PG&E Geosciences Calculation No. GEO.DCPP.15.02, Revision 3, 9 October.

Pacific Gas and Electric Company (PG&E), 2024, Diablo Canyon Updated Seismic Assessment, Response to Senate Bill 841, unpublished technical report, dated February 1, 2024.

Pacific Northwest National Laboratory (PNNL), 2014. *Hanford Sitewide Probabilistic Seismic Hazard Analysis*, Report prepared for the U.S. Department of Energy, November.

Simms, A. R., Rouby, H., and Lambeck, K., 2016, Marine terraces and rates of vertical tectonic motion: The importance of glacio-isostatic adjustment along the Pacific coast of central North America: Geological Society of America Bulletin, v. 128, p. 81-93.

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