Independent Peer Review Panel

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CALIFORNIA GOVERNOR'S OFFICE OF EMERGENCY SERVICES
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CALIFORNIA SEISMIC SAFETY COMMISSION, COUNTY OF SAN LUIS OBISPO

IPRP Report No. 6, August 12, 2013

Site shear wave velocity at Diablo Canyon: summary of available data and comments on analysis by PG&E for Diablo Canyon Power Plant seismic hazard studies

BACKGROUND

In 2006, the California Legislature enacted Assembly Bill (AB) 1632, which was codified as Public Resources Code Section 25303. AB 1632 directed the California Energy Commission (CEC) to assess the potential vulnerability of California's largest baseload power plants, which includes Diablo Canyon Power Plant (DCPP), to a major disruption due to a major seismic event and other issues. In response to AB 1632, in November 2008 the CEC issued its findings and recommendations in its AB 1632 Report, which was part of its 2008 Integrated Energy Policy Report Update.

In Pacific Gas and Electric Company's (PG&E) 2007 General Rate Case decision D.07-03-044, the California Public Utilities Commission (CPUC) directed PG&E to address and incorporate the recommendations from the AB 1632 Report into its feasibility study to extend the operating licenses of its Diablo Canyon Units 1 and 2 for an additional 20 years.

In November 2009, PG&E submitted its formal application with the Nuclear Regulatory Commission (NRC) to extend the licenses of DCPP Units 1 and 2. In 2010 PG&E filed for cost recovery with the CPUC for expenditures associated with the enhanced seismic studies recommended by the CEC's AB 1632 Report. The motions for cost recovery were subsequently approved in 2010 and 2011. CPUC Decision D.10-08-003, issued on August 16, 2010, established that the CPUC would convene its own Independent Peer Review Panel (IPRP) and invite the CEC, the California Geological Survey (CGS), the California Coastal Commission, and the California Seismic Safety Commission to participate on the panel. Under the auspices of the CPUC, the IPRP is conducting an independent review of PG&E's seismic studies including independently reviewing and commenting on PG&E's study plans and the findings of the studies.

The comprehensiveness, completeness, and timeliness of these studies will be critical to the CPUC's ability to assess the cost-effectiveness of Diablo Canyon's proposed license renewal. As noted in the CEC's AB 1632 Report, a major disruption because of an earthquake or plant aging could result in a shutdown of several months or even cause the retirement of one or more of the plants' reactors. A long-term plant shutdown would have economic, environmental and reliability implications for California ratepayers.

In contrast to previous reports of the IPRP, which commented on studies by PG&E to investigate potential earthquake sources near Diablo Canyon, this report focuses on the site amplification factor - an important factor in the calculation of ground motion from any earthquake. The report summarizes data that are available to constrain the site amplification factor and uncertainties in its value, and then provides comments on analyses performed by PG&E using their preferred method of considering that parameter. We chose to focus on site amplification at the Diablo Canyon site because "site conditions" modify earthquake shaking from any earthquake. In sensitivity studies by CGS for the IPRP, site amplification factor has a large effect on calculated seismic shaking potential at DCPP.

INTRODUCTION

Estimated ground motion hazards can be altered significantly by site conditions, and different methods used to incorporate the effects of site conditions often result in different ground motion estimates. Three approaches have been used in engineering practice to incorporate the effects of site conditions on estimated ground motion hazards: 1. Scaling based on soil classifications, for example, the National Earthquake Hazards Reduction Program (NEHRP) site classifications used in building codes; 2. Using ground motion prediction equations (GMPEs) that incorporate the average shear wave velocity of the uppermost 30 meters of a site (V_{S30}) as an approximation for site condition; and 3. Site response analyses using near surface site-specific or generic soil profiles. The NEHRP scaling approach is simple, conservative, and often used only for an approximate estimation of design ground motion values. In most modern GMPEs, such as the Next Generation Attenuation (NGA) relations, V_{S30} is treated as an independent variable along with earthquake magnitude, site-to-source distance, etc.; and ground motions for a specific site are calculated by entering the site-specific V_{S30} value directly in the GMPEs. For sites with V_{S30} values outside the data range that adequately constrains the GMPEs, however, direct use of V_{S30} in GMPEs may not be appropriate. In such cases, other methodologies, such as site response analysis, are utilized.

PG&E uses a new method to incorporate site effects based on recorded ground motions at Diablo Canyon. A site amplification term has been developed based on ground motion residuals at the site from two locally recorded earthquakes. Uncertainty in site amplification is based on the epistemic uncertainty due to systematic differences in the site amplification between sites with the same V_{S30} in a single station sigma approach. Compared to traditional approaches, the PG&E method resulted in lower ground motion hazard estimates, particularly in the spectral period range important to DCPP (3.5 to 8 Hz), as reported in the Shoreline Fault Report (SFR) (PG&E 2011a). The PG&E method is based on state-of-the-art research and is technically sound. However, additional data, clarification, and documentation are required to justify the applicability of the method to the DCPP site.

In this memo, we summarize PG&E's determination of the mean site V_{S30} value and discuss variability in near surface shear wave velocity (V_S) illustrated in PG&E data. We demonstrate that a lower V_{S30} value is more consistent with other soft rock sites in California and is within the range of uncertainty observed at the DCPP site. A lower V_{S30} brings the estimated ground motion hazards beyond the original design level when used in typical, state-of-the-practice seismic hazard analysis using GMPE's. Given the significant effects of site V_{S30} value and uncertainty in near surface V_S on ground motion estimation using a traditional approach, we suggest that PG&E present an evaluation on whether the large uncertainty in near surface V_S is captured adequately in their site amplification approach that is based on two historical earthquakes and the single station sigma concept.

DCPP SITE V_{S30} VALUES

PG&E determined that the DCPP power block foundation has a mean V_{S30} value of approximately 1,200 m/s, corresponding to a hard-rock site. This mean V_{S30} value was determined based on downhole velocity surveys in four deep boreholes (Figure 1) near the power block conducted in 1978 as part of the PG&E Long Term Seismic Program (LTSP) and two velocity profiles measured in 1998 at the Independent Spent Fuel Storage Installation (ISFSI) site as part of the ISFSI site characterization (Figure 2). The ISFSI site is located approximately 400 m away from

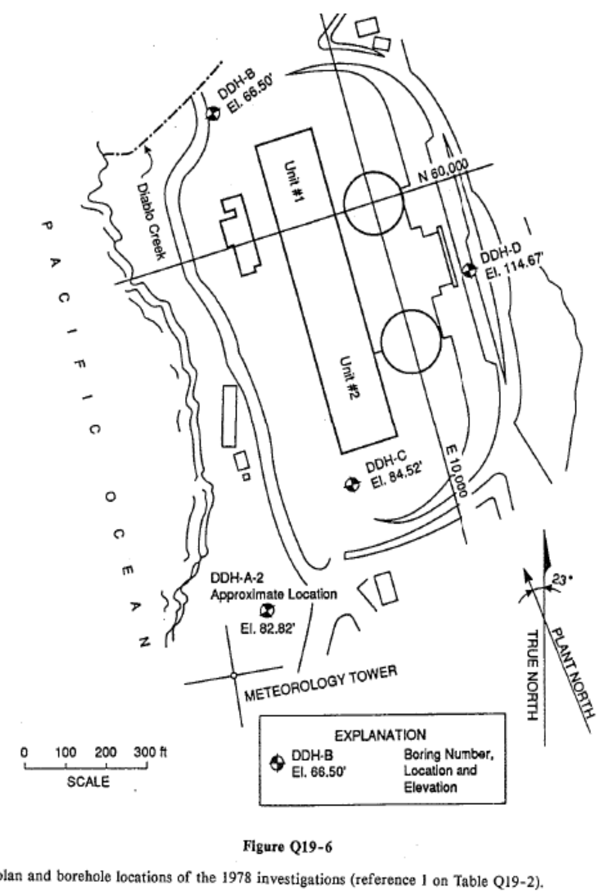


Figure 1. Location of four downhole velocity survey boreholes near the power block (provided by PG&E).

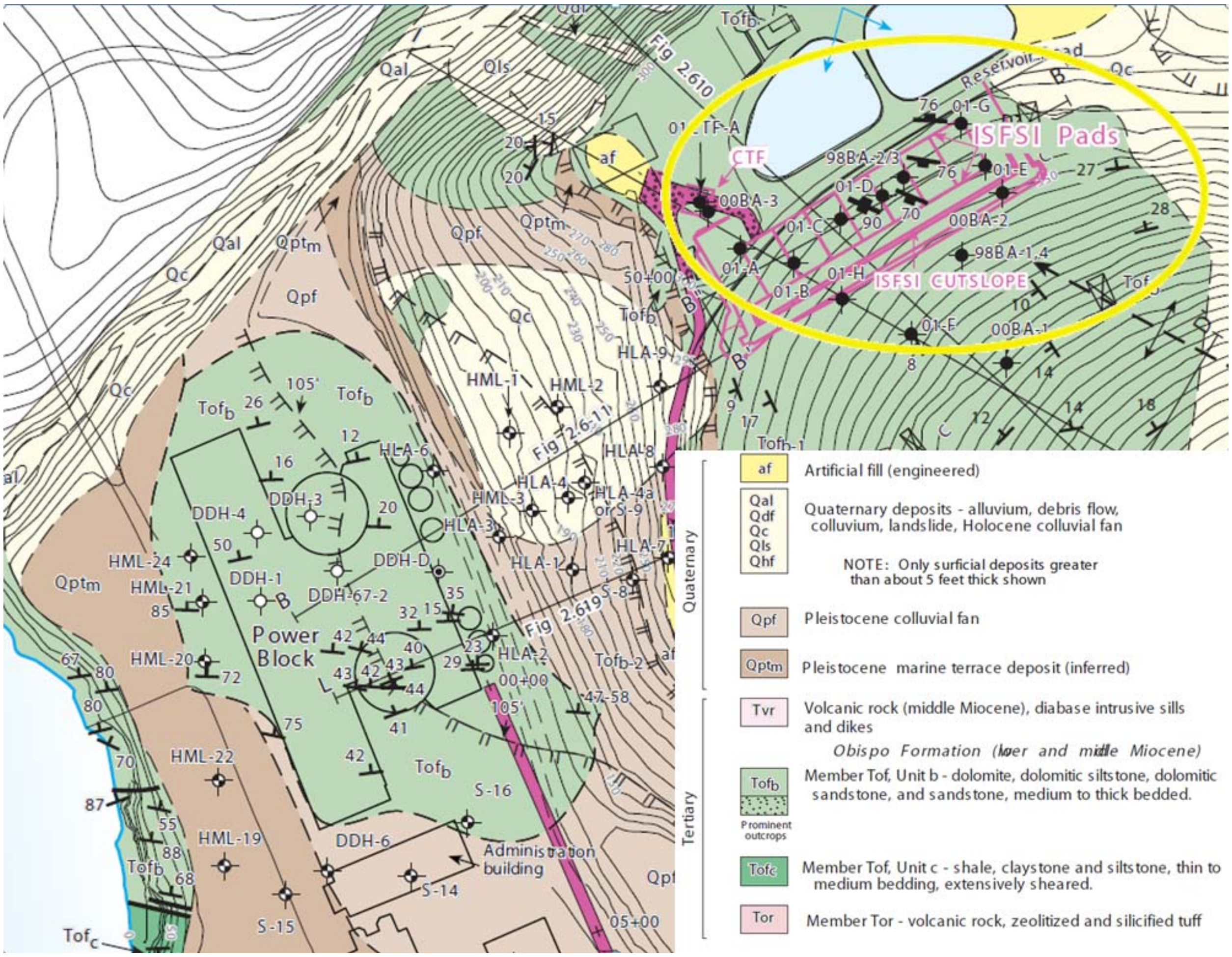


Figure 2. Location of ISFSI site (provided by PG&E). The two ISFSI boreholes were located in the highlighted area.

the power block. V_{S30} values were determined to be 1,212 m/s, 1,228 m/s, and 1,215 m/s for the mean 1978 profile near the power block and the two 1998 profiles at the ISFSI site. PG&E noted that the accuracy of the computed V_{S30} values for the ISFSI site is a few percent because the digitization of the ISFSI profiles has a limited accuracy of a few percent. The accuracy of the 1978 profile at the power block is not determined. PG&E also noted that the V_{S30} value of 1,200 m/s is at the power block embedment depth of 32.4 ft (or approximately 10 m) determined by the lower range of the original surface elevation of 85 ft (from mean sea level) minus the power block foundation elevation of 52.6 ft. We note that according to Figure 5-3 in the DCPP LTSP report (PG&E, 1991) (reproduced as Figure 3 in this memorandum), 52.6 ft represents the deepest part of the power block foundation. A considerable portion of the Turbine Building and Containment Structure is located less than 10 m from the surface and the Auxiliary Building is approximately at the level of the down-slope surface (i.e., elevation of 85 ft). A conservative measure would assume that these structures are located on the

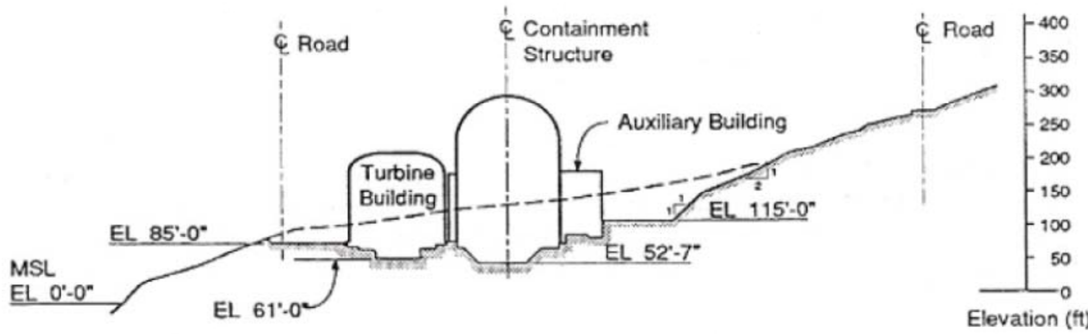


Figure 3. Cross section of DCPP (Figure 5-3 in DCPP LTSP report, PG&E, 1991). The dashed curve is the original ground surface.

ground surface. V_{S30} for the ground surface would be lower than at 10 m depth. PG&E indicated during meetings with IPRP that soil structure interaction (SSI) analysis is used to estimate ground motions at different elevations (or embedment levels), and the SSI analyses will incorporate a range of site-specific V_S profiles.

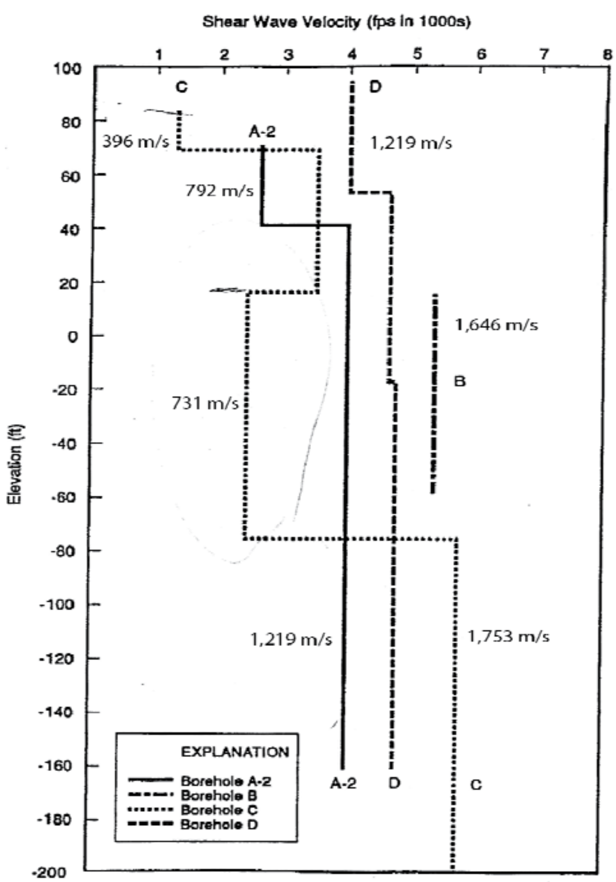


Figure 4. Shear wave velocity profiles from 1978 downhole velocity surveys (provided by PG&E).

In response to our request for additional information on the V_S measurements near the power block, PG&E provided the IPRP with its response to an NRC request for additional information (RAI) made in January 1989 (Question 19) that included shear wave measurements in the four deep boreholes drilled in 1978 near the power block (provided by Richard Klimczak via email dated April 22, 2013). Figure 4 shows these V_S profiles. Considerable variability in measured V_S is observed in this figure. For example, at mean sea level (zero elevation), the measured V_S varies from 731 m/s to 1,646 m/s, a range of over 900 m/s, over a depth range of 80 ft (≈ 24 m). According to PG&E's calculation (Excel spreadsheet file provided by Richard Klimczak via email dated April 22, 2013), V_{S30} values from these four boreholes are 981 m/s, 1,646 m/s, 764 m/s and 1,347 m/s. The shear-wave velocity profile from borehole "B", however, does not include any measurement from within 80 feet of the surface, so is not appropriate for use in calculating V_{S30}. Excluding borehole "B", the mean is 1,031 m/s and standard deviation is 295 m/s, but even this mean is probably higher than the actual V_{S30} at the site. Borehole "C" includes no velocity measurements within 15 feet of the surface and Borehole "A-2" includes no velocity measurements within 30 feet of the surface. Considering that near-surface weathered rock is almost always lower in velocity than deeper unweathered rock, both the mean velocity and range of velocities in the upper 10 m are probably overestimates. In its response to the NRC RAI, PG&E developed a mean V_S profile and lower and upper bounds based on the four 1978 boreholes. Previous soil-structure interaction analyses using this range of uncertainty in V_S profiles found a significant effect of uncertainty in near surface V_S on soil-structure interaction. This effect may have been underestimated because of overestimates of Vs at shallow depths in the average profile by PG&E. Considering the three usable measured profiles, A-2, C, and D, the mean value at 10 m is approximately 800 m/s, considerably below PG&E's mean of 1200 m/s. A mean value at 5 m is problematic because only profiles C and D measured velocities at that depth. If A-2 had the same velocity as C at a depth of 5 m, consistent with the relative weathering described in the borehole logs, the mean velocity at that depth would be about 650 m/s, also below PG&E's mean value of 1000 m/s. The lower bound profile also appears to be overestimated at all depths because it approximates the measured velocities in borehole C. With only three profiles, it is unlikely that one of them represents the lowest velocity material underlying the plant. Some of the variability seen in the 1978 data may reflect poor quality of the V_S measurements made 35 years ago. Interpretations of that data, however, appear to include unconservative assumptions of velocity in boreholes where no velocity was recorded in the upper parts of the soil profile. Alternative interpretations suggest overall lower velocity of the rock underlying the plant and greater variability of velocity across the plant footprint. A complete consideration of site conditions across the plant footprint requires additional V_S measurements using modern technology to constrain the uncertainty and yield more reliable site V_S values.

PG&E relied on the two newer profiles at the ISFSI site to justify the use of a mean V_{S30} value of 1,200 m/s because both the ISFSI and the power block are located on the same geologic unit (the Miocene Obispo Formation, which is composed of tuffaceous and diatomaceous sandstone and silty sandstone). Although the V_{S30} values derived from the two V_S profiles at the ISFSI site (1,228 m/s and 1,215 m/s) are consistent with a V_{S30} of 1,200 m/s, these two profiles do not give consistent V_S measurements at given depths. Considerable variability exists at some depth ranges (see Figure 5). V_{S30} values from these two boreholes would be 993 m/s and 1,214 m/s, respectively, if calculated from the surface instead of from 10 m depth. While these two measurements support the high velocity measured in borehole D in 1978, they do not help constrain the lower bound or range of velocity at the plant site.

Geological formations elsewhere in California that are similar to the formations at the power block and the ISFSI site show considerable variation in V_{S30} values. Tertiary sandstone measured in California have an average V_{S30} of 555 m/s and Tertiary volcanic rocks have an average V_{S30} of 609 m/s (Wills and Clahan, 2006). Since the Obispo Formation at the power plant is relatively well indurated sandstone, above average V_{S30} values are expected, but 1,200 m/s is higher than the expected range of values for this type of rock. Additional V_S measurements near the power block would give better assurance that variability in site V_{S30} value as well as near surface V_S profile is adequately captured and the values used in hazard analysis are well constrained, particularly because the rock at the DCPP site is both faulted and folded, leading to greater variability.

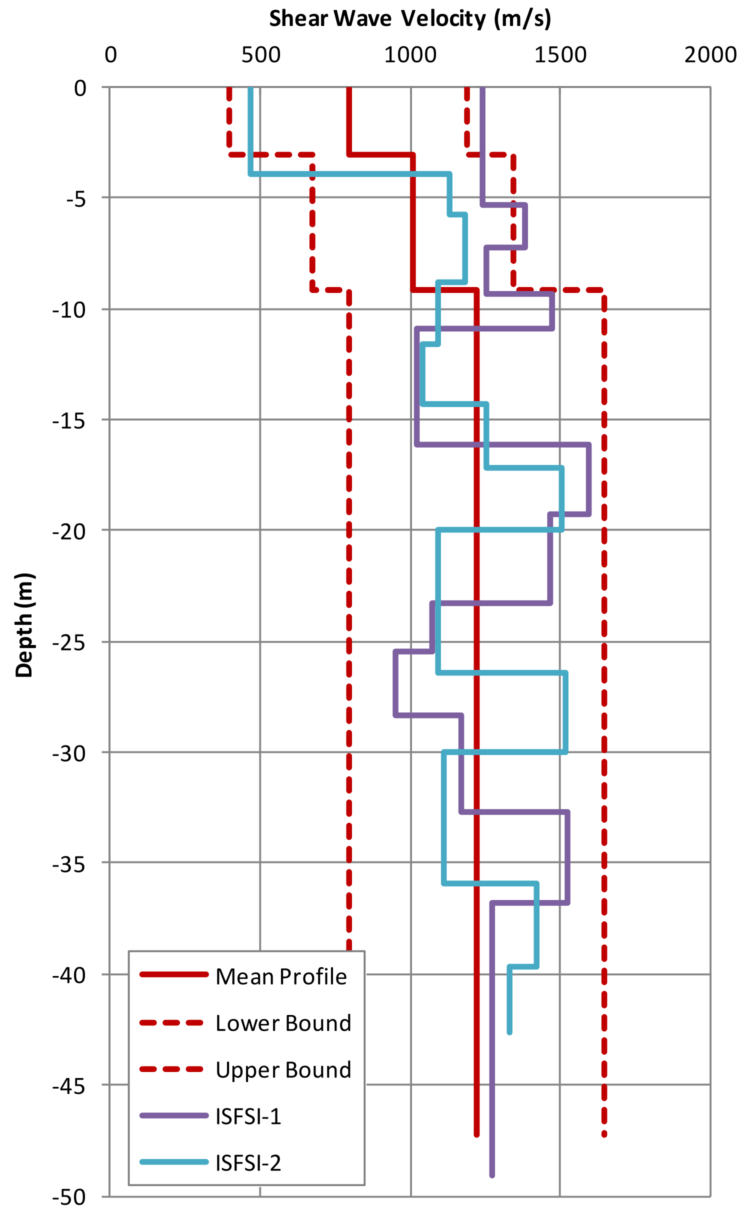


Figure 5. Mean shear wave velocity profile and uncertainty from 1978 downhole velocity surveys and the simplified shear wave velocity profiles from ISFSI borings (plotted using data provided by PG&E).

PG&E APPROACH FOR HARD-ROCK SITE EFFECTS

PG&E used an indirect approach to account for hard rock effects. The PG&E approach includes: (1) using the NGA relations to calculate median ground motions and associated standard deviations for a generic “firm rock” condition with V_{S30} of 760 m/s, and (2) using amplification factors derived by Silva (2008) from generic site response analyses for hard-rock sites to adjust the NGA-predicted median (for a V_{S30} of 760 m/s) to a generic hard-rock condition (V_{S30} of 1,200 m/s). PG&E stated that the reason it did not use NGAs to calculate ground motion for V_{S30} of 1,200 m/s is because this V_{S30} value is outside of the range of V_{S30} that is well constrained by the empirical data used to derive the NGAs. Silva (2008) derived amplification factors relative to a V_{S30} of 1,100 m/s for 64 cases with different velocity profiles, including rock profiles. PG&E chose two of Silva’s 64 cases (Cases 61 and 64 with V_{S30} of 760 m/s and 3,150 m/s, respectively) as relevant to the DCPP site based on similarity in kappa (κ) values (approximately 0.04 second, PG&E determined that κ for the DCPP site is 0.042 second). It was determined from these two cases that the site amplification is close to a linear function with site V_{S30}. Therefore, the amplification factors from V_{S30} of 760 m/s to 1,100 m/s were used to extrapolate to the DCPP site (V_{S30} of 1,200 m/s). The raw values were smoothed and are shown in Figure 6-6 of the SFR (PG&E, 2011a). Values of hard rock amplification factors (a_1) are listed in Table 6-5 of SFR.

As indicated in the SFR, κ of 0.04 second is the justification for using the Silva (2008) generic amplification factors for the DCPP site. However, in the NGA dataset, κ of about 0.04 second is found for generic soft-rock sites in California. For hard-rock sites, the κ values can be much smaller (0.01 – 0.02 second).

There is an inconsistency in the DCPP site condition indicated by the site-specific V_{S30} value of 1,200 m/s (hard rock) and by the site-specific κ value of 0.042 second (soft rock). This inconsistency makes application of the Silva (2008) scaling factors questionable. Furthermore, the κ value for the DCPP site isn’t well constrained, as discussed in the next section. However, the Silva (2008) scaling factors were used mainly to compute event-corrected ground motion residuals to derive site-specific site amplification terms using the new site amplification approach, as discussed in a later section.

KAPPA AND DCPP KAPPA VALUE

κ is a seismological parameter that reflects the observable high frequency decay of Fourier amplitude spectra in ground-motion recordings. Although the Fourier amplitude spectra of recorded ground motions are usually jagged, their characteristic shapes can be seen more easily when they are plotted on logarithmic scales. Fourier acceleration amplitudes tend to be largest over an intermediate range of frequencies bounded by the corner frequency on the low side and the cutoff frequency on the high side. The corner frequency is shown theoretically (Brune, 1970) to be inversely proportional to the cube root of the seismic moment. Therefore, smaller magnitudes have higher corner frequencies and large earthquakes produce greater low-frequency motions than do smaller earthquakes.

Anderson and Hough (1984) characterized the shape of the spectrum at high frequencies as exponentially decaying, given by:

$$a(f) = A_0 \exp(-\pi \kappa f) \qquad \text{for } f > f_E$$

where f_E is a frequency above which the decay is approximately linear on a plot of log amplitude against linear frequency, A_0 is Fourier amplitude, which is dependent on source and propagation path, and κ controls the rate of amplitude fall-off with frequency.

Although κ is accepted as a parameter representing the behavior of Fourier spectra at high frequencies, the mechanism causing this observed fall-off is under debate. Hanks (1982) suggested site effects in near-surface materials; Papageorgiou and Aki (1983) prefer a source-dependency (source does not produce high frequencies due to fault nonelasticity); Anderson and Hough (1984) found that κ increases with epicentral distance; and Tsai and Chen (2000) suggested a combined effect of source, distance, and site, with the distance being the least significant of the three. To obtain a more meaningful parameter, the distance dependency can be eliminated by extrapolating the $\kappa(r)$ trend to zero epicentral distance (r = 0). The intercept, κ_0, is believed to denote the site attenuation a few kilometers immediately beneath the station (Hough et al., 1988). κ_0 is a commonly applied high-frequency filter parameter. Silva and Darragh (1995) show that near-source attenuation modeled through κ mainly influences response spectra content for frequencies greater than about 5-10 Hz. Average κ_0 value is 0.037 second for western North America and 0.008 second for eastern North America, demonstrating the difference in rock spectral content in eastern and western North America. Houtte et al. (2011) observed predominant influences of superficial layers of soil on κ_0. Although small, a source component of κ_0 is clearly observable. κ_0 is often calculated from ground motion recordings as the fitted slope of Fourier amplitude spectra. It can also be estimated from site material properties.

An alternate approach was used to determine the κ value at the DCPP site. PG&E (2011a) used the stochastic point source model of Boore (2000) with a κ value of 0.042 second and stress drop of 120 bars to simulate ground motions of a 2003 M3.4 Deer Canyon earthquake at a hypocentral distance of 7.8 km. Because the resulting response spectrum compares well with the average horizontal spectrum of the free-field recordings at the DCPP from the 2003 M3.4 Deer Canyon earthquake, κ value for the DCPP site is said to be 0.042 second. This κ value is not well constrained. It is not clear why κ isn't calculated by fitting the Fourier spectrum of the recorded motions or estimated from material properties as noted above.

PG&E APPROACH TO SITE-SPECIFIC AMPLIFICATION

In the SFR, PG&E derives site-specific amplification factors based on recorded ground motion data from two earthquakes: the 2003 M6.5 San Simeon earthquake and the 2004 M6.0 Parkfield earthquake. Site-specific amplification factors are derived for each earthquake event through the following procedure: (1) Determine event terms for a suite of frequencies. For each frequency, the event term is the average of residuals (within-event residuals) from recordings within a chosen distance range that approximately centers on the rupture distance at the DCPP site. The event term is meant to remove source-specific effects; (2) GMPEs are used to calculate median ground motions from the earthquake for the DCPP site rupture distance and a V_{S30} of 760 m/s. The GMPE-predicted median ground motions are corrected by the event term from step 1 and scaled to a generic free-field site condition with V_{S30} of 1,100 m/s (reference V_{S30}), representative of surface V_{S30} value at the DCPP site, using Silva (2008) scaling factors; (3) The average median spectra from all GMPEs (from step 2, event term corrected and V_{S30} scaled) are compared with the observed free-field ground motion spectrum at the DCPP site and the differences (i.e., event-term corrected residuals) represent site-specific amplification compared to a generic site with the reference V_{S30} value. Finally, site-specific amplification factors are determined as the mean residuals from the two available earthquakes (averaged period by period and smoothed over a period range). The values of the smoothed mean residuals (i.e., site-specific amplification factors, a_2, for reference V_{S30} of 1,100 m/s) are listed in Table 6-7 of SFR. Because a_2 in Table 6-7 of SFR is derived for reference V_{S30} of 1,100 m/s (DCPP surface condition), the overall site amplification factor for NGA medians calculated with V_{S30} of 760 m/s to DCPP surface condition is the sum of a_2 in Table 6-7 plus a_1 for V_{S30} of 1,100 m/s in Table 6-5 of SFR. The overall amplification factor for NGA medians calculated with V_{S30} of 760 m/s to the DCPP power block foundation is approximated as a_2 in Table 6-7 plus a_1 for V_{S30} of 1,200 m/s in Table 6-7 of SFR. Note that a_1 and a_2 in these SFR tables are in natural log units. The overall amplification factor in linear units is the exponential of a_1+a_2 and is reproduced in Figure 6 (solid curve) of this report.

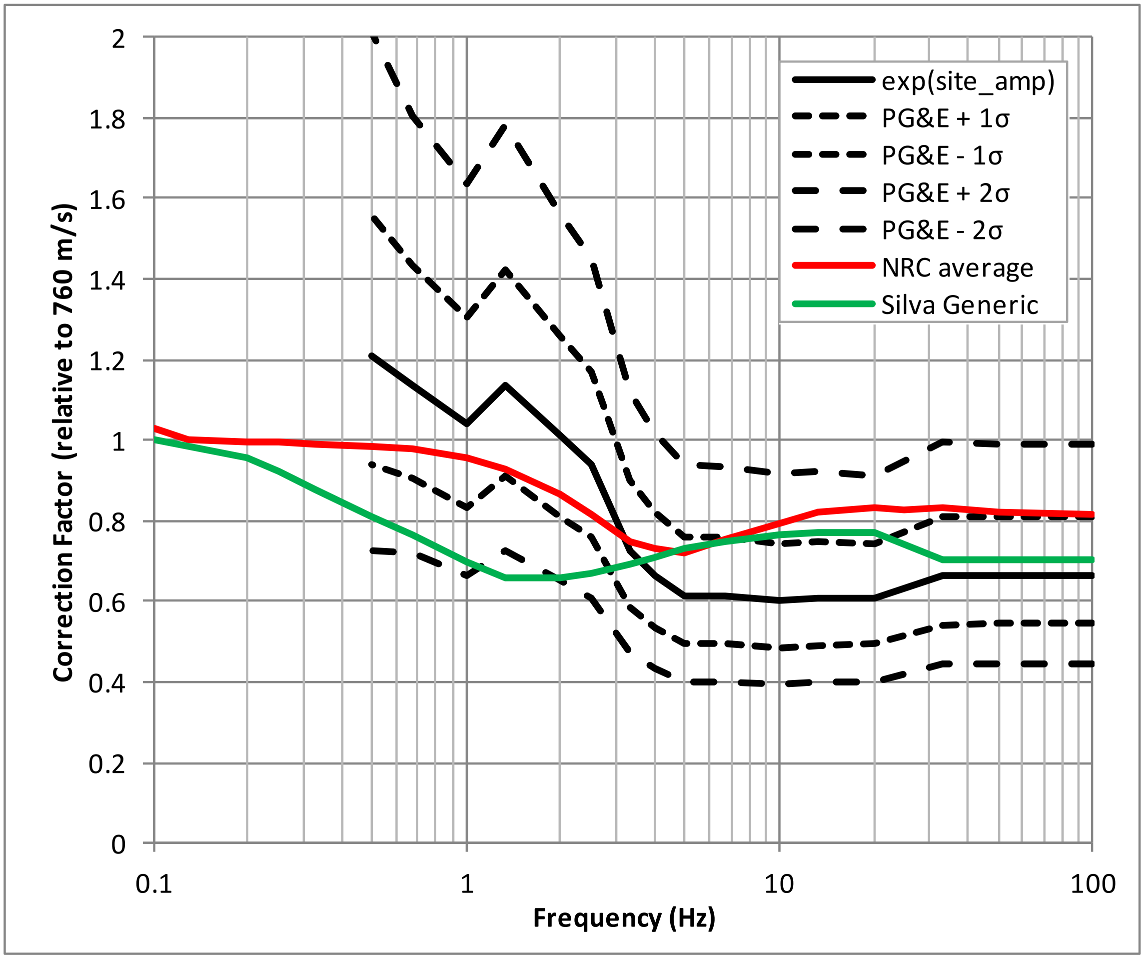


Figure 6. Site-specific amplification relative to V_{S30} of 760 m/s and associated uncertainty (reproduced based on presentation by Norm Abrahamson on June 6, 2013). exp(site_amp) is the exponential of PG&E site amplification term and is used to scale GMPE median predictions, and σ is standard deviation applied to PG&E site amplification term.

The uncertainty in the mean residual value (i.e., epistemic uncertainty in site-specific amplification factor) has a variance of $\sigma_{S2S}^2(T)/N$, where *N* is number of observations (i.e., earthquake events) and $\sigma_{S2S}^2(T)$, termed site-to-site uncertainty in the single station sigma approach, is the variance of the epistemic uncertainty due to systematic differences in the site amplification between sites with the same V_{S30} value. $\sigma_{S2S}(T)$ is calculated as:

$$\sigma_{S2S}^2(T) = \sqrt{\sigma^2(T,M) - \sigma_{SS}^2(T,M)}$$

where $\sigma^2(T,M)$ is the standard deviation given by GMPEs. It is a function of earthquake magnitude, *M*, and is often given as discrete values for a series of spectral periods (*T*). $\sigma_{SS}(T,M)$ is single station sigma, representing a reduced standard deviation for single sites. In the SFR, PG&E used a preliminary model for single station sigma derived for the NGA models (BCHydro, 2010):

$\sigma_{SS}(T, M) = (0.87 + 0.0037\ln(T))\sigma(T, M)$

In the SFR, $\sigma_{S2S}(T)$ is averaged over M6, M6.5, and M7 to capture standard deviation for the magnitudes relevant for the DCPP site. It also is averaged over the five NGA models used for DCPP ground motion hazard studies. $\sigma_{S2S}^2(T)/N$ for the DCPP site is listed in the last column in Table 6-7 of the SFR. In the SFR, this epistemic uncertainty on site amplification is combined with ground motion aleatory uncertainty in the ground motion hazard calculation for computational efficiency. PG&E indicated that in future analyses this epistemic uncertainty will be accounted for using the standard logic-tree approach for epistemic uncertainties, and the range of ±2 standard deviations will be considered. This uncertainty range also is reproduced in Figure 6 of this report for reference.

In the single station sigma approach employed in SFR, ground motion hazards are calculated by integrating a lognormal distribution with single station sigma as the standard deviation instead of the standard deviation from GMPEs.

NRC REVIEW OF PG&E SITE EFFECTS

In its review of PG&E's SFR, the Nuclear Regulatory Commission (NRC, 2012) concluded that PG&E's site-specific V_{S30} value of 1,200 m/s is reasonable. This conclusion is based on evaluation of the same three velocity profiles used by PG&E. The NRC agreed that using such a high V_{S30} value with the NGAs would not be appropriate. The NRC staff considered PG&E's scaling approach for incorporating site effects appropriate. However, it questioned the applicability of the specific scaling factors and developed an independent set of site correction factors based in its independent site response analyses using PG&E's near surface V_S profile. The NRC site correction factors are plotted in Figure 6 (red curve) for comparison. Also plotted in Figure 6 is Silva's (2008) factor (i.e., a_1) for scaling from a generic site with V_{S30} of 760 m/s to a generic hard rock site with V_{S30} of 1,200 m/s. This figure shows that within the period range important to DCPP, the NRC correction factor is similar to the Silva amplification factor for generic hard rock sites, and DCPP site-specific amplification factor is lower than both the NRC and Silva factors for frequency greater than 4 Hz.

EFFECTS OF SITE AMPLIFICATION FACTORS ON ESTIMATED DCPP GROUND MOTION HAZARDS

To demonstrate the significant effect of site amplification on estimated ground motion hazards at the DCPP site, we reproduced PG&E's deterministic ground motions (dashed curves in Figure 7) for the four main fault sources (the Hosgri fault, Los Osos fault, Shoreline fault, and San Luis Bay fault) and then did the same analysis for other site conditions. For dipping faults, the cases with the lowest estimated dip angles were analyzed. Table 1 lists input parameters for these deterministic calculations. These calculations used the same four NGAs used by PG&E: Boore and Atkinson (2008), Campbell and Bozorgnia (2008), Chiou and Youngs (2008), and Abrahamson and Silva (2008). Figure 7 compares PG&E 84th percentile deterministic ground motions (dashed curves) with those from three sensitivity cases (solid curves in Figures 7a, 7b, and 7c). The PG&E 1991 LTSP/SSER 34, the 1977 HE (Hosgri Earthquake) design spectrum, and the frequency range important to DCPP structures (marked by vertical dark grey lines) are plotted for reference. The PG&E calculation uses PG&E site-specific amplification factors derived from ground motion residuals, epistemic uncertainty in site-specific amplification factors, and single station sigma. The three sensitivity cases are: (i) a generic site with V_{S30} of 1,200 m/s (scaled from GMPE-predicted median for V_{S30} of 760 m/s using Silva scaling factors, single station sigma); (ii) a generic site with V_{S30} of 760 m/s (GMPE-predicted median without scaling) using single station sigma; and (iii) a generic site with V_{S30} of 760 m/s (GMPE-predicted median without scaling) using sigma from GMPEs (i.e., ergotic sigma). This figure shows significant effects of site condition

Table 1. PG&E selected deterministic earthquake scenarios (modified from Table 6-8 of the Shoreline Fault Report)

Fault Source	Magnitude[1]	Dip (º)	Rupture Distance (km)[2]			Sense of slip[3]
			R_{Rup}	R_{JB}	R_X	
Hosgri	7.1	80	4.9	2.3	4.9	Strike Slip
Los Osos	6.8	45	7.6	0.0	9.9	Reverse/Oblique
Shoreline	6.5	90	0.6	0.6	0.6	Strike Slip
San Luis Bay	6.3	50	1.9	0.0	2.5	Reverse

[1]90th fractile of the mean characteristic magnitude distribution for non-linked cases from source characterization logic tree (see Figure 6-17, PG&E, 2011a)
[2]R_{JB} is closest horizontal distance to the surface projection of the rupture plane, R_{Rup} is closest distance to the rupture plane, and R_x is horizontal distance from the top edge of the rupture, measured perpendicular to the fault strike (it is positive over the hanging wall and negative over the footwall)
[3]DCPP site is on the hanging wall of Hosgri, Los Osos, and San Luis Bay faults.

on deterministic ground motions. Compared to a generic rock site with V_{S30} of 1,200 m/s, the PG&E site-specific amplification factors shift peak spectral response toward lower frequency. They also lead to slightly lower peak spectral response for all four scenarios (Figure 7a). Compared to a generic site with V_{S30} of 760 m/s, the PG&E site specific ground motions are significantly lower, except for frequencies lower than approximately 2 Hz (Figures 7b and 7c). Comparison of these figures also shows that reducing the aleatory uncertainty in ground motion from GMPE sigma to single station sigma reduces predicted ground motion amplitudes across the spectrum (compare the set of solid curves in Figure 7b with that in Figure 7c). These two figures also show that if DCPP site had a V_{S30} value of 760 m/s rather than 1,200 m/s, and if the site behaves more like an average site in ground motion amplification, some deterministic spectra would exceed the 1991 LTSP spectrum.

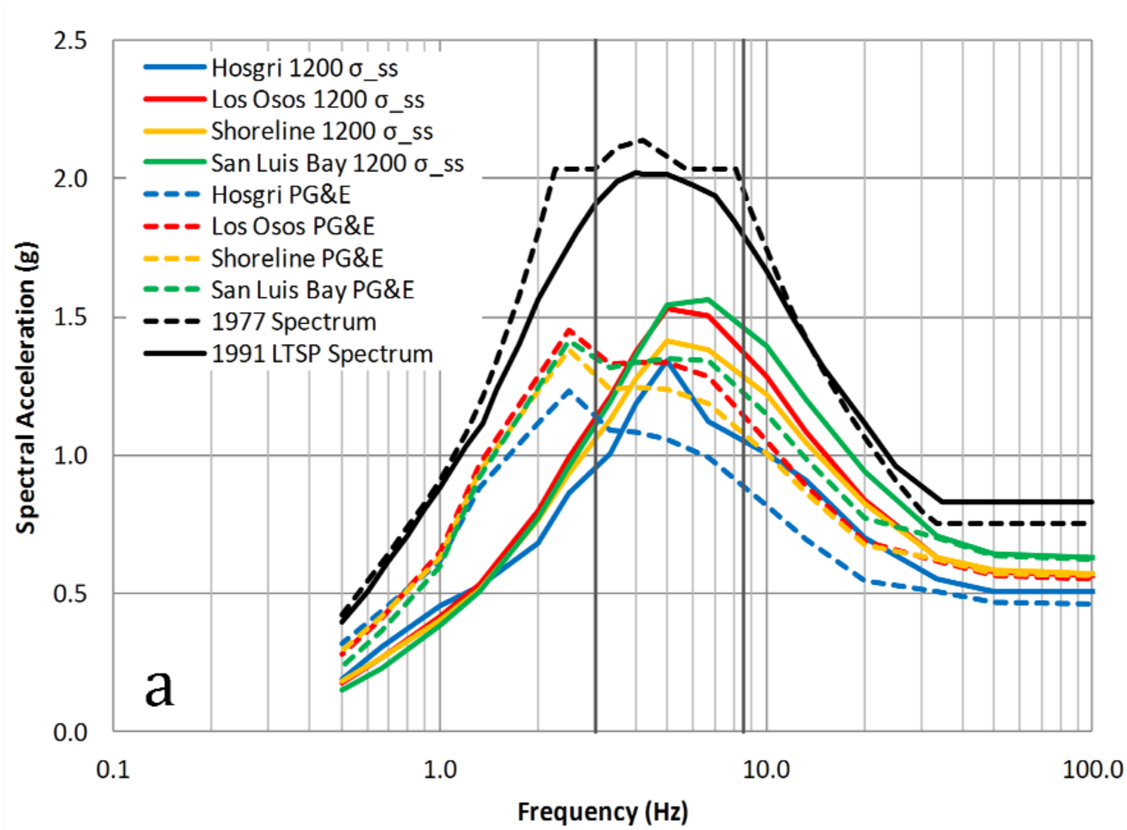
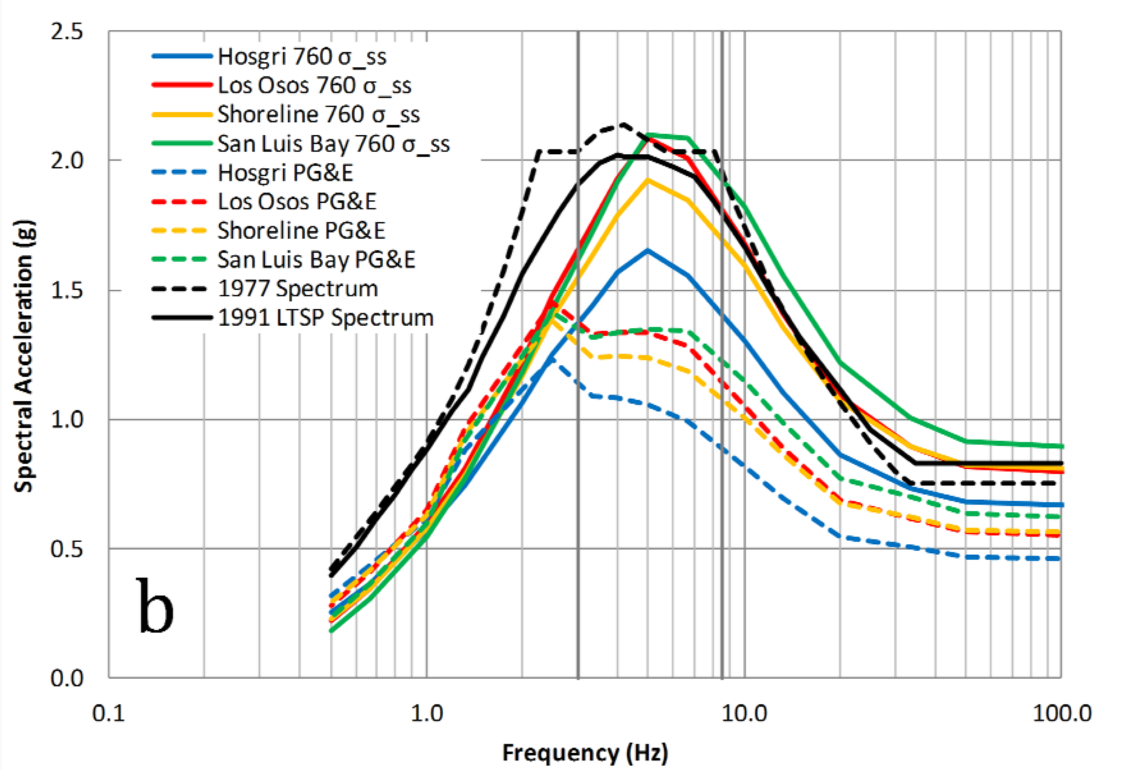


Figure 7. Comparison of deterministic ground motion spectra from PG&E for the DCPP site (dashed color curves; using site amplification term, its uncertainty, and single station sigma) with deterministic spectra of three sensitivity cases (solid curves): (i) a generic site with V_{S30} of 1,200 m/s and single station sigma (Figure 7a); (ii) a generic site with V_{S30} of 760 m/s and single station sigma (Figure 7b); and (iii) a generic site with V_{S30} of 760 m/s and sigma from GMPEs (ergotic sigma, Figure 7c). The PG&E 1991 LTSP/SSER 34, the 1977 HE (Hosgri Earthquake) design spectrum, and the frequency range important to DCPP (marked by vertical dark grey lines) are also plotted for reference.

(Continued)



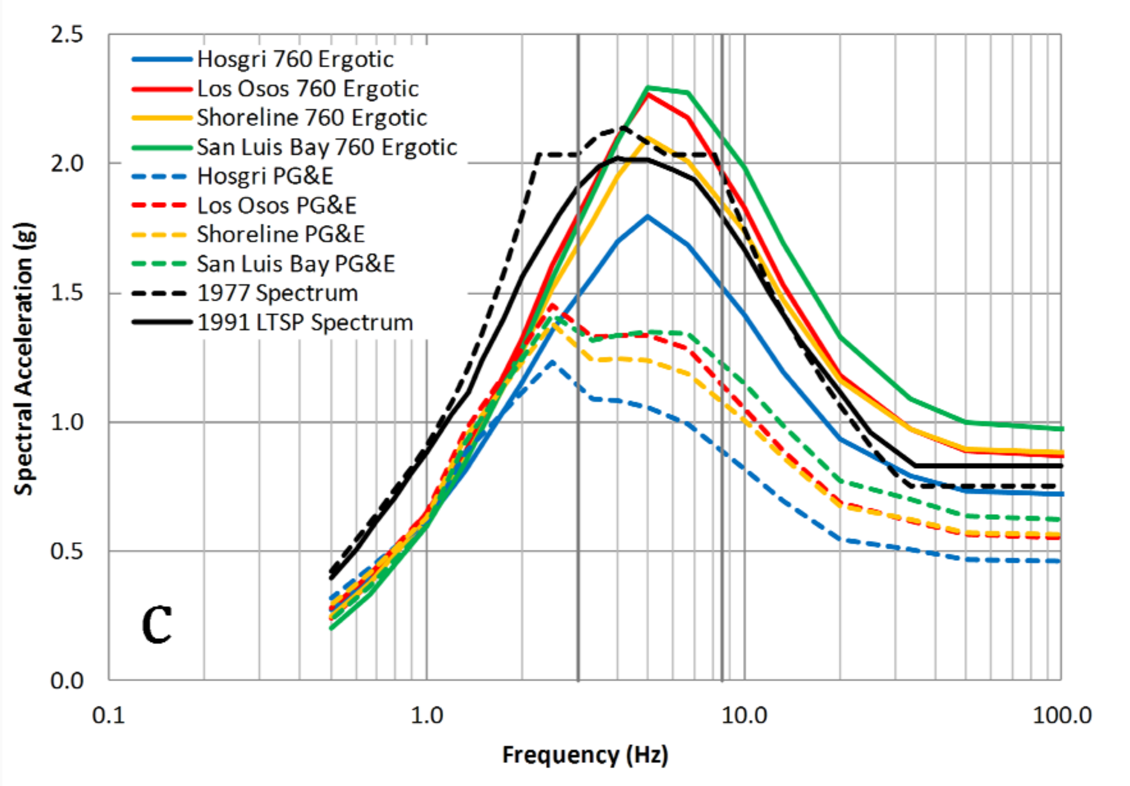


Figure 7. Continued.

We also calculated probabilistic ground motions using PG&E's probabilistic seismic hazard analysis codes provided by Norm Abrahamson. The calculations were based on an input file (also provided by Norm Abrahamson) that contains the input parameters and the full logic tree of the PG&E base case. We made changes to the input files in order to look at the sensitivity of estimated probabilistic ground motion hazards to site amplification.

Figure 8 compares the total hazard curve that we reproduced using the PG&E base case input file provided by Norm Abrahamson without modification (solid red curve, using site-specific amplification term, a V_{S30} of 1200 m/s scaling, and single station sigma) with two sensitivity hazard curves: (i) for a generic site with V_{S30} of 760 m/s (dashed red curve, no scaling, single station sigma); and (ii) for a generic site with V_{S30} of 1,200 m/s (solid green curve, Silva scaling factor, single station sigma). This figure, once again, shows significant increase in ground motion hazards when PG&E site-specific amplification factors are not used and as V_{S30} value is decreased from 1200 m/s to 760 m/s.

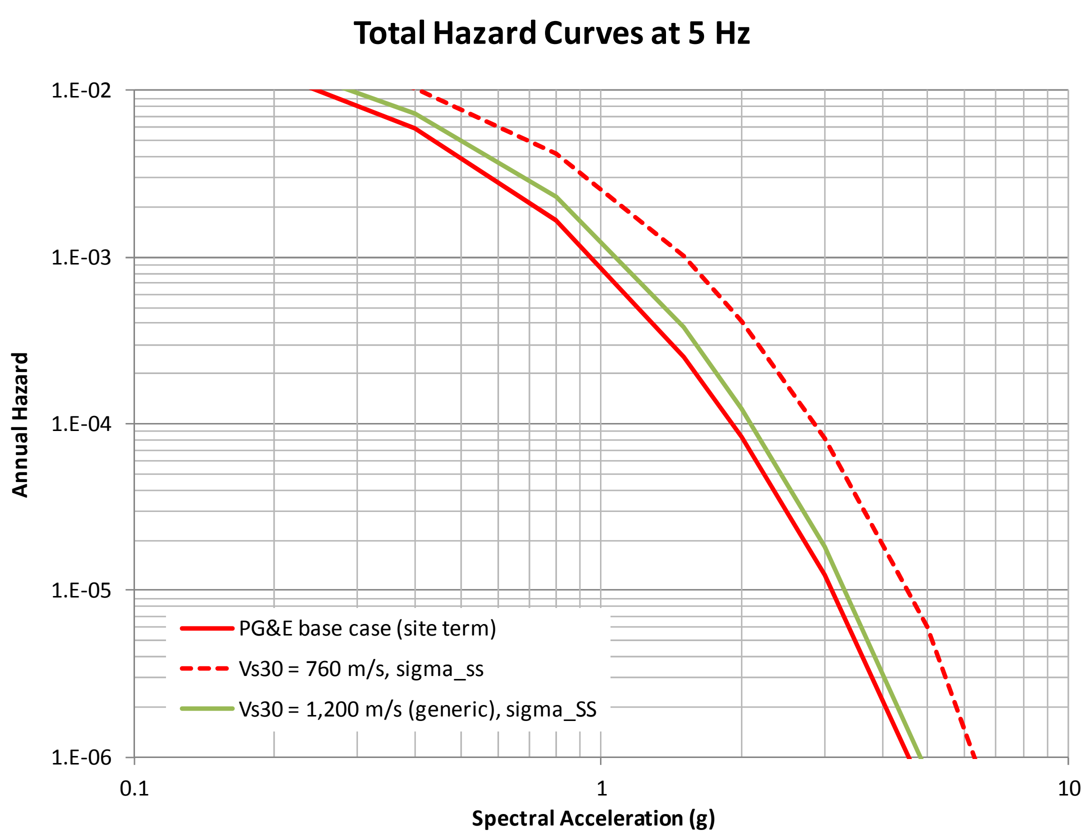


Figure 8. Comparison of the total hazard curve at 5 Hz obtained from PG&E base case input file provided by Norm Abrahamson (used site-specific amplification factor) with hazard curves for generic sites with V_{S30} of 760 m/s (GMPE-predicted median without scaling) and 1,200 m/s (using Silva scaling factors), respectively. Single station sigma is used in all cases.

Sensitivity analysis for probabilistic hazards was conducted by PG&E (2011b) to address an IPRP request to test the main targets of the onshore and offshore geophysical studies. Probabilistic hazard sensitivities to individual targets are demonstrated by comparing hazard curves in Figures 2 through 11 of PG&E's response to IPRP (PG&E, 2011b). Sensitivity of the 5 Hz hazard at 2 g ground motion level for different sensitivity cases are summarized and ranked in a "tornado plot" shown in Figure 12 of PG&E (2011b). The tornado plot is reproduced in this memorandum as Figure 9 for reference. The x-axis value is the ratio of 5 Hz hazard at 2 g spectral acceleration to the reference hazard of 10^{-4} (i.e., the approximate base case hazard for 5 Hz at 2 g spectral acceleration level). This figure shows that probabilistic hazard is most sensitive to Hosgri slip rate. Uncertainty in Hosgri slip rate may lead to calculated ground motion hazard that varies by a factor of nearly 2.

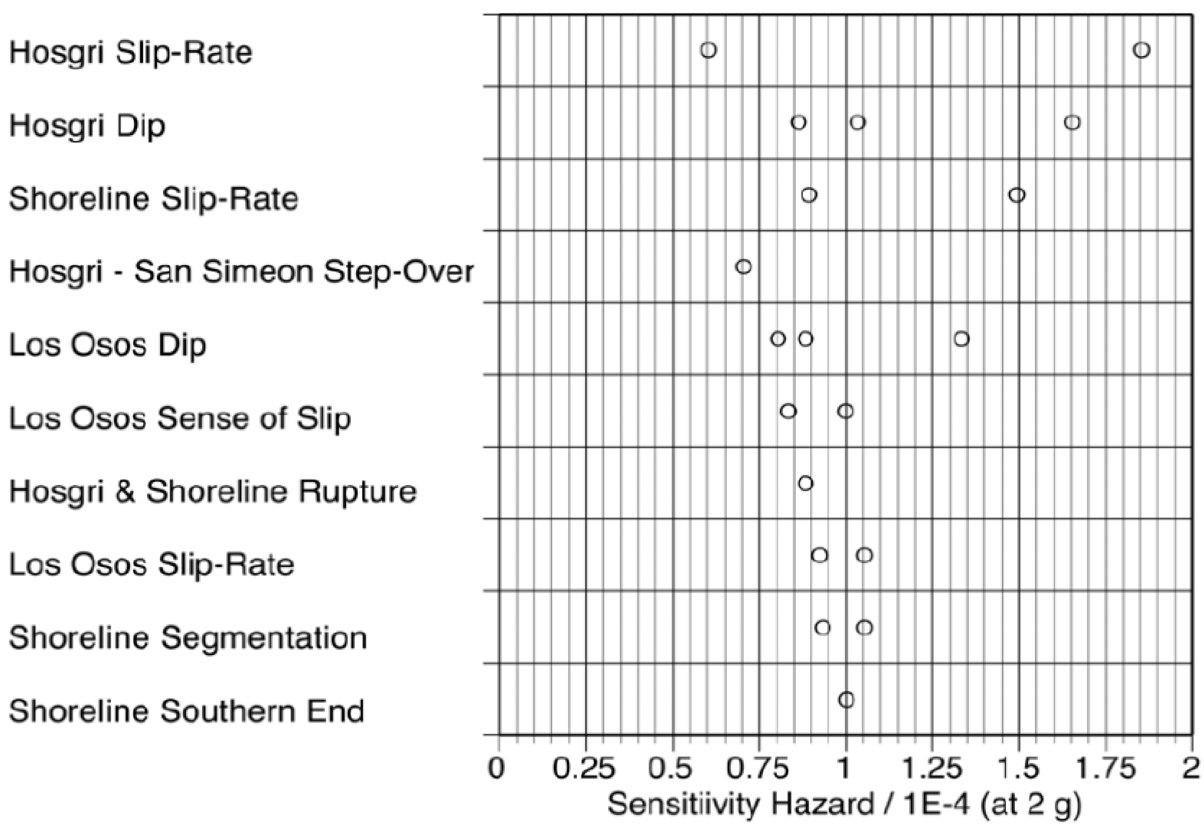


Figure 9. PG&E Summary of hazard sensitivity showing effect on 5 Hz hazard for a reference hazard level of 10^{-4} (after PG&E, 2011b)

We constructed a similar “tornado plot” (Figure 10) to put the effect of site condition in the same perspective as source parameters studied by PG&E (2011b). In Figure 10, the horizontal axis is the ratio of 5 Hz sensitivity case hazard to base-case hazard at spectral acceleration of 2g. PG&E base case used site-specific amplification term, its uncertainty, and single station sigma. All other cases used unscaled GMPE medians with V_{S30} values indicated in the figure. This figure shows that changing site condition from PG&E characterized DCPP site to a generic site with V_{S30} of 760 m/s increases the hazard by more than a factor of 3 (compare hazards for PG&E base case and the 760 m/s case). Changing site condition from PG&E base case to a generic site with V_{S30} of 1000 m/s increases hazard by a factor of 2.

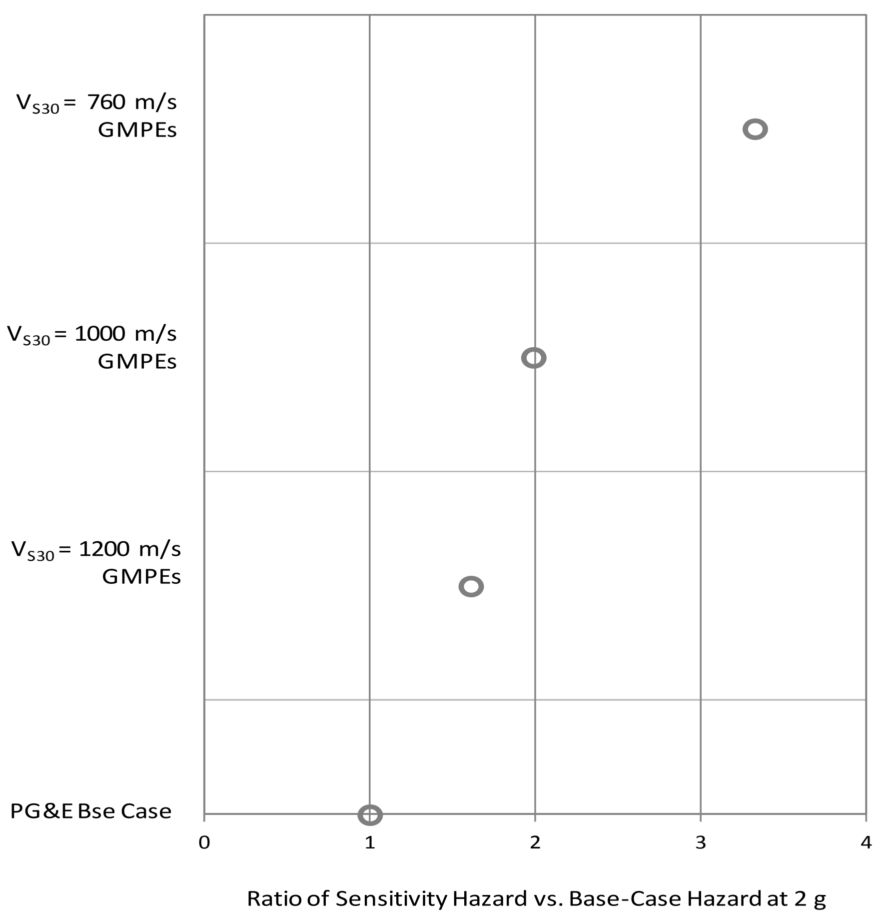


Figure 10. Sensitivity shown as the ratio of sensitivity case hazard to PG&E base-case hazard for 5 Hz spectral acceleration at 2 g.

The fragility used for DCPP is based on the spectral acceleration averaged over the frequency band of 3 – 8.5 Hz. Figure 11 shows the significant effect of site condition on this ground motion parameter. Also plotted on this figure is the 1988 LTSP hazard curve for comparison. This figure shows that changing site condition from PG&E characterized DCPP site to a generic site with V_{S30} of 760 m/s brings the average ground motion over the frequency band of 3-8.5 Hz above the 1988 LTSP curve (PG&E, 1988) for acceleration greater than about 1.5 g (i.e., hazard level of approximately 7×10^{-4} or return period of approximately 1,428 years).

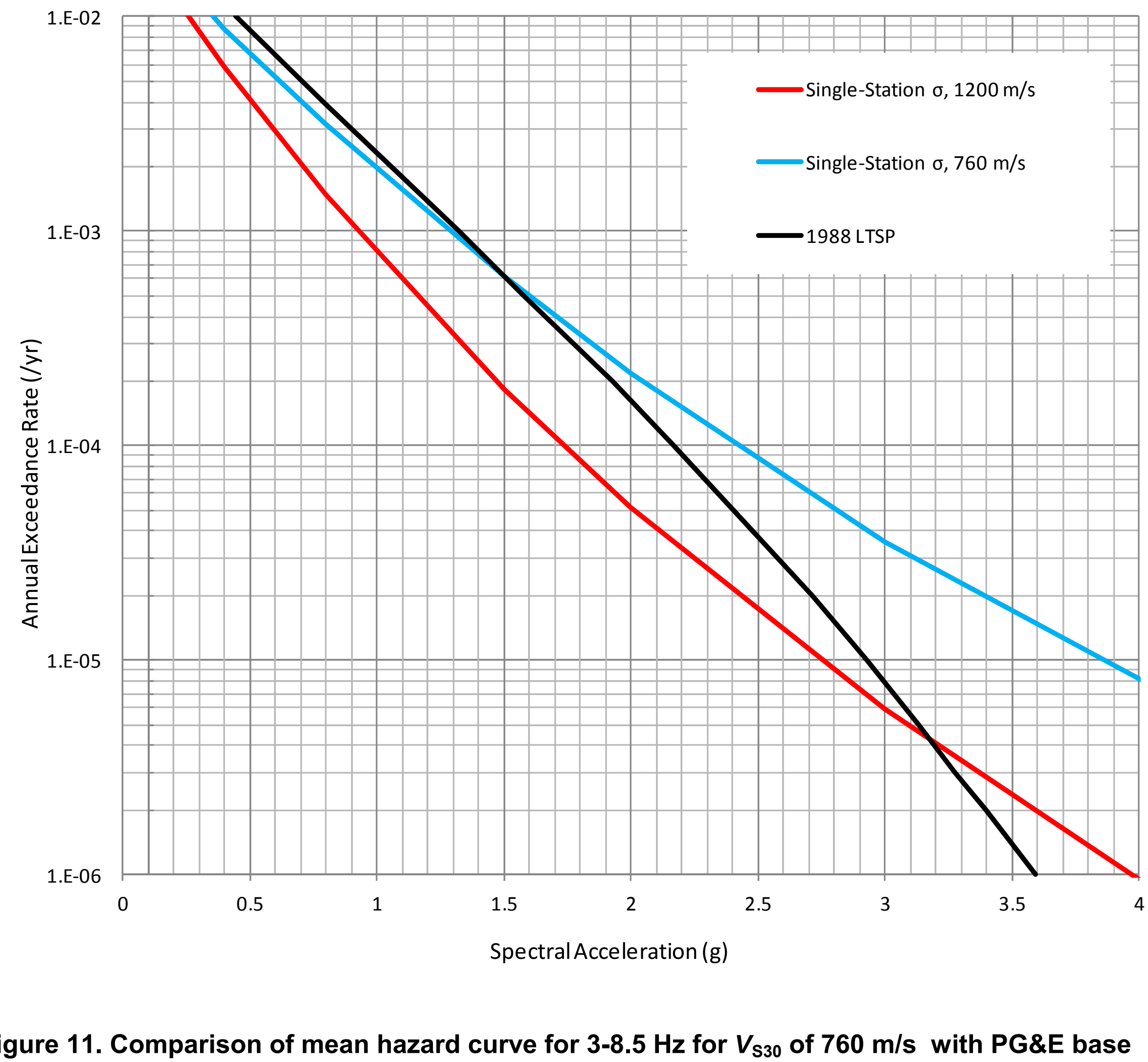


Figure 11. Comparison of mean hazard curve for 3-8.5 Hz for V_{S30} of 760 m/s with PG&E base case and the 1988 LTSP curves.

DISCUSSION AND RECOMMENDATIONS

In summary, PG&E determined that the V_{S30} value for DCPP Site is 1,200 m/s, similar to a hard rock site. Because NGAs are not well constrained for V_{S30} greater than approximately 1,000 m/s, NGAs were used to calculate median ground motions for a generic "firm rock" site with V_{S30} of 760 m/s. Empirical site-specific amplification terms were developed as mean residuals (event corrected) of ground motions recorded at the site from two locally recorded earthquakes. Site-specific amplification terms (relative to V_{S30} of 760 m/s) were then used to scale NGA-predicted median ground motions to the DCPP site condition. Uncertainty in site-specific amplification is characterized by station-to-station uncertainty in the single station sigma concept and is combined with single station sigma and integrated in hazard calculations for computational efficiency.

In the frequency range important to DCPP, PG&E site-specific amplification factors are significantly lower than scaling factors for generic sites (Silva, 2008), NRC factors derived from site-response analysis for the DCPP site as part of their independent analysis, and conservative factors in current California and building codes for conventional and critical facilities. So far, PG&E has not captured epistemic uncertainty in available approaches for the effect of site conditions on ground motion hazards. At the IPRP meeting on July 11, 2013, PG&E indicated it would study site amplification analytically and make use of its detailed 3D velocity data for the DCPP site.

We conclude that PG&E's state-of-the-art approach to site amplification (based on recorded ground motions) and ground motion variability (single station sigma) is reasonable and makes intuitive sense. However, we conclude that further justifications/clarifications to the PG&E approach are necessary, particularly because the PG&E approach gives lower ground motion hazard estimates in the period range important to DCPP compared to other state-of-the-practice approaches used currently in the U.S. National Seismic Hazard Maps and in International and California building codes.

PG&E should demonstrate that the low site amplification seen at the DCPP site is due to site effects, not specific to the azimuths and distances traveled by the recorded ground motions at the site from the two earthquakes used. PG&E should also justify the adequacy of using only two earthquakes to characterize site amplification, particularly because these two earthquakes cover only a small range of the azimuths that seismic waves can travel toward the DCPP site.

Near surface V_S data at the DCPP site indicate significant variability/uncertainty (V_{S30} ranging from 696 m/s to 1,646 m/s). PG&E should evaluate whether and how this site-specific variability/uncertainty is captured adequately by its approach that quantifies uncertainty in site amplification based on site-to-site uncertainty (not a site specific parameter) in the single station sigma method.

PG&E's approach in κ estimation is different from approaches that are commonly applied. Usually, κ is estimated from the Fourier spectra of recorded ground motions or from subsurface material properties. We would appreciate justifications/explanations to the PG&E's approach.

In a public meeting held on July 11, 2013, PG&E indicated that they plan to conduct further studies to improve the quantification of site amplification:

1. PG&E will use new data from recently completed on-land exploration geophysics surveys to develop a new model of V_S beneath the plant site. Initial results of surveys presented by PG&E from one profile suggest that this analysis will result in a well-constrained 3-D model of shear-wave velocity beneath the plant.
2. PG&E will analyze broad band ground motion data to rule out path effects in the current site-specific amplification terms. Since data from two earthquakes are not sufficient to demonstrate that the amplification factors include only modifications of the shaking due to site effects, recorded motion from other earthquakes, particularly earthquakes from the south and west, may help rule out path effects in the amplification terms.
3. PG&E will evaluate site amplification using analytical approaches in which seismic waves are propagated through a velocity model. This approach is more typical of state-of-the-practice for critical facilities and will provide a comparison to the ground shaking evaluation using the site-specific amplification factors.

The additional studies by PG&E appear to be well conceived to address the uncertainty in site conditions at DCPP. Considering the large effects on seismic hazard results from different estimates of site conditions and different methods in considering site conditions in seismic hazard analysis, the IPRP will be interested in additional briefings by PG&E on the results of their surveys and analyses.

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