Research Information Letter 09-001: Preliminary Deterministic Analysis of Seismic Hazard at Diablo Canyon Nuclear Power Plant from Newly Identified "Shoreline Fault"

Introduction

On November 14, 2008, the Pacific Gas & Electric (PG&E) Company informed the U.S. Nuclear Regulatory Commission (NRC) that it had identified a zone of seismicity that may indicate a previously unknown fault located offshore of the Diablo Canyon Nuclear Power Plant (DCNPP). The licensee identified the potential fault as a result of a collaborative research program between PG&E and the U.S. Geologic Survey (USGS)—the PG&E-USGS Cooperative Research and Development Agreement (CRADA). This program, which focused on increasing the understanding of tectonics in the region of the DCNPP, included both new geophysical field studies and the application of advanced seismological techniques to small-magnitude recorded earthquakes. Shortly after PG&E notified the NRC, it provided the Agency with sets of initial scientific information related to the hypothesized fault (ML090690193, ML090690218), which PG&E informally named the "Shoreline Fault." In discussion with the NRC staff, the licensee described its preliminary assessment that the hazard potential of the Shoreline Fault is bounded by the current review ground motion spectrum for the facility.

Based on the initial information provided by PG&E and the USGS, NRC staff undertook a preliminary review of possible implications of the potential Shoreline Fault to the DCNPP to determine if an immediate safety concern existed for the facility. The purpose of this letter is to expand on the Staff's preliminary review with a more thorough discussion of the data, the parameters used, and the basis for the Staff's initial conclusions. The data used in this review is summarized throughout the text, and analysis results are provided.

This review consists of two parts. First, using the new seismological and tectonic information provided by the USGS and PG&E and coupled with existing information as detailed in earlier reports, the Staff performed a preliminary deterministic seismic hazard assessment. The Staff compared the resulting seismic ground motions to loading levels for which the plant has been previously analyzed, as detailed in NUREG-0675 Supplement No. 34 (US NRC, 1991). This preliminary assessment indicates that the best estimate 84th percentile deterministic seismic-loading levels predicted for a maximum magnitude earthquake on the potential Shoreline Fault are slightly below those levels for which the plant was previously analyzed in the Diablo Canyon Long-Term Seismic Program. In the second part of this review, NRC staff has identified and discussed a series of ongoing or broader issues related to the seismicity of the Diablo Canyon nuclear power plant (NPP) area that NRC staff is currently considering.

As noted, this work is based on the limited preliminary information currently available to the NRC staff. Additional information will be reviewed as it is obtained by the USGS and PG&E as a result of ongoing field work.

Background (Historical Context and Recent Events)

The DCNPP has a unique and complex seismic design and licensing bases. A brief review of the history of the DCNPP is provided to explain both the basis for NRC review of the potential new fault and the context of the research program that identified the potential fault.

The Atomic Energy Commission originally issued construction permits to PG&E for DCNPP Units 1 and 2 in 1968 and 1970, respectively. Later, as the plant was under construction and the operating license applications were under development, proprietary oil company studies describing a significant and previously unknown seismic zone offshore near the DCNPP were made public. PG&E included a brief discussion of this seismic zone in the Diablo Canyon final safety analysis report (FSAR) that was submitted in 1973. PG&E called the zone the East Boundary Fault Zone in the FSAR, but it is now known as the Hosgri Fault Zone.

In the years following the FSAR submittal, PG&E investigated the Hosgri Fault Zone in response to NRC requests for additional information. At the same time, the USGS also performed an independent investigation of the fault zone for NRC. Based on USGS recommendations and on requirements contained in 10 CFR Part 100, Appendix A (which was newly issued at that time), NRC required a significant increase in the seismic design basis to what is now known as the Hosgri ground motion. This safe shutdown earthquake (SSE) ground motion has a horizontal peak ground acceleration (PGA) of 0.75 g based on the assumption of a magnitude 7.5 earthquake on the Hosgri Fault, which is located 5 km (3 mi) from the DCNPP. Consequently, PG&E reanalyzed and upgraded the plant design to accommodate the Hosgri seismic design basis.

In addition to the increase in the seismic design ground motion and the associated reevaluation and retrofit required prior to licensing, the Diablo Canyon Unit 1 full-power license DPR-80 also has a license condition (2.C.(7)) that required a future reevaluation of the seismic design basis of the plant. This was included in response to the ACRS recommendation that ". . . the seismic design of Diablo Canyon be re-evaluated in about ten years taking into account applicable new information." To meet this requirement, PG&E developed the Long-Term Seismic Program (LTSP).

As part of the LTSP, PG&E performed a full seismic reevaluation of the DCNPP between 1985 and 1988. Both a seismic margins assessment (SMA) and a probabilistic risk assessment (PRA) were undertaken as detailed in the Final Report of the Diablo Canyon Long Term Seismic Program (PG&E, 1988) and as summarized in the Seismic Safety Evaluation Report, NUREG-0675 Supplement No. 34 (U.S. NRC, 1991). During that reevaluation, the licensee determined that the Hosgri Fault was still the controlling fault. However, NRC staff came to believe that the faulting may have a larger component of reverse-slip than was previously accounted for, leading to higher review shaking levels over some ground motion frequencies. As a result of NRC staff comments, the licensee increased the review spectrum over part of the frequency range, and undertook a reevaluation of the plant with this new "LTSP spectrum." The LTSP spectrum is essentially a Hosgri spectrum that is enhanced over some frequencies. The LTSP response spectrum is the current review spectrum for the plant and is used as a point of comparison in this study.

Because the science and tools available to study the seismic zone continue to evolve over time, the licensee committed, in the Final Report of the Diablo Canyon LTSP, to continue to study seismic issues and to perform periodic seismic reviews of the DCNPP. This commitment to ongoing research and review led to development of the PG&E-USGS CRADA program, which identified the possible Shoreline Fault.

Although the CRADA is a long-term program that has been in place since 1997, the USGS identified the potential Shoreline Fault during a new phase of the CRADA that was recently implemented. In discussions with the NRC staff, the licensee described the ongoing work under the CRADA. This work will increase understanding of the tectonics in the region nearby the DCNPP and includes both a large set of new field studies and the application of new advanced seismological techniques to small magnitude recorded earthquakes. According to the licensee, the motivation for the new phase of the CRADA was twofold. First, technological innovation in recent years has led to significant improvements in the ability to collect high-quality geophysical data over large areas. New data would likely lead to an increased understanding of the Hosgri Fault Zone and the surrounding region than was possible even a few years ago. Second, evaluating new data on the Hosgri Fault Zone is consistent with the commitments made in the LTSP program and report, described above. The NRC staff and members of the broader seismic community are aware of the work being undertaken through the CRADA program and will continue to monitor any results as they become available.

The development phase of the new CRADA research was initiated in 2007 and has just completed its second year. Program initiation and coordination was ongoing in much of 2007, and field studies were initiated in late 2007. The USGS initiated analysis of each of the data sets as information was obtained during 2008. As originally planned, preliminary results of the full complement of work for the region would be available publically in 2010. The identification of the potential new fault has caused changes to the original timeline and scope of work. In the short term, PG&E and USGS plan to reallocate resources to characterize the Shoreline Fault rather than retaining the original focus that is more regional in nature. This reallocation effort is documented in the licensee's "Action Plan for the Study of the Shoreline Fault" (ML090720505).

Overview of Deterministic Analyses and Inputs Used

To verify the adequacy of PG&E's initial deterministic evaluation of the potential Shoreline Fault, and in keeping with the deterministic design basis for the facility (10 CFR Part 100, Appendix A), the NRC staff conducted a deterministic hazard analysis. Probabilistic methods are currently being used to license new reactors (10 CFR 100.23); however, due to the limited and preliminary nature of the required probabilistic input parameters, the Staff used a deterministic approach.

A deterministic hazard analysis considers a single scenario earthquake. Typically, the analysis is based on the largest earthquake that the fault is considered to be capable of (i.e., its maximum magnitude). In this review, the 84th percentile ground motion of the assumed maximum magnitude earthquake is used for comparison to the LTSP ground motion.

In performing a deterministic analysis, a number of inputs need to be determined. These inputs include the ground motion prediction equations to be used, earthquake magnitude, distance from the rupture plane to the site, type of faulting, shear wave velocity of the site, depth to rupture, depth to engineering foundation materials, dip angle of fault plane, and near field effects. The following sections discuss each of these inputs and the means by which they were determined for this study. In addition to developing a best estimate value for each of these inputs, the Staff analyzed a range of values for several parameters to understand the impact of uncertainty in some of the key variables.

Review of Currently Available Geophysical and Seismological Data

Although the investigation has only recently begun, some preliminary interpretations are possible. This is in part because of the high quality of the data obtained and in part because the data sets appear to be providing a consistent—although still very blurry—picture of the area. The key datasets considered by NRC staff for this review were the seismicity data, the marine magnetic data, the aeromagnetic data, and the seismic profile imaging.

The original piece of information that led to the identification of the postulated Shoreline Fault was the recorded seismicity that had been recently reprocessed using an advanced technique called double-difference tomography (tomoDD). Figure 1 shows seismicity in the vicinity of Diablo Canyon NPP. Double-difference tomography methods perform an inversion of datasets of seismic recordings, which provides both a 3-dimensional velocity model of the region that the seismic waves travel through and highly improved estimates of earthquake location. Prior to using this processing technique, a high level of uncertainty existed concerning the location of offshore earthquakes and, as a result, they appeared to be more scattered. This uncertainty resulted because the seismograph stations that recorded the earthquakes are all located onshore and, therefore, do not surround the epicenters. This is shown in Figure 2, which presents regional seismicity based on a local velocity model. The position of the seismographs relative to the earthquake epicenters creates issues with the triangulation methods normally used for determining earthquake locations. When the locations of recorded seismicity were reanalyzed using the tomoDD method, the seismicity appeared to resolve into a more vertical surface, thereby indicating a fault structure may be present.

Subsequent to this postulated structure being identified, the NRC staff participated in the periodic conference call for the CRADA program in November 2008 to understand the new information related to the potential Shoreline Fault. During this conference call, the Staff was informed of new high-quality marine magnetic data and aeromagnetic data. When first presented to NRC staff in November 2008, these data were still in an unprocessed state. Preliminary processing was quickly performed by the USGS, who presented the results to the public at the American Geophysical Union (AGU) annual meeting in San Francisco in December 2008.

The NRC staff used seismicity and marine magnetic data together to independently develop the parameters used for this study. Figure 3 shows the seismicity overlaid on the marine magnetic data, which demonstrates that the seismicity just offshore is aligned with strong magnetic anomalies. These anomalies may be indicative of significant discontinuities in the type of foundation rock found at that location. Upon taking a closer look at the magnetic data in Figure 3, two separate anomalies appear to each trend northwest-southeast, with the change in structure located just northwest of the DCNPP. The seismicity data—as shown in the plan view and in cross section C-C' of Figure 1 and again in Figure 4—appear consistent with the marine magnetic data in that at least two separate structures appear to exist with different seismicity characteristics. The break in the two magnetic anomalies appears to correspond to an area in which the shallow seismicity stops and deeper seismicity begins (with the deeper seismicity possibly trending more westerly than the predominant direction of the anomalies). The anomalies themselves appear to be more associated with shallow seismicity. Currently, the exact cause of the anomalies and the seismicity is unknown. However, Figure 5 shows a USGS poster presentation at the AGU national meeting that depicts the break in the anomalies in the vicinity of the contact between the Diablo block and the Pismo block. The apparent consistency of the signals indicates that significant knowledge about the Hosgri seismic zone may be gained as a result of the ongoing work. The picture will continue to become clearer as additional small earthquakes are recorded and field data are obtained.

The magnetic anomaly located closest to the DCNPP appears to be correlated with the zone of seismicity that PG&E refers to as the Shoreline Fault. Taking the seismicity profile and the magnetic anomaly together, NRC staff determined a best estimate for the length of the Shoreline Fault to be 16 km. This measurement is based on locating the fault between 35.215° N, 120.87° W and 35.13° N, 120.75° W and using the Haversine formula. This best estimate is slightly longer than, but similar to, the PG&E estimated length of 15 km. The deepest recorded seismicity associated with the anomaly offshore from the DCNPP is 11 km. However, it is somewhat common to assume a depth of seismicity on a fault at least as large as the length of the fault; and Figure 1 shows the seismicity extends to approximately 15 km to the NW. This, coupled with the assumption that the fault can rupture to the surface, leads to a best estimate of the depth of the fault of 16 km. This leads to an estimate of fault plane area of 256 km^2.

Ground Motion Prediction Equations

The most important elements of both deterministic and probabilistic analyses are the ground motion prediction equations (GMPEs). These equations, also known by the term “attenuation relationships,” are statistically-based relationships that have been developed from large sets of recorded earthquakes. GMPEs determine likely shaking levels that would occur at a site as a result of a specific earthquake scenario. They can provide information on both the most probable and the possible range of shaking that could occur at a particular site, based on the range of earthquake motions recorded in the past. As noted above, the 84th percentile ground motion (i.e., the mean +1 standard deviation ground motion) is used for comparison to the LTPS review spectrum. This is the motion that is exceeded only 16 percent of the time for a given scenario earthquake.

All other parameters discussed in this section are inputs to the GMPEs. Because the GMPEs are developed using a limited dataset from specific tectonic environment, care must be taken in choosing appropriate GMPEs to use. For this study, a recently developed set of GMPEs called the Next Generation Attenuation (NGA) models were chosen. These GMPEs were developed for shallow crustal interplate earthquakes (such as found in coastal California) during the recent NGA project managed by the Pacific Earthquake Engineering Center at the University of California, Berkeley. The NGA GMPEs are detailed in a special publication of the professional journal *Earthquake Spectra* that was published in February 2008. These GMPEs are considered state-of-the-art. The four GMPEs used were those developed by Abrahamson and Silva (2008), Chiou and Youngs (2008), Campbell and Bozorgnia (2008), and Boore and Atkinson (2008). The four relationships were equally weighted. The table below summarizes all parameters for the four GMPEs (including those for options that were not used) and provides the values of the parameters used in this study. This is provided to allow for easy comparison when additional information is obtained, to clarify the study itself, and to allow for peer review and repetition of analyses.

Table 1. Parameters for the NGA Models and Parameter Values Used in this Study (after Table 5 in Abrahamson, et al., 2008)

Input Parameter	Parameter Notation in GMPEs				Values Used in This Study
	AS08	BA08	CB08	CY08	
Moment Magnitude	M	M	M	M	Best estimate of 6.4, with an upper bound of 6.85. A range of 6.25 to 6.85 was analyzed
Dept to top of rupture (km)	Z_{TOR}		Z_{TOR}	Z_{TOR}	Assumed to be 0 km (surface rupture)
Reverse style-of-faulting flag	F_{RV}	RS	F_{RV}	F_{RV}	Strike slip assumed; flag not applied
Normal style-of-faulting flag	F_{NM}	NS	F_{NM}	F_{NM}	Strike slip assumed; flag not applied
Strike-slip style-of-faulting flag		SS			Strike slip flag applied
Unspecified style-of-faulting flag		US			Strike slip assumed; flag not applied
Aftershock flag				AS	Main shock desired; flag not applied
Dip (degrees)	δ^a		δ^a	δ^a	Not applied because parameter used for HW scaling only.
Down-dip rupture width (km)	W^a				Not applied because parameter used for HW scaling only.
Closest distance to the rupture plane (km)	R_{rup}		R_{rup}	R_{rup}	Best estimate of 1 km based on interpreted fault geometry. A range of 0.6 to 1.4 was analyzed.
Horizontal distance to the surface projection of the rupture (km)	$R_{jb}{}^a$	R_{jb}	$R_{jb}{}^a$	$R_{jb}{}^a$	For BA08 assumed to be same as R_{rup} based on vertical faulting. Not applied to other models as only used for HW scaling.
Horizontal distance to the top edge of the rupture measured perpendicular to strike (km)	$R_x{}^a$			$R_x{}^a$	Not applied because parameter used for HW scaling only.
Hanging Wall flag	F_{NM}			F_{NM}	Not applied due to assumption of vertical strike slip faulting
Average shear-wave velocity in the top 30 m (m/s)	V_{S30}	V_{S30}	V_{S30}	V_{S30}	Best estimate of 1100 m/s. Lower and upper bound values assumed to be 800 m/s and 1,600 m/s, respectively
Depth to V_S=1.0 km/s (km)	$Z_{1.0}$			$Z_{1.0}$	Best estimate of 0 m for the best estimate and upper bound V_S profiles. For the lower bound V_S profiles the value is 40 m.
Depth to V_S=2.5 km/s (km)			$Z_{2.5}$		Default value of 2 km was used based on recommendations in Campbell and Bozorgnia (2007)
Rock motion PGA for non-linear site response				$Y_{ref}(T)$	Non-linear site response is not required as the shear wave velocity exceeds the rock limit
V_{S30} of rock motion used for nonlinear site response (m/s)	1100	760	1100	1130	The values shown are the V_{S30} used for each GMPE relationship. As noted, the best estimate V_{S30} at the site exceeds these values for all practical purposes.
[a] used for headwall (HW) scaling only					

Type of Faulting Mechanism

In the past, seismologists have recognized that the faulting mechanism of a particular earthquake has a statistically significant impact on observed ground motions during that earthquake. As a result, the GMPEs used in this study have all incorporated faulting mechanism as a first-order parameter. The initial information on the potential Shoreline Fault indicates a fault with a predominant strike slip orientation (i.e., minimal reverse or normal components). Figure 6 shows the possible mechanisms.

A predominantly strike-slip orientation is indicated by both the focal mechanisms of recorded earthquakes on the potential fault and by the physical orientation of the fault as implied by a 3-dimensional plot of the recorded earthquakes. Figure 7 shows the focal mechanisms of recorded earthquakes along the potential fault through the use of seismic “beach ball” graphs for each of the recorded earthquakes. It can be seen that both the individual and the composite (average) orientation of the earthquakes that have been recorded have had a dominant strike-slip orientation. Figure 1 shows the hypocentral locations of recorded earthquakes on cross section projections along and across the postulated fault. The cross sections AA’ and BB’, which are taken perpendicular to the plane of the fault, also indicate a predominantly vertical orientation of a strike-slip faulting mechanism.

As a result of the evidence showing a vertically oriented strike-slip fault, this mechanism was used as the input to the GMPEs for this study. The assumption of a vertically oriented strike-slip plane, coupled with the conservative assumption that the potential fault is capable of surface rupture, can be used to develop assumptions for a number of the other input parameters. As additional data on the Shoreline Fault is obtained, a small amount of oblique motion may become evident. If that is the case, an analysis based on oblique motion should be undertaken and the results of the two fault mechanisms should be weighted as the data indicates. It currently appears that this would have very limited impact due to dominance of the strike-slip component.

Maximum Magnitude

The maximum magnitude earthquake used by the Staff in the analysis was determined based on the sets of relationships most commonly used for active crustal interplate regions. These relationships are described in Wells and Coppersmith (1994) and Hanks and Bakun (2002). The relationships that apply to the potential Shoreline Fault are as follows, Wells & Coppersmith (1994) equation for strike-slip earthquakes: $M = (1.02 \pm 0.03) \log A + (3.98 \pm 0.07)$, and Hanks and Bakun (2002) relationship where $A \leq 537$ km^2: $M = \log A + 3.98 \pm 0.03$. The parameter A is the area of the rupture plane in km^2 in both relationships.

As noted, the best estimate of the fault length at this time is considered to be 16 km. The maximum depth of the fault plane is assumed to be 16 km. This leads to an area of 256 km^2 and a corresponding maximum moment magnitude of 6.4 for both relationships considered. Using the uncertainty information provided in the Wells and Coppersmith reference with the area of 256 km^2, a median +1 standard deviation maximum magnitude of 6.6 is calculated. To be clear, this is an estimate of the maximum magnitude of the fault if the length of the fault is approximately 16 km. Alternately, although less likely, a scenario in which a fault with the full length and depth of the recorded seismicity ruptures also was considered. In this case, the hypothetical Shoreline Fault extends all the way to the Hosgri Fault (24 km), and the depth of the actual recorded seismicity (16 km) is assumed. This leads to a median maximum magnitude of 6.6 and a median +1 standard deviation maximum magnitude of 6.85. The length and depth of the fault are key pieces of information that will come out of the site studies as they progress, and new information should be checked against this assumption once available.

The best estimate value that PG&E calculated was magnitude 6.25 based on the width of 15 km and a depth of 12 km. They estimated an upper bound of 6.5 based on the length of the rupture plane extending to the Hosgri Fault (24km) and the same 12 km. Thus, the numbers used in this analysis are slightly higher than those developed by PG&E. This is a reasonable range given the uncertainty in the data. A best estimate of maximum magnitude of 6.4 was used in the NRC analysis, and a magnitude range of 6.25 to 6.85 was analyzed.

Shear Wave Velocity

Shear wave velocity (V_S), is the velocity at which shear waves travel through geologic materials. It is a key parameter used in seismic hazard studies and seismic engineering. In addition to being a direct measure of an important property, V_s also acts as a general proxy for the stiffness of geologic materials. Shear wave velocity is used as a first-order parameter in GMPEs because the stiffness of geologic materials underlying a site has a significant impact on how seismic waves behave once they reach that particular site. A shear wave velocity profile is used to determine $V_{S,30}$, the average shear wave velocity in the top 30 meters (approximately 100 feet). The shear wave velocity profile also is used to obtain the parameter noted as $Z_{1.0}$, the depth to where a shear wave velocity of 1,000 m/s is reached (where the depth is determined in meters). The parameter $Z_{2.5}$ is a similar parameter for 2,500 m/s that is used to address effects associated with geologic basins, which can have significant impacts on incoming ground motions.

For this review the Staff determined input shear wave velocity profiles under the containment structure of the DCNPP based on Figures 5-3 and 5-5 of the Diablo Canyon Long Term Seismic Program report. These figures, with additional annotation by NRC staff, are provided as Figures 8 and 9. Typically shear wave velocity profiles are recorded in the free field. During the construction process, the V_S profile may be impacted by the excavation and construction processes. For this study, NRC staff assumed that a compensated foundation exists (i.e., the weight of the structure is approximately equal to the weight of material removed) and that the V_S profile preconstruction can be used for the postconstruction values.

Using Figure 9, the Staff determined that the best estimate of $V_{S,30}$ at the site is 1,100 m/s and the $Z_{1.0}$ is zero[1]. In this case, information to directly determine $Z_{2.5}$ was not available. For this reason, the Staff used the estimation techniques described in Campbell and Bozorgnia (2007). The equations provided (where all depths are in km) are as follows:

$Z_{2.5} = 0.519 + 3.595\ Z_{1.0}$ with a $\sigma_z = 0.711$ or $Z_{2.5} = 0.636 + 1.549\ Z_{1.5}$ with a $\sigma_z = 0.864$

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[1] Note that $V_{s,30}$ is not obtained by proportionally averaging the velocities directly but rather by averaging the slowness of the wave. Because the V_s profile provided in the existing documentation is constant over the top 30 m, this calculation is not necessary at this time. However, this information is provided for completeness because this calculation should be performed if additional V_s data is provided.

As noted, the depth to $Z_{1.0}$ varied from 0 to 40 m (0.04 km). Figure 9 shows that $Z_{1.5}$ (the depth to 1.5 km/s) is 0 m in the upper bound profile, is 40 m in the best estimate profile, and is undetermined in the lower bound profile. Thus, the values for $Z_{2.5}$ range from 0.03 km (the minimum value based on the bottom of the profile) to 1.4 km. Because higher values of $Z_{2.5}$ are conservative and functionally any value between 1.0 km and 3.0 km is treated the same in the GMPE, the default value of 2 km provided by Campbell and Bozorgnia was used.

Upper and lower bound analyses also were performed using the V_S profiles from Figure 9. The values used in this study are shown below. In performing their study, the licensee used a V_s of 800 m/s, which is slightly more conservative than the best estimate value used by NRC staff.

Table 2: Shear Wave Velocity Parameters Determined from the PG&E Final Report of the Long Term Seismic Plan (1988)

	$V_{S,30}$	$Z_{1.0}$	$Z_{2.5}$
Best Estimate	1,100 m/s	0 m	2 km
Lower Bound	800 m/s	40 m (130 ft)	2 km
Upper Bound	1,600 m/s	0 m	2 km

Distance and Fault Orientation

Parameters related to distance are required as inputs to the GMPEs used for the deterministic analysis. These parameters can be challenging to determine if complex geometries exist between the fault plane and the site. In this case, the recorded seismicity implies a vertical or nearly vertical fault, which greatly simplifies the development of the distance and fault orientation parameters. Given a vertical fault configuration, the distance parameters R_{jb} and R_x would be the same as the closest distance from the site to the rupture plane, R_{rup}. Based on the available information, the best estimate of distance is 1 km. In addition, NRC staff used a range of 0.6 to 1.4 km to assess the sensitivity of this parameter. The vertical fault orientation also simplified the analysis because the fault orientation parameters associated with the hanging wall were not included.

Results of Analysis

Response spectra were calculated using the four GMPEs and the parameters described above. The results were then compared to the LTSP spectrum. Figure 10 shows a comparison of the LTSP spectrum with the suite of the GMPEs using the best estimates of the 84th percentile. The results give an indication of the uncertainty associated with the GMPEs. The figure shows that the best estimate values provide an average predicted ground motion for all frequencies that is essentially at or below the LTSP spectrum for which the plant was previously analyzed. The motions are very close to the LTSP in the high-frequency range but fall below the LTSP in the long-period range. This is to be expected because the LTSP is essentially the Hosgri spectrum that was developed based on a magnitude 7.5 earthquake located farther from the site than the potential magnitude 6.4 Shoreline Fault. Figures 11 to 13 show the results of the parametric analyses for magnitude, distance, and shear-wave velocity. In the case of magnitude and distance, the range of predicted values resulting from the analyses generally remains approximately at or under the LTSP spectrum at all frequencies. This is as expected because of the very close location of the DCNPP to the postulated fault. The motion at the site is controlled by the portion of the plane in close proximity, and the energy is essentially saturating the area.

In the case of shear wave velocity, the lowest shear wave velocity profile does show greater variance from the average value and exceeds the LTSP spectrum by a small amount over some frequencies. Interestingly, this parameter relates to a property of the site, not of the fault itself. This is somewhat typical as the properties of material near the surface can have significant effect on the amplitude of the incoming waves.

The result of the NRC analyses can be compared to those provided by PG&E, as shown in Figure 14. Generally, the two sets of analyses show similar results. This similarity is due to PG&E's use of the conservatively lower V_s estimate of 800 m/s in combination with a slightly lower magnitude for the postulated Shoreline Fault.

In conclusion, the NRC staff's assessment indicates that the best estimate 84th percentile deterministic seismic-loading levels predicted for a maximum magnitude earthquake on the Shoreline Fault are slightly below those levels for which the plant was previously analyzed in the Diablo Canyon Long-Term Seismic Program. Taking the results of the deterministic analyses as a whole and the current level of uncertainty, the postulated Shoreline Fault will not likely cause ground motions that exceed those for which the plant has already been analyzed.

Issues for Consideration

The effort by the licensee and the USGS to investigate the potential Shoreline Fault and the regional tectonics is ongoing. The data that the Staff has reviewed to date is preliminary. As a result, the Staff expects to supplement its assessment as the licensee acquires and provides additional information. The following list includes several items that the NRC staff may consider reevaluating in the future.

- Near-fault effects, such as directivity of ground motion
- Fault dimensions
- Fault mechanism
- Maximum magnitude
- Local shear wave velocity profiles (V_s)

The precise location of the fault and the near-surface properties are important for determining the potential for surface rupture to impact the site. The closest postulated distance of the fault to the site is approximately half a kilometer. Based on the NRC staff's current understanding of the fault orientation, surface rupture under the facility is highly unlikely. Although the fault rupture is unlikely to occur directly under the plant, it may cause deformations in the near field. PG&E noted that ancient faulting at the site may show some deformations as a result of either the direct rupture or the ongoing stress accumulation in the rock. The action plan provided by PG&E details a path to acquire the data needed to appropriately address the issue.

The CRADA program is expected to provide significant new information regarding the larger tectonic picture of the area. The NRC staff's initial assessment was deterministic, consistent with the design basis of the facility. Currently, probabilistic methods are available to more accurately characterize the hazard of the region surrounding the site. Further, regional moment balancing could also more accurately characterize the regional hazard, both independently and as part of a probabilistic hazard assessment. As more information becomes available (such as the slip rate of the potential Shoreline Fault or any additional information about the Hosgri Fault), the NRC staff expects to evaluate the regional seismic hazard and perform a probabilistic study, when the available data is sufficient.

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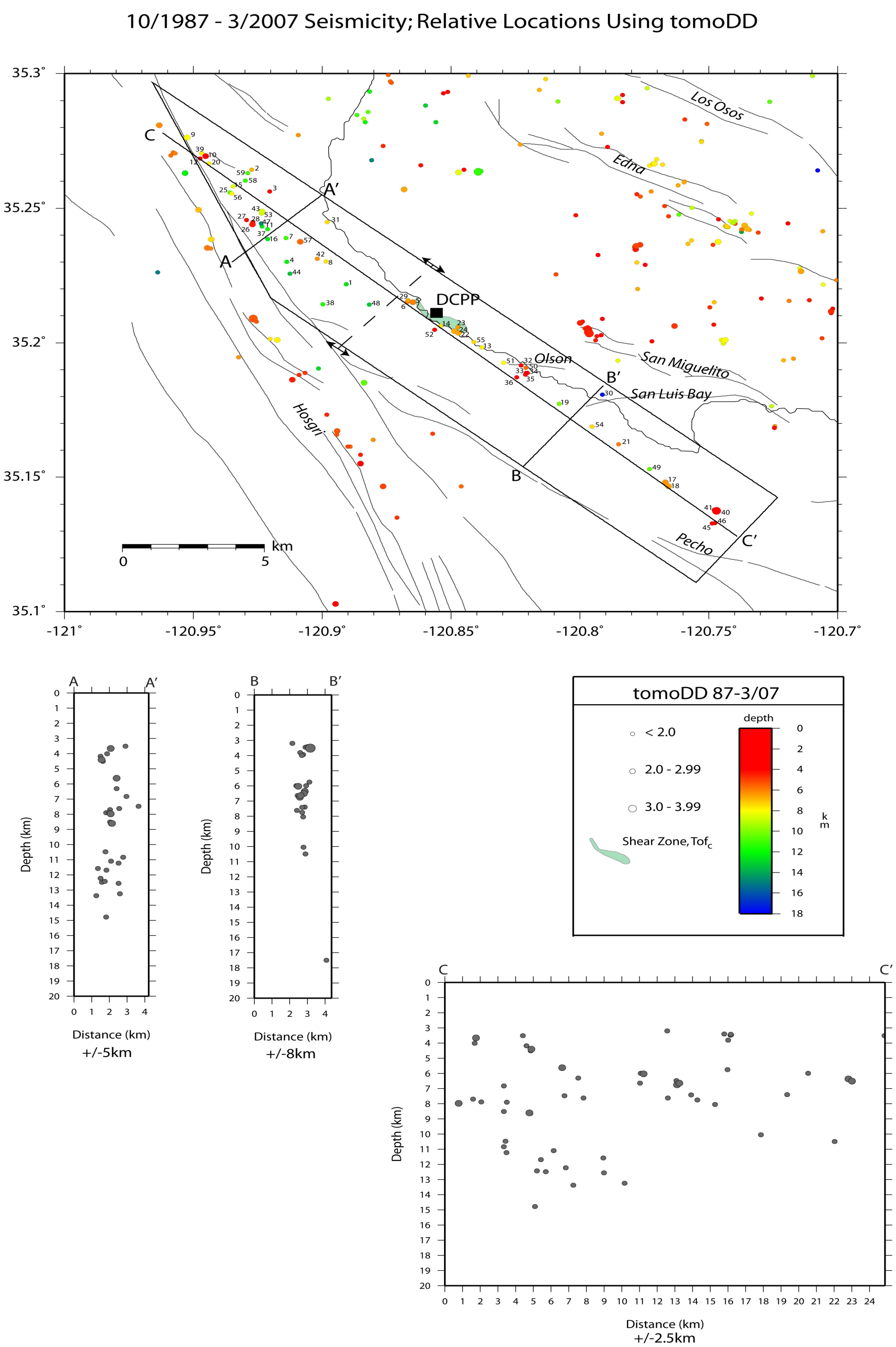
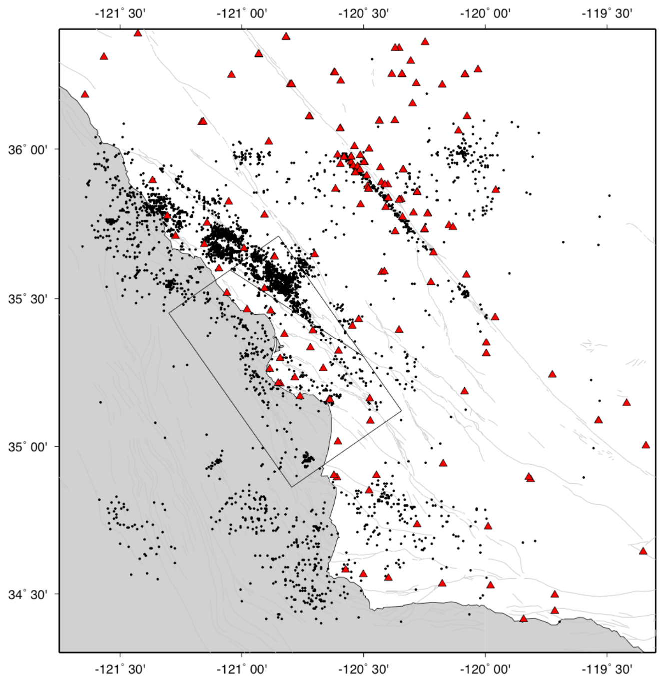


Figure and underlying data from the PG&E-USGS CRADA

Figure 1. Seismicity in Vicinity of Diablo Canyon NPP



<u>Double-difference Tomography (tomoDD):</u>

- solves jointly for velocity model and earthquake locations
- absolute and relative arrival times
- improves both absolute and relative earthquake locations

<u>Earthquake Data:</u>

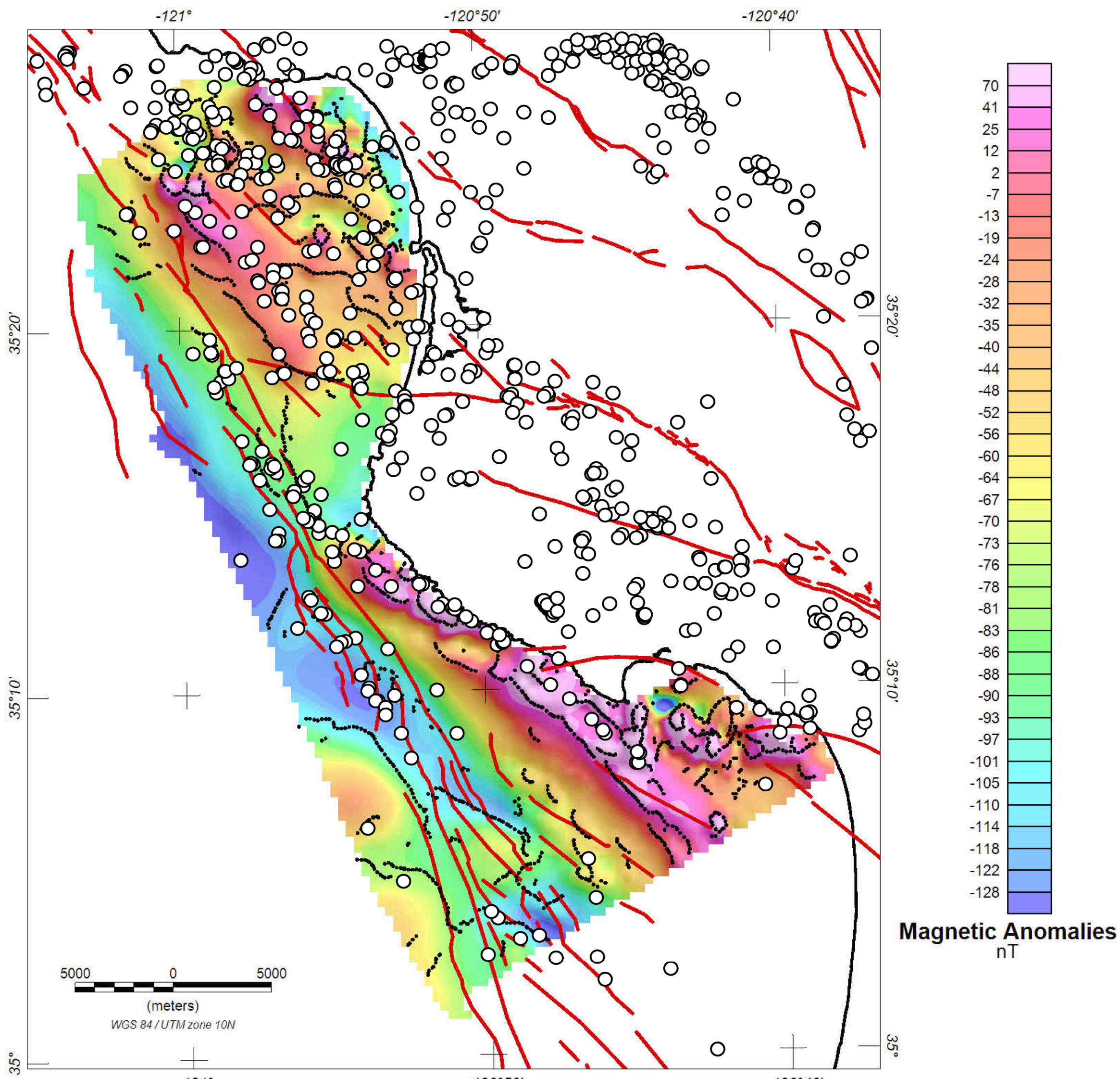
- ~1400 earthquakes (exclude San Simeon aftershocks)
- ~26,000 P-wave and ~3000 S-wave absolute arrival times
- ~11,000 P-wave and ~5000 S-wave relative arrival times from waveform cross-correlation

• Earthquake epicenters
▲ Seismograph stations

The figure shows magnitude 0.1 to 6.5 earthquakes recorded from 10/1/87 to 3/1/07

Figure and underlying data from the PG&E-USGS CRADA

Figure 2. Regional Seismicity Based on Local Velocity Model



The figure shows magnitude 0.2 to 4.1 earthquakes recorded from 10/1/87 to 3/1/07. The data was provided by the USGS.

Figure 3. Seismicity Comparison with Marine Magnetic Data

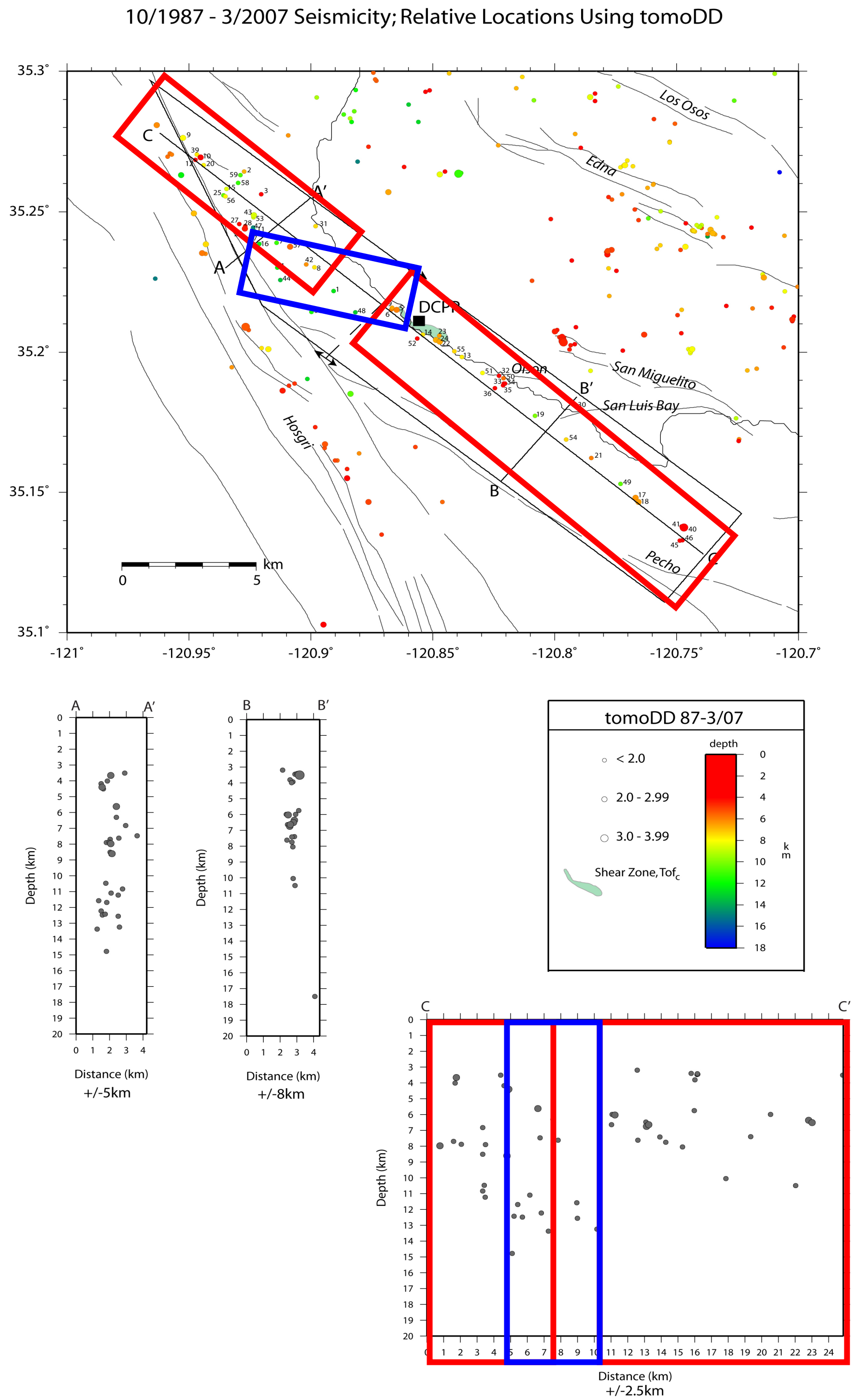


Figure 4. Seismicity in Vicinity of Diablo Canyon NPP Annotated with Interpretation by NRC Staff

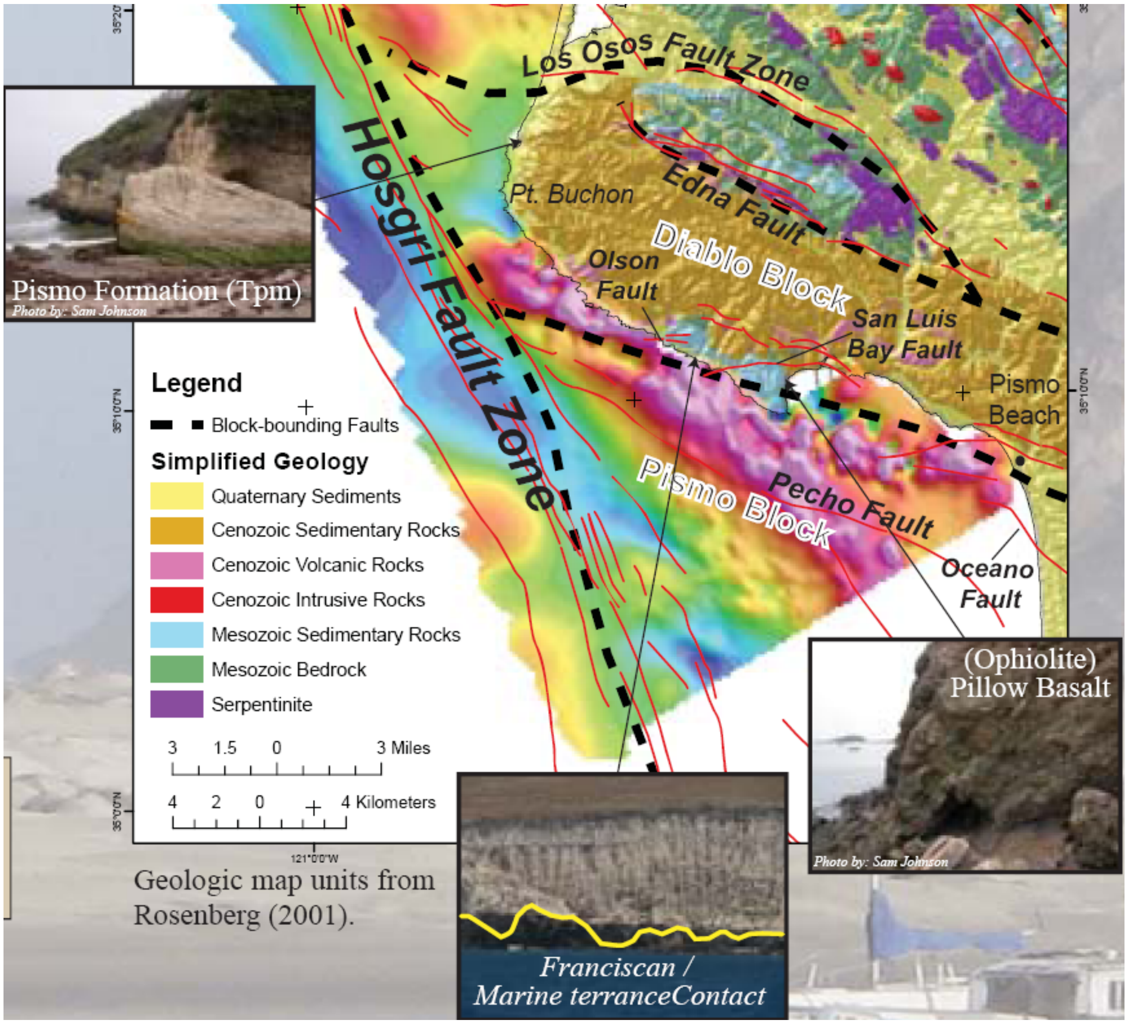


Figure 5. Portion of "The Hosgri Fault Zone, Central California: Collection and Preliminary Analysis Of Marine Magnetic And Seismic Reflection Data" AGU 2008 Annual Meeting Poster Presentation by Watt, Fisher, Scheirer, Johnson, Sliter, and Hart of the USGS

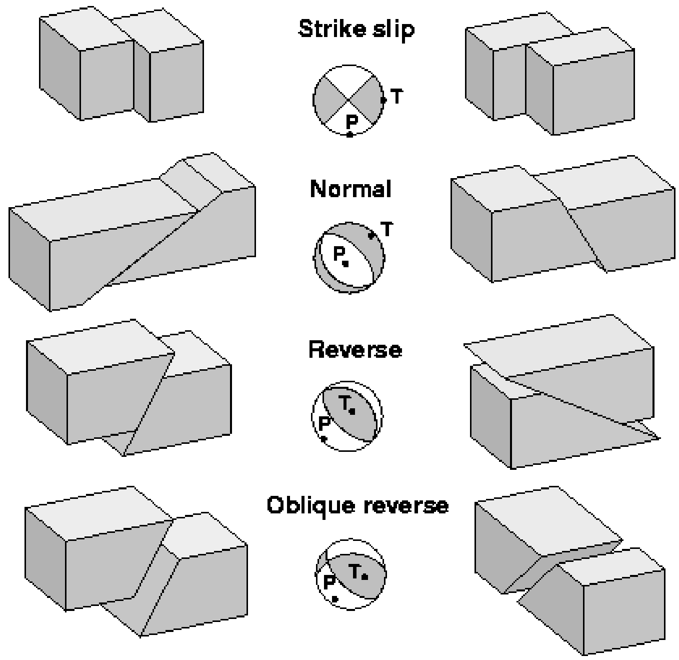
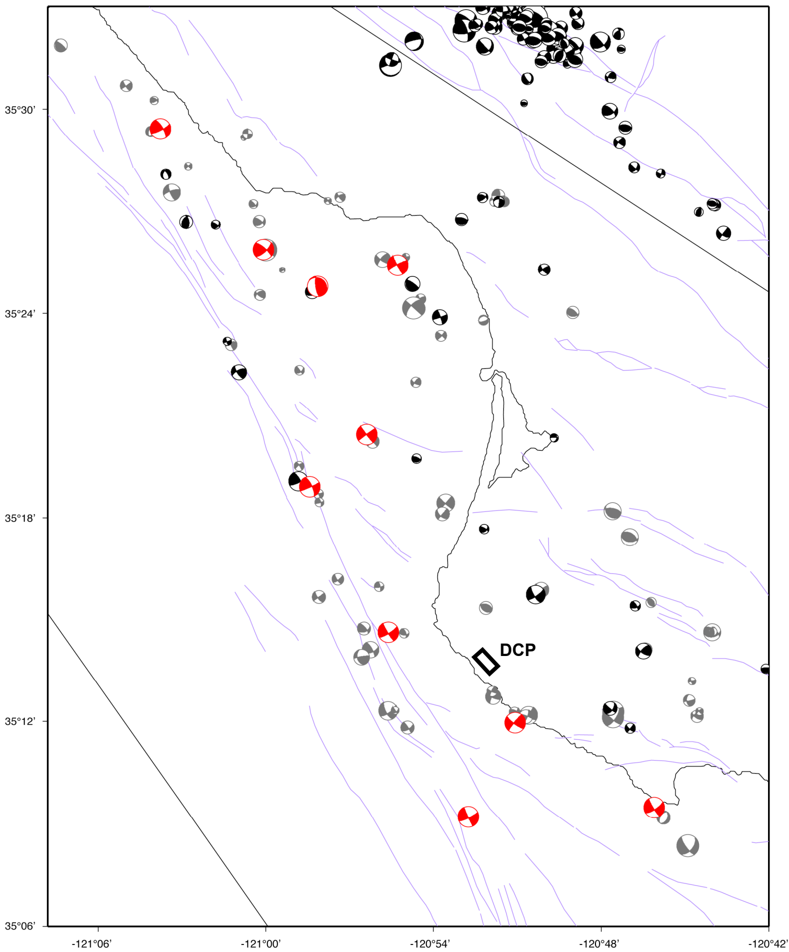


Illustration of faulting mechanisms by the USGS

Figure 6. Types of Faulting Mechanisms



<u>Focal Mechanisms</u>
Ray tracing in 3D velocity model.

Black: good quality (A-C of Hardebeck & Shearer) single-event mechanisms.

Grey: lower quality single-event mechanisms, checked for reasonableness.

Red: composite mechanisms.

The figure shows magnitude 1.1 to 4.6 earthquakes recorded from 10/1/87 to 3/1/07

Figure and underlying data from the PG&E-USGS CRADA

Figure 7. Focal Mechanisms Recorded in Vicinity of Diablo Canyon NPP

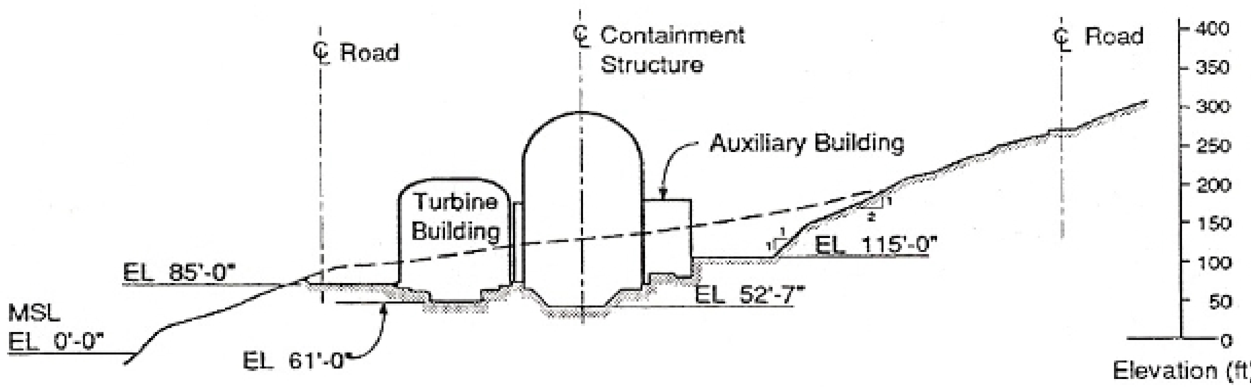


Figure 8. Cross Section of Diablo Canyon Plant
(Figure 5-3 in DCPP LTSP Report)

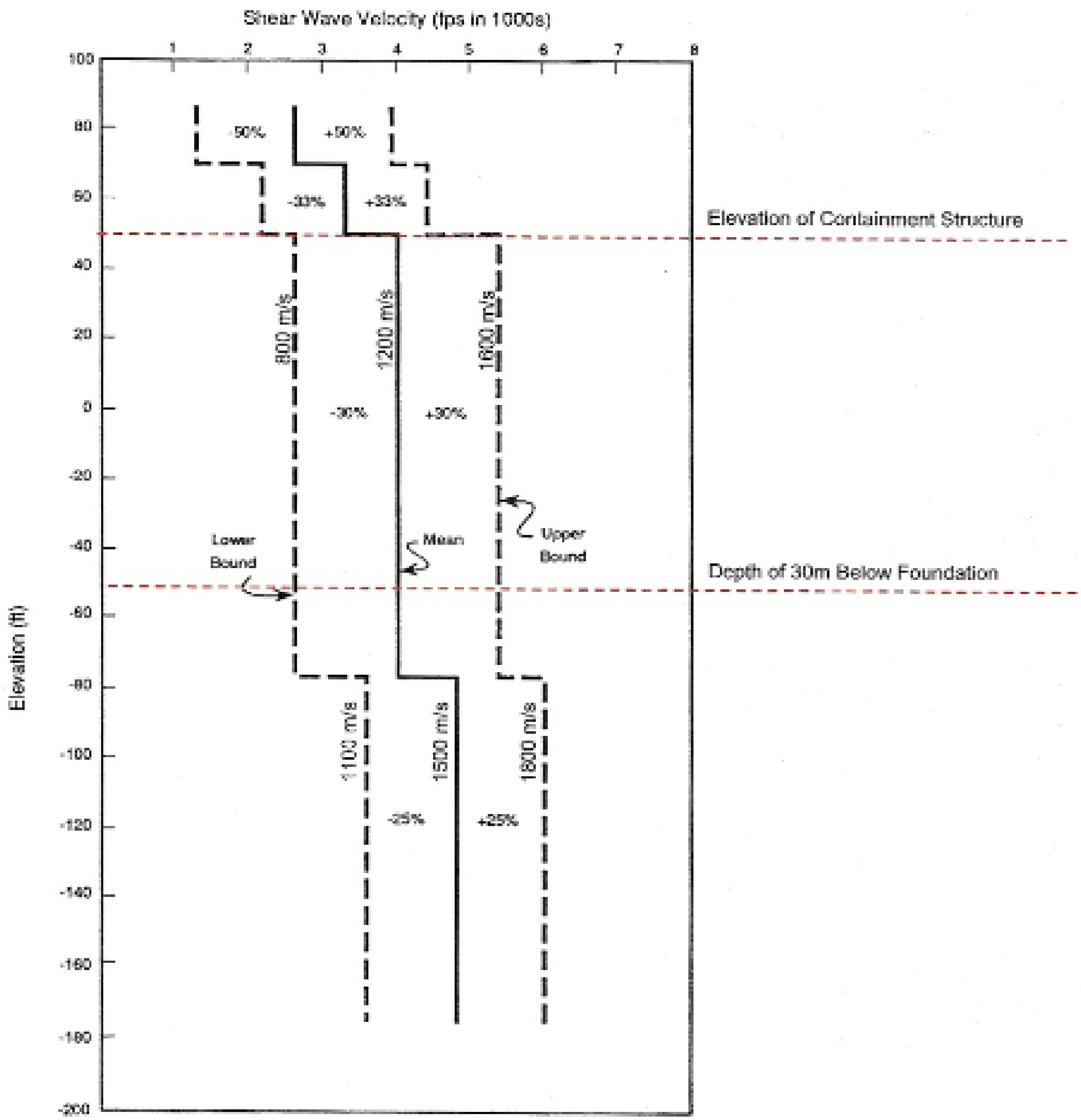


Figure 9. Site Shear Wave Velocity Profiles from 1978 Downhole Measurements (Figure 5-5 in DCPP LTSP Report) with Annotation by NRC Staff

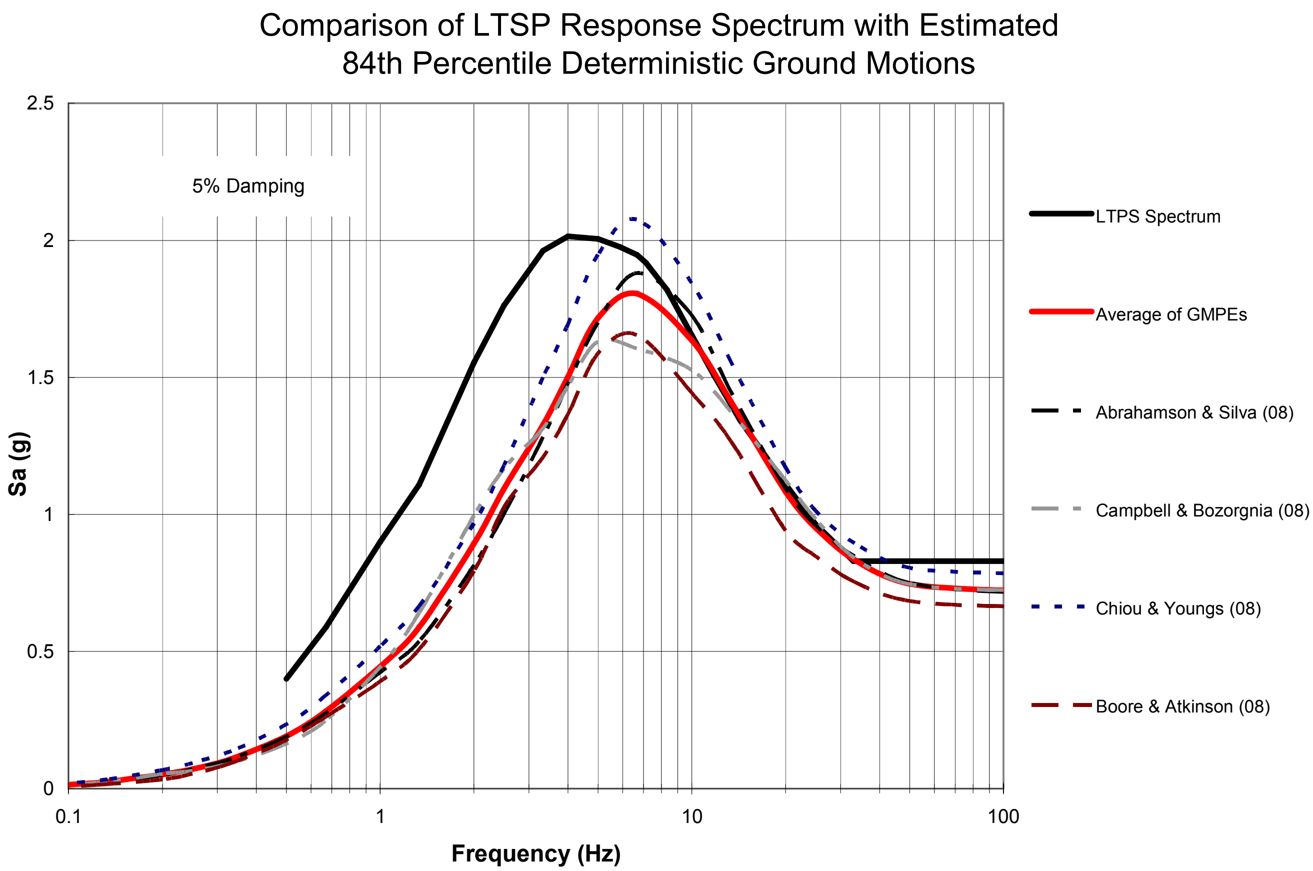


Figure 10. Comparison of Individual 84th Percentile Ground Motion Prediction Equations with Best Estimate Parameters and Diablo Canyon Review Spectrum

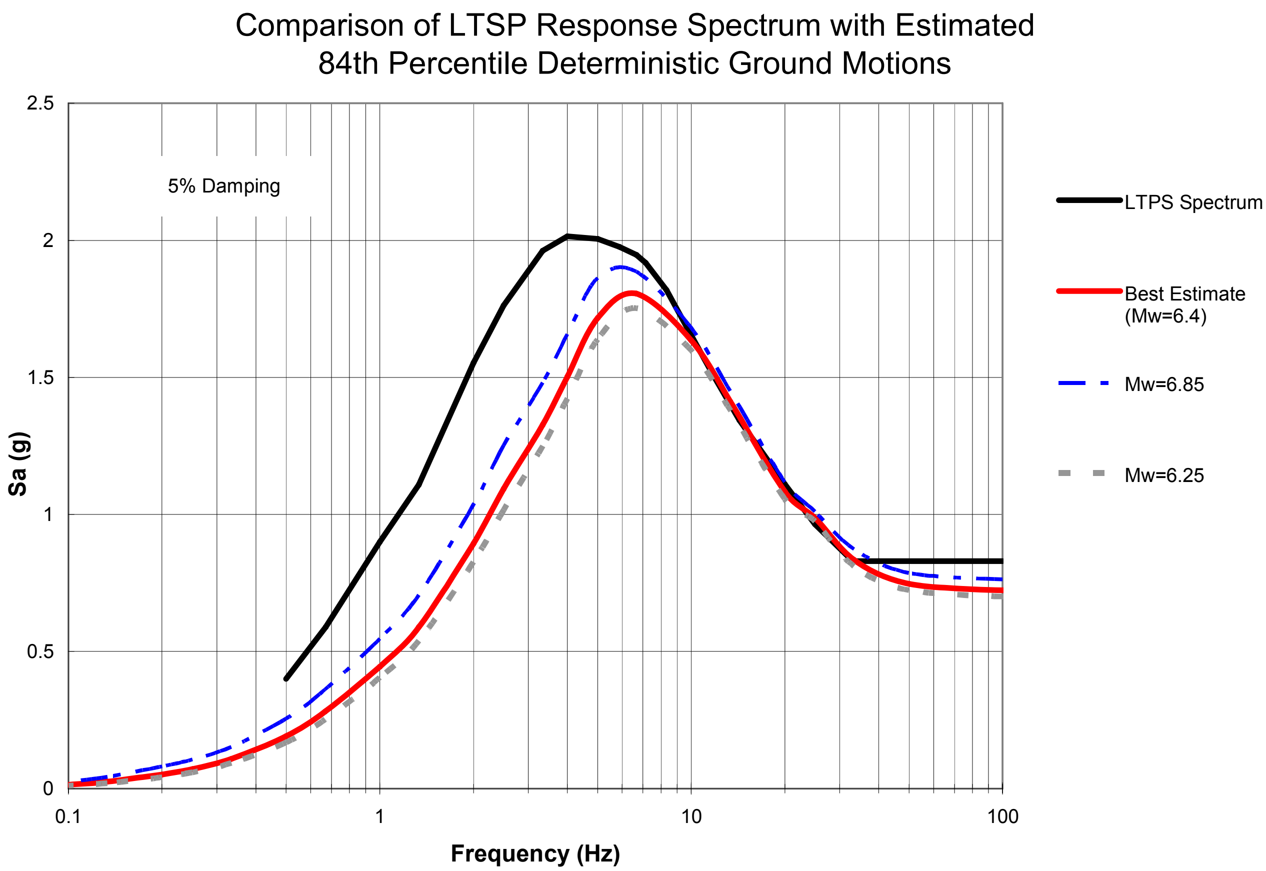


Figure 11. Comparison of Average Results of 84th Percentile Ground Motions with Varying Maximum Magnitudes

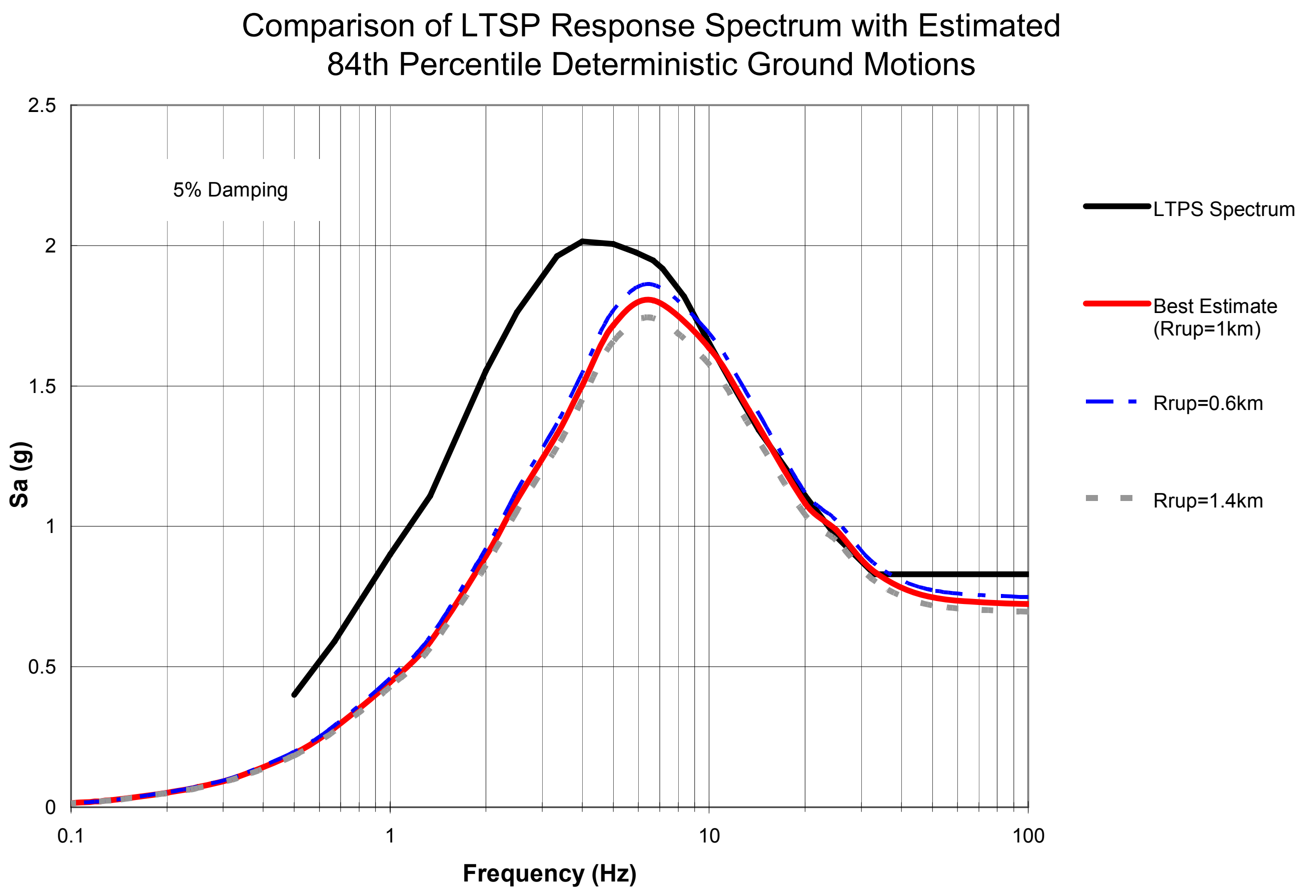


Figure 12. Comparison of Average Results of 84th Percentile Ground Motions with Varying Distance to Fault

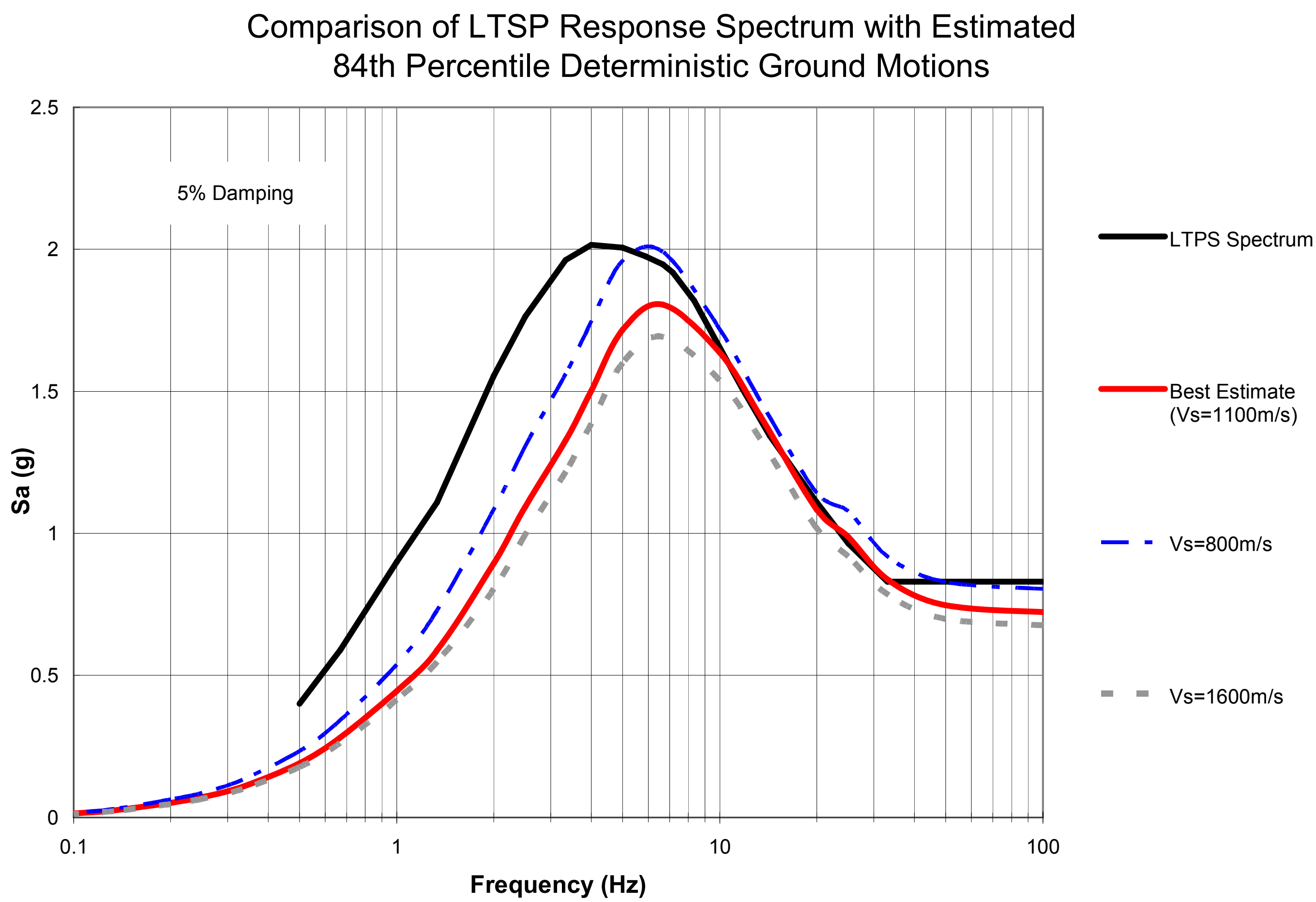


Figure 13. Comparison of Average Results of 84th Percentile Ground Motions with Varying Site Shear Wave Velocity Profiles

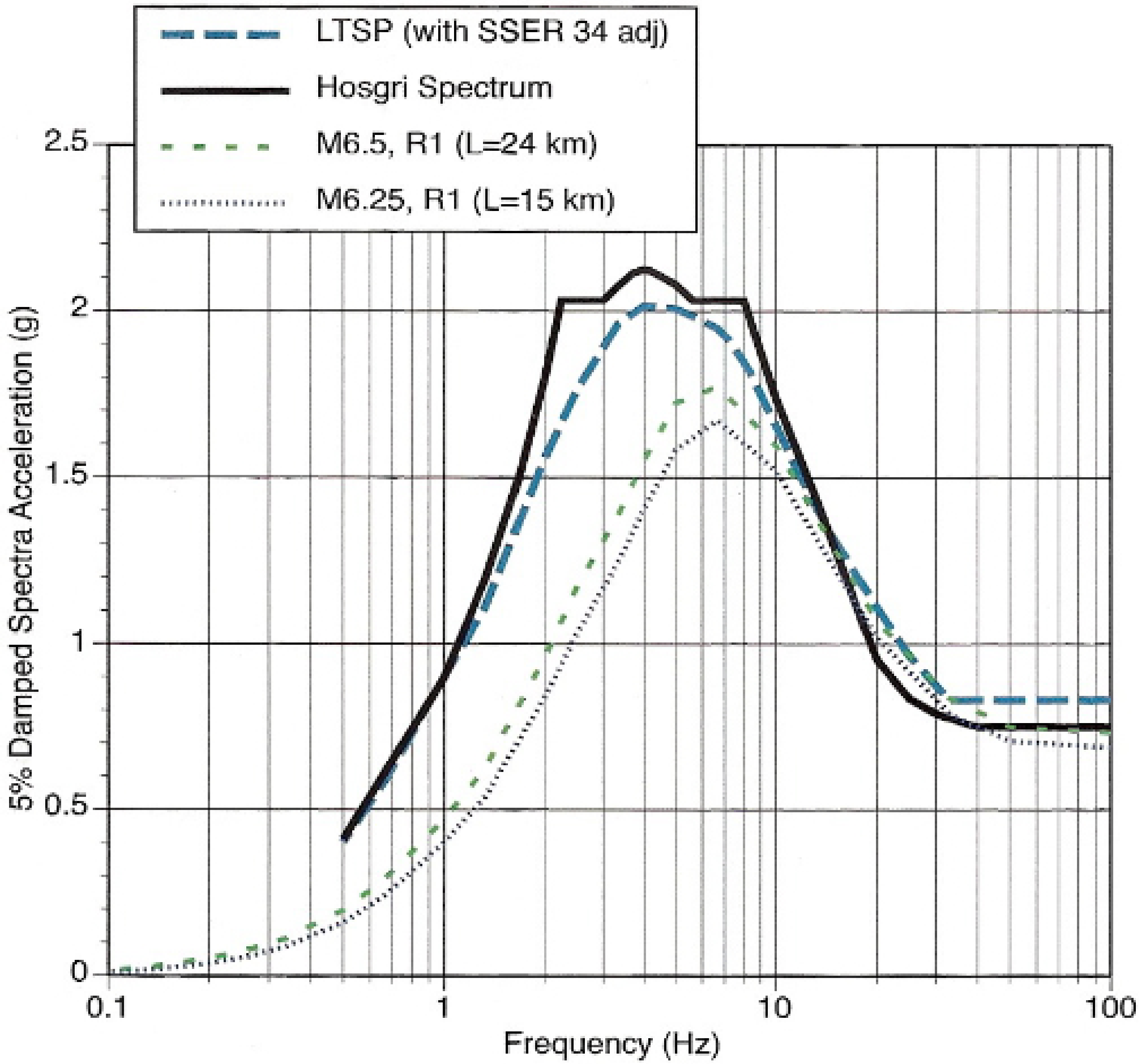


Figure 14. Comparison of Spectra Developed and Provided by the Pacific Gas & Electric Company