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 EMERGENCY MANAGEMENT AGENCY, CALIFORNIA ENERGY COMMISSION
CALIFORNIA SEISMIC SAFETY COMMISSION, CALIFORNIA PUBLIC UTILITIES COMMISSION
COUNTY OF SAN LUIS OBISPO

IPRP Report No. 5

Slip Rate of the Hosgri Fault: summary of available data and comments on ongoing investigations 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 Geologic Survey (CGS), the California Coastal Commission (CCC), and the California Seismic Safety Commission (CSSC) 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 currently planned or underway by PG&E, this report focuses on one parameter that is important to seismic hazard analysis, summarizes the data that are available to constrain the value of that parameter and uncertainties in its value, and then comments on studies that are currently underway or could be conducted to better constrain its value. We chose to focus first on the slip rate of the Hosgri fault because in sensitivity studies by PG&E and by CGS for the IPRP this parameter has the largest effect of any fault characteristic on calculated seismic shaking potential at Diablo Canyon Power Plant.

INTRODUCTION

This report summarizes the current state of knowledge of the Hosgri fault as a seismic source. This report is provided to help guide the IPRP in forming an opinion in regards to future geologic investigations. Considering the abundance of data that could be reviewed in detail, selections were made to match our resources and follow NRC guide lines (NUREG, 2007), that promote a focus on evaluating pertinent new information by comparison with existing parameters being used. Additionally, we attempted to cover the range of observations and interpretations critical in determining seismic source parameters. This report focuses on the Hosgri fault slip rate because the probabilistic seismic hazard assessment is particularly sensitive to this parameter, as it is effectively proportional to large magnitude earthquake frequency. The Hosgri fault zone has been mapped as a zone of parallel fault strands of various continuity, and with different fault names on the limited onshore portions.

HOSGRI FAULT

The Hosgri fault appears to be the westernmost major right lateral fault accommodating motion between the North American and Pacific plates (Argus and Gordon, 2001, McCaffrey, 2005, Meade and Hager, 2005). Specifically, the Hosgri fault has been interpreted to be part of a zone of faults referred to as the Hosgri fault zone located almost entirely offshore and extending from offshore Point Arguello for approximately 400 km north to the junction of the San Gregorio fault with the San Andreas fault near Bolinas (Hanson et al., 2004, Lettis et al., 2004, Dickinson et al., 2005). The work by Johnson and Watt (2012) demonstrates that an essentially continuous active fault trace exists within this zone of mapped fault traces. At the DCPP the fault parallels the coast approximately 4 km offshore. North of DCPP, the Hosgri fault includes two onshore portions, an onshore section of the fault from San Simeon Point to Piedras Blancas has been named the San Simeon fault (Lettis et al., 2004). Johnson and Watt, (2012) recently reevaluated the continuity of faulting between the Hosgri and San Simeon faults and consider the Hosgri and San Simeon faults to be sections of the same fault.

The second onshore portion is located near Point Sur, where the fault is named the Sur fault. Offshore surveys are not currently sufficient to show if the Sur fault is continuous with the offshore faults in the fault zone. Relatively low cumulative displacement on the Sur fault (Underwood et al., 1995) indicates that the onshore Sur fault may be one of additional parallel active faults which make up the Hosgri-San Gregorio fault zone. If this is the case, some slip may take place on parallel faults offshore. From Monterey Bay north, the fault is named the San Gregorio fault. The long-term slip of the San Gregorio fault has been reported to be decreasing through time with estimated slip rates of: 25-30mm/yr for 8-10 Ma, 16mm/yr for 3-8 Ma and 6mm/yr for 0-3 Ma (Clark et al., 1999).

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 assessing what controls the uncertainty of the slip rate estimate.

Fault Displacements

The distance that a geologic feature has been offset is the fault displacement, and on strike-slip faults is a horizontal map distance. Measurements typically include an estimate of the uncertainty associated with projecting a feature of interest to the fault plane. The fact that the original shape of the offset geologic feature is rarely known precisely often results in considerable uncertainty. The original shape is needed because the features rarely extend to the actual fault plane, but usually must be projected to it. Complicating this task is the uncertainty in the fault location, or width of fault zone. For example, the Hosgri fault zone includes extensive mapped portions that consist of multiple fault strands. Often offset measurements do not include individual features that cross all strands. Projections across an entire fault zone often include a subjective measure and hence are not unique. What is probably of greater importance is that projections should include the entire range of possibilities. In practice, most workers report the entire offset range and sometimes a preferred narrower range. The criteria for the preference vary greatly and often include considerations that are separate from the actual field observations, such as consistency with other measurements elsewhere.

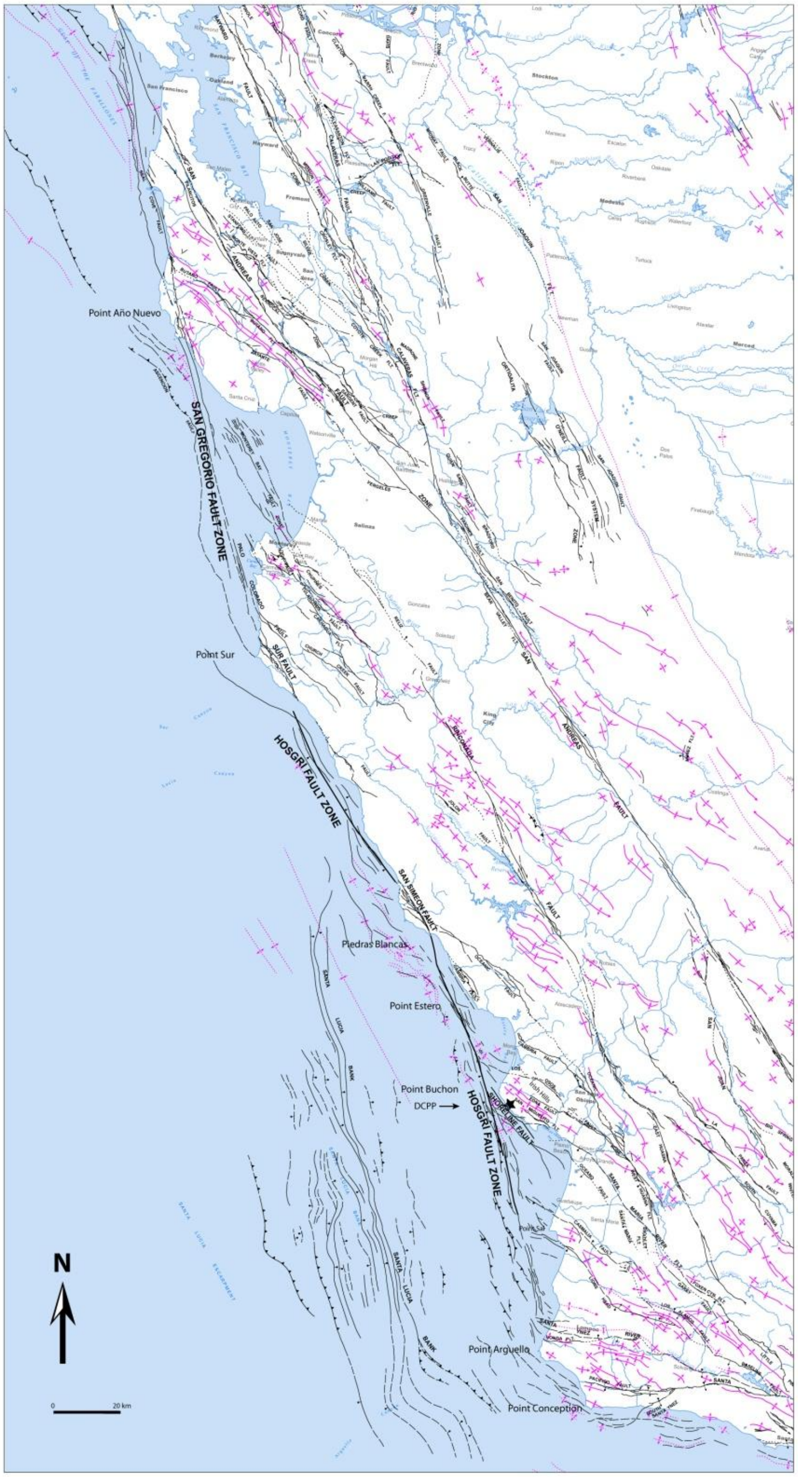

Figure 1 Regional Hosgri Fault Zone Map. The Hosgri Fault Zone links continuously with the San Gregorio Fault Zone to the north. The onshore fault portions were named differently before it was recognized that they are part of the longer mostly offshore fault zone. Located nearest to and north of DCPP is the San Simeon Fault, which provides most of the direct geologic slip rate estimates. Prominent coastal landmarks are indicated from Point Conception to Point Año Nuevo.

Chronology

The time measurement in a fault slip rate calculation is the age of the geologic feature. Chronologic methods to determine geologic ages are quite varied, but can be separated into two groups, absolute and correlative methods. Absolute or numerical methods include radiometric methods, such as radiocarbon (C-14), Th/U (Thorium-Uranium), H/U (Helium-Uranium), luminescence methods, including TL (Thermoluminescence), OSL (Optically Stimulated Luminescence), and cosmogenic radionuclide surface exposure dating (CNS). These methods have distinct advantages over correlative methods as they can avoid the additional uncertainty of miscorrelations. That is, in principle, the age of the feature of interest can be measured directly. Generally, the uncertainties cited are restricted to the analytical methods. Additional uncertainty, often not explicitly considered, is the context uncertainty. This is the degree to which the dated sample represents the age of the feature of interest. For example when the objective is to determine the age of a soil infilling a faulted channel deposit, one may sample detrital charcoal from the channel fill. The charcoal can be radiocarbon dated and may yield a relatively precise age determination with a well defined analytical error. However, suppose the detrital charcoal was derived from an old growth tree that was 2000 years old when it burned, and then it took an additional 500 years until it was incorporated into the channel fill deposit. The radiocarbon age in this case would overestimate the age by 2500 years due to the context uncertainty that is often unknown and difficult to estimate.

CNS dating differs from traditional radiometric methods in that it employs an accumulation clock as opposed to a decay clock. Traditional radiometric dating relies on the radioactive decay of an unstable isotope, and hence measures the ratio of unstable to stable isotope that deceases with age. In general, a decay method’s useful age range is ten half lives of the unstable isotope. With the CNS methods, the unstable isotope is being produced as a result of cosmogenic radiation and hence it accumulates. This means that the older the sample, the greater the amount of the unstable isotope. The unstable isotopes still undergo decay; however the half lives of the CNS isotopes are generally relatively long and losses through decay can be corrected for in determining ages of deposits. CNS dating is relatively new and has not been extensively applied to the marine terraces along the California coast.

Marine terraces, relatively planar gently sloping surfaces formed by wave erosion, are commonly used to estimate fault slip rates along the California coast. Terraces, or deposits overlying terrace surfaces, can be directly dated as described above, or terrace ages can be estimated by correlation with terraces elsewhere, or by correlation to global sea level curves. Correlative methods include those based on world-wide sea level changes characterized by oxygen isotope ratios, which can be correlated to marine terrace elevations, and those based on faunal assemblages from the terrace deposits which were correlated to dated terraces elsewhere using paleoclimatic analysis. Utilizing the paleo sea-level information involves various assumptions and is often simplified when workers assume that terraces form during sea level high stands; the peaks in the sea level curve. In this scheme, less developed terraces are commonly associated with less prominent sea level high stands. A subgroup of correlative methods involves measurements that are calibrated to known ages such as: degree of soil development or amino acid racemization of marine shells. Another method of terrace dating is by comparing the development of soils on their surfaces. The relative soil development method is quite effective for correlating terrace surfaces in a geographically restricted area where soil development factors are relatively uniform. Quantitative age results derived from relative soil development indices have very large uncertainties. An example of applying the soil development to terrace correlations at San Simeon is provided by Rockwell et al. (1994).

Slip Rate Time Spans

Utilizing fault slip rates for Probabilistic Seismic Hazard Analysis requires the consideration of the slip rate time span, and specifically whether the slip rate estimate accurately represents current fault behavior. Fault systems are dynamic, and are continually evolving to new geometries. This is clearly evident in fault maps in which most faults are no longer active. However, these changes occur over fairly long time periods perhaps on the order of more than 100 ka, to more than 1 ma. For this reason, seismic hazard analyses generally use slip rates based on offset of geologically recent features. Offset of Holocene and late Pleistocene features generally are thought to be representative of current fault behavior. In general, the younger the geologic feature, the better it can be geomorphically characterized, resulting in more precise offset measurements. At the shorter end of the time spectrum, very short slip rate estimates that approach the recurrence intervals of the faults may not be representative of the long term seismic potential of the fault.

Geodetic Slip Rate Estimates

Geologic slip rate estimates can be compared with completely independent estimates based on geodetic studies. Geodetic slip rate determinations are derived from survey stations that are precisely located by GPS (Global Positioning System) measurements. The raw survey data are modeled and can be used to estimate fault slip rates. This method measures very small distance changes (in the mm range) over relatively short time spans (years). The short time span compared to other fault slip rate measurements requires additional considerations related to the individual earthquake occurrences, which perturb the deformation field due to viscoelastic plate motion behavior. This method excels at determining slip rate budgets over regional areas. However, the method is challenged when individual fault slip rates are sought. Modeling these data has shown how adjacent faults have very highly correlated slip rates, hence any applied slip rate constraints to individual faults have a great effect on the faults with unknown rates. This characteristic has been exploited by geodetic modelers and can be used to estimate slip rates on faults that are not accessible, such as offshore faults.

SUMMARY OF SLIP RATE STUDIES ON THE HOSGRI FAULT

Geologic Slip Rate Estimates

The geologic slip rate estimates from previous studies will be presented below in order from south to north. Slip rate values and uncertainties are summarized in Table 1 and on Figure 2.

The Airport Creek site fault trench investigation (Hall et al., 1994) at San Simeon yielded three slip rate estimates (2,3,4; Table 1, Fig. 2).These slip rate estimates are for features dating from 5 to 14 ka, and include important assumptions in projection and feature characterization. The apparently offset features consist of a basal terrace gravel, a terrace margin and a vertically separated soil layer. The confidence levels for the central estimates of these slip rates are weak although the range of the estimates (0.9-3.4 mm/yr) appear reasonable. A series of emergent marine terraces (5,6,7; Fig.2) at San Simeon Point ranging in age from 80 ka or 105 ka to 210 ka are offset by the San Simeon fault (Hanson and Lettis, 1994). In order to measure the lateral displacements across the two fault strands comprising the fault zone, sophisticated geometrical reconstructions were used. Additionally, the vertical separations across the fault zone were considered. For each of these marine terraces, two slip rates were calculated, the first based on the lateral displacement and the second inferred from the vertical separation. In general, the more straight forward estimate based on the lateral offsets yielded higher rates: (5) < 11.2 or <8.6 mm/yr for the San Simeon Terrace (80 or 105 ka), (6) 0.8-7.8 mm/yr for the Tripod Terrace (120 ka), and (7) 0.7 - 2.6 mm/yr for the Oso Terrace (210 ka). In contrast the slip rates inferred from the vertical separations were generally lower (5) 1.6-3.6 or 1.2-2.2 mm/yr, (6) 0.7-1.5mm/yr and (7) 0.4-1.0 mm/yr. This lower set of values based on the vertical separations appears to be more consistent with geodetic rates and was thus preferred by the authors. However, both estimates are permissible because the higher lateral-offset derived rates from the San Simeon terrace (5) represent maximum rates. Hanson and Lettis (1994) comment that measuring the vertical separations does not require the more involved and uncertain projections and reconstructions of the lateral offset measurements, even though the use of slickensides from a distant trench as the parameter to convert vertical into lateral displacement estimates is required.

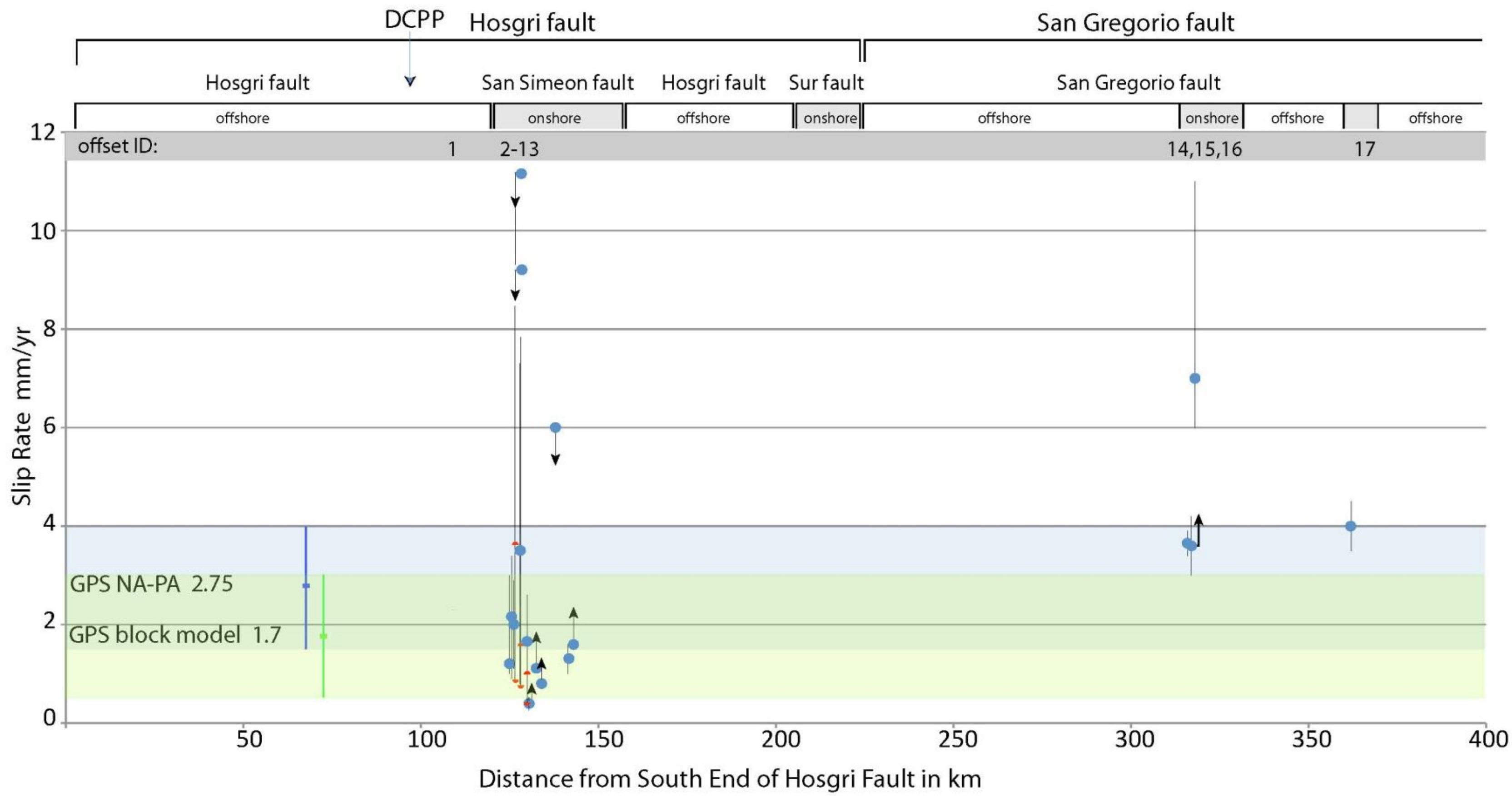

Figure 2 Hosgri –San Gregorio Fault Slip Rates. Geologic fault slip rates are shown with blue dots and associated errors. Downward pointing black arrows indicate a maximum rate whereas upward pointing black arrows indicate minimum rates. Red half dots indicate offset terrace slip rates inferred from 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).

ID	feature	km	offset m	age ka	rate mm/yr	type	reference
1	submerged prograde sandbar target	109					Johnson,2012
2	Airport Soil Horizon	125	10.18-13.32	9.24-9.91	1.0-3.0, best 1.0-1.4		Hall et al., 1994
3	Airport Basal Terrace Margin	126	9.37-11.42	8.95±0.26	0.9-3.4		Hall et al., 1994
4	Airport Basal Terrace Gravel	127	16-28	10.8-13.8	1.1-2.9		Hall et al., 1994
5	San Simeon Terrace	127.5	<900	80 120	<8.6,*1.2-2.2* <11.2,*1.6-3.6*	max	Hanson and Lettis, 1994
6	Tripod Terrace	128	100-930	120	0.8-7.8,*0.7-1.5*		Hanson and Lettis, 1994
7	Oso Terrace	130	150-550	210	0.7-2.6,*0.4-1.0*		Hanson and Lettis, 1994
8	Creek Margin n1	130.5	100-175	<330	0.3-0.5	min	Hanson and Lettis, 1994
9	Stream Channel n2l a	132.5	360	<430	1.1	min	Hanson and Lettis, 1994
10	Stream Channel n2 b	134	360	<480	0.8	min	Hanson and Lettis, 1994
11	Arroyo de la Cruz Channel n3	138	3000	>480	6	max	Hanson and Lettis, 1994
12	Arroyo de Los Chinos n5	141.5	430	320-500	1-1.6	min	Hanson and Lettis, 1994
13	Arroyo de Los Chinos n6	143	360-550	<330	>1.6	min	Hanson and Lettis, 1994
14	SG Ano Nuevo Terrace 5a Channel	316	250-350	<83	3.4-3.9	min	Caskey, 2012
15	SG Ano Nuevo Terrace 5a Margin	317	280-320	<83	3.0-4.2	min	Caskey,2012
16	Ano Nuevo	318			6.0-11.0		Weber et al., 1995; Clark et al., 1999
17	SG Seal Cove	362			3.5-4.5	min	Simpson et al., 1999

Table 1 Hosgri –San Gregorio Geologic Fault Slip Rates. Offset ID 1-17 are used for reference in text and on Figure 2. Distance is in km from Point Arguello. Offset distance shown in meters. The age of the offset feature is shown in thousand years (ka). If the slip rate represents a limit it is indicated, as a maximum or minimum, and shown in Figure 2 with an arrow.

Along the entire San Simeon fault a series of stream drainages (8,9,10,11,12,13; Table 1,Fig. 2) appear to be offset across the fault zone (Hanson and Lettis, 1994). The main assumptions inherent in these slip rate estimates are that one can confidently correlate drainages across the fault zone and that the apparent deflections are entirely due to fault displacement. Only limiting age control is provided by the drainages being incised into known age surfaces; one does not know how long after formation of the surface this incision occurred. Hence these resulting slip rates are minimum estimates with the exception of (11). The Arroyo de la Cruz Channel offset (11) is reported as a maximum rate of 6mm/yr, because the channel deflection cannot entirely be attributed to fault displacement with confidence. The age estimates for these terraces range from 320 ka to 500 ka. The resulting slip rate minimums range from 0.3 to 1.6 mm/yr. Minimum slip rate estimates are not as valuable in seismic hazard analysis as more precise values, but they do provide constraints to combine with other slip rate estimates.

At the Ano Nuevo headlands two offset features along the San Gregorio fault have been reevaluated by Caskey (2012) using LiDAR as presented by Hanson (2012). These offsets (14,15) consist of an offset terrace riser (83 ka or 105 ka) and the Green Oaks Creek drainage incised into the 83 ka surface. The resulting slip rates estimated by Caskey are 3.4-3.9 mm/yr and 3.0-4.2 mm/yr, respectively. Previous workers (Weber et al., 1995; Clark et al., 1999) calculated higher rates(16), mainly due to additional offset inferred on an eastern strand that Caskey asserts does not exist or is no longer active.

Geodetic Slip Rates

GPS (Global Positioning System) geodesy provides overall crustal deformation rates of central coastal California. Geodesy complements geologic slip rate data by providing a more robust total deformation budget across a region. This is largely due to the wide aperture and distribution of observations as contrasted with the inherently narrow fault-specific perspective provided by geologic investigations. Because faults usually are locked at the surface, and do not move between earthquakes, determining fault specific rates with geodesy requires sophisticated modeling. Various modeling approaches spanning the spectrum from relative rigid block models to continuum models provide bounds on deformation rates within regions that span multiple faults in California. The results, however, are non-unique with respect to the details of slip on individual faults. The data consist of a combination of continuously-recording and campaign-style survey stations located throughout North America. The fault-specific central coast geodetic analysis relied on data spanning the past 16 years from a relatively dense network network. Models focus on the kinematics of the Sierra Nevada micro-plate versus the Pacific plate and consistently estimate ~5 mm/yr lower slip rates across the San Andreas fault compared to geologic studies. The significance of this discrepancy is that if the geodetic rates truly represent current deformation then more deformation must be occurring on other faults to the west. Murray et al. (2012) tested a variety of block models with different constraints, which resulted in possible Hosgri fault slip rates in the range from 0.5-3mm/yr. DeMets (2012) focused his analysis on Sierra Nevada versus Pacific plate motion in central California and concluded that 3-4 mm/yr of plate-boundary-parallel motion is occurring on faults west of the West Huasna fault. He presented an alternative interpretation that allows for deformation within the Pacific plate, which results in 1.5-2.5 mm/yr on these faults, but deemed it less likely. This study assumes minimal viscoelastic residual motion from the largest recent San Andreas fault earthquakes that occurred in 1857 and 1906. The overall bounds for deformation west of the West Huasna fault are between 1.5±1 mm/yr and 4±1 mm/yr (both at the 95% confidence level).

Ongoing Studies

Ongoing geologic studies to refine estimates of the slip rate on the Hosgri fault slip rate target were presented by Johnson and Watt (2012; Figure 14), at the second SSHAC seismic source characterization workshop (November 7, 2012) and AGU (Johnson and Watt, 2012) and by PG&E at the IPRP meeting on February 25, 2013. Johnson and Watt (2012) have mapped a fairly linear ridge which crosses the Hosgri fault at a high angle and appears to be offset. It is located about 15 km south of where the Hosgri fault and San Simeon coast intersect. This feature has been imaged by high- resolution multibeam bathymetry and by high-resolution seismic profiles. Further analysis based on a new (2012), focused, USGS multibeam bathymetric survey, and age estimates based on paleo sealevel should lead to a robust slip-rate estimate.

As shown in Johnson and Watt (2012; Figures 14-18) the Hosgri fault branches into a western and eastern branch approximately 25 km south of San Simeon. Although it is clear that the eastern strand is the more continuous through-going active fault from the branch point north, an unknown, but probably lesser amount of slip may occur on the western branch. Seismic reflection profiles show the western strand terminates into the Piedras Blancas fold belt. Johnson and Watt interpret that this western strand of the Hosgri fault bends further west and transitions into a series of eastward dipping blind thrust faults beneath the Piedras Blancas fold belt (Johnson and Watt, 2012; Figure 18). Johnson and Watt (2012) assert that because slip has been accommodated in the Piedras Blancas fold belt to the north associated with this western fault strand, the overall slip rate should increase south of the fault juncture of the east and west fault strands.

PG&E (1990) quantified the amount of slip in the Piedras Blancas fold belt as a total of 0.3±0.1 mm/yr of crustal shortening, with normal and tangential components resolved at 0.3mm/yr and <0.1 mm/yr, respectively. These slip rate analyses were made with the assumption that there is a clear step-over from the western active fault strand to the south to the San Simeon fault to the north. These rates could be higher if the deformation initiated or increased more recently than assumed.

At the February 25 IPRP meeting, PG&E presented ongoing work being undertaken to further characterize the Hosgri slip rate. They defined two areas along the Hosgri fault where they have collected low energy high resolution 2D survey grids (Figure 3). The areas are elongate fault parallel boxes designed to capture geologic structures that cross the fault. The survey box dimensions are approximately 4 x 18 km and 4 x 35 km, for the northern and southern boxes, respectively. The northern survey box extends along the fault from the latitude of Cayucos south, and the southern survey box extends south from Pismo Beach. Apparently the survey box locations were selected based on the perception that they were likely to include offset fault-crossing structures such as buried channels. During the last glacial maximum (LGM) approximately 20 ka ago, the sea-level was 130 m below current sea level. Both survey boxes are located at depths shallower than the LGM sea-level and hence may contain channels eroded during the LGM. Similar sea levels occurred during marine stages 5e approximately 130ka ago, 7a, and 9c. Given the data we have reviewed, it is not clear how comprehensive this selection of focused survey targets has been. However, the value of slip rate determinations in these areas is very high.

The northern survey area includes considerable fault complexity as it extends from north of the Los Osos fault intersection to south of the Shoreline fault intersection. Within the survey box the water depth along the Hosgri fault is approximately 80m. The northern end of the Shoreline fault trace is based on a projection of a modeled fault plane using micro earthquake locations at depths of 5-12 km. Recent mapping by PG&E has identified a fault slightly northeast of the originally mapped northern Shoreline fault, which they named the Point Buchon fault. This fault and its associated traces extend to within 500m of the Hosgri fault trace.

The southern box is located between the Pecho and Casmalia fault intersection projections. Within the survey box the water depth along the Hosgri fault is approximately 110m to 120m. The Casmalia fault bends northward as it approaches the Hosgri fault from the east, and trends parallel to it at a distance of approximately 2 km. The northern end of the Casmalia fault zone terminates in shorter discontinuous faults. The Pecho fault, possibly an extension of the onshore Oceano fault, and perhaps bounding the southern end of the Shoreline fault, is much less expressed compared to the Casmalia fault and has been mapped as transitioning into a series of folds which approach the Hosgri fault. These fold structures bend northward and become parallel to the Hosgri fault.

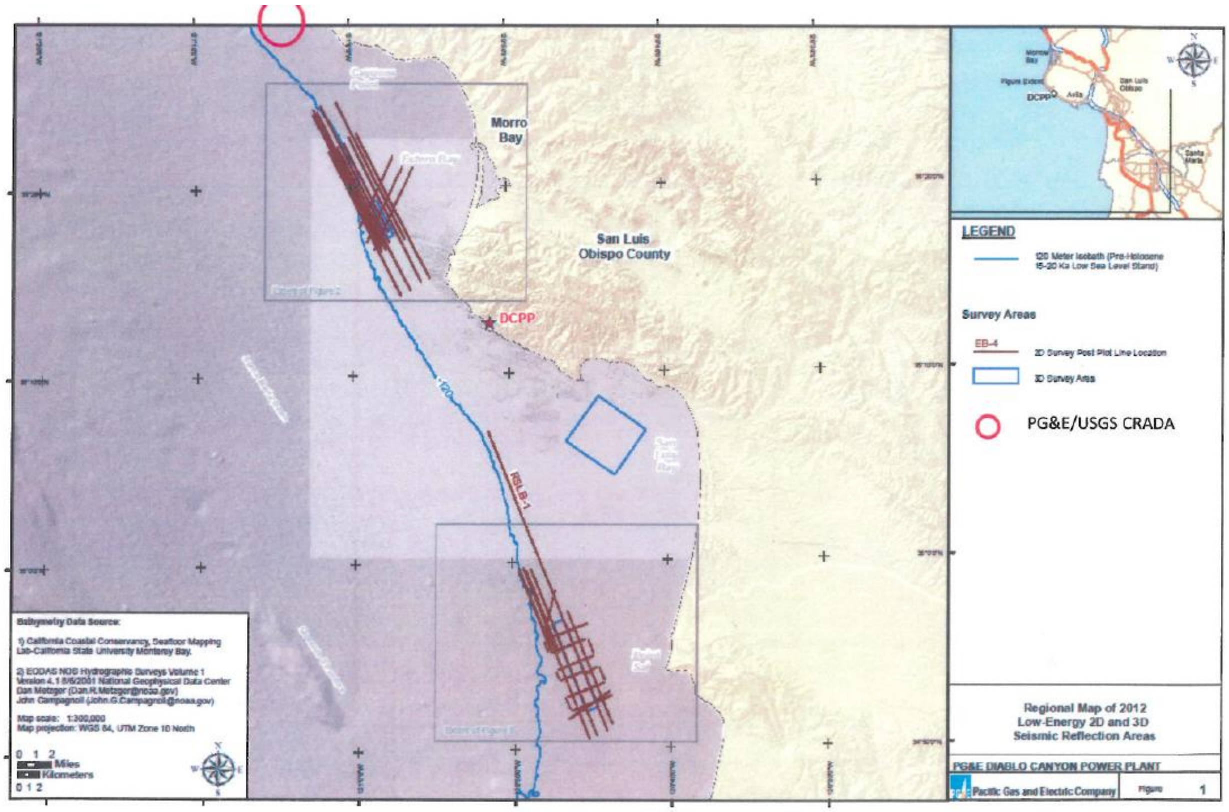

Figure 3 Ongoing PG&E Hosgri Fault Slip Rate Targets. The two survey boxes (northern and southern in text) include the seismic reflection profile survey tracks (red lines), which are parallel to and straddle the Hosgri fault zone. This configuration is used to identify potential piercing structures offset by the fault, which may provide slip rates.

Summary

The slip rate on the Hosgri fault is one of the most important parameters in seismic hazard analysis for Diablo Canyon Nuclear Power Plant. Slip rate can be determined from geologic data or geodetic data. Geologic slip rate values are based on total fault offset since a geologic feature was formed, so are averages over many earthquakes. Geodetic values are based on recent surveys, so give rates of strain that currently are accumulating and may be released in earthquakes. Given the differing time spans of these data sets and uncertainties in both, the similar values derived from geologic and geodetic data suggest that these values accurately represent the amount of strain available to be released in earthquakes.

Geologic slip rate studies have been restricted to on-land parts of the Hosgri fault until recently. Studies of the fault onshore north of San Simeon are the primary constraint on slip rate on the Hosgri fault. Although there was some uncertainty about how slip on the fault at San Simeon applies to slip on the Hosgri fault offshore when these studies were done, recently collected high-resolution multibeam bathymetry supplemented by high-resolution seismic profiling (Johnson and Watt, 2012) shows the offshore Hosgri fault to have a continuous surface trace with the San Simeon fault. This new finding of a continuous fault strengthens the use of onshore San Simeon slip rate estimates as representative for the Hosgri fault to the south. There are several structural complexities that justify some possible along-strike variability in the slip rate of this fault system. Attempts have been made to quantify the bounds of this possible variability (Hanson et al., 1994; Hanson and Lettis, 2004; Johnson and Watt, 2012). The decrease or increases in slip rate to the south of San Simeon are minor (in the 0.1 mm/yr range for the component resolved in a strike-slip direction) compared to the overall errors in the aggregate of estimates. The legacy assessment of the Hosgri slip rate ranged from 0.5 to 6 mm/yr with a preferred rate of 2.0 mm/yr. The current findings justify reducing the upper bound. All determinations above 4 mm/yr have been reported as maximums.

The geodetic constraints add bounds on the Hosgri slip rate as indicated in Figure 2. A wider aerial perspective is provided by assessing the rate in relation to the entire Pacific plate, resulting in a best averaged rate of 2.75 mm/yr (DeMets, 2012). This rate represents the entire offshore slip rate budget west of DCPP. Block modeling allows a more fault-specific slip rate determination but is very sensitive to the details of the block boundary geometries and any constraints put on individual boundaries. Because most of the Hosgri fault is offshore, with no direct slip rate determinations to date, this modeling provides an approach to assessing the offshore rate by improving our slip rate estimates on all other faults, most of which are located onshore. Sorlien (2012) presented the possibility that slip may be occurring on faults west of the Hosgri fault. If true, this would decrease the Hosgri slip rate (DeMets, 2012).

Ongoing studies of offshore geologic features that may be offset by the Hosgri fault are closer to Diablo Canyon than the previous studies near San Simeon. Johnson and Watt (2012) have identified a linear ridge that appears to be offset by the Hosgri fault. PG&E has conducted surveys in two locations where channels eroded during the last glacial maximum may have crossed the fault and subsequently been offset. The IPRP finds that this type of study has a high likelihood of further deceasing the uncertainty in the slip rate on the Hosgri fault and thus the uncertainty in seismic hazard at Diablo Canyon.

REFERENCES

Argus, D.F., and Gordon, R.G., 2001, Present tectonic motion across the Coast Ranges and San Andreas fault system in central California: Geological Society of America Bulletin, v. 113, p. 1580–1592.

Caskey, J., 2012, Hosgri-San Simeon Fault Zone Geologic Slip Rate; presented by Hanson, K.L. at Diablo Canyon SSHAC workshop, Nov. 7, 2012

Clark , J.C., Weber, G.E., Rosenberg, L.I., and Burnham, K., 1999, Neotectonics of the San Gregorio fault zone, Central Coastal California: Pacific Section AAPG Field Trip Guide, April 28, 1999, p. 119-144.

DeMets, C, 2012, Kinematics of central coastal California inferred from GPS geodesy, Diablo Canyon SSHAC workshop, Nov. 7, 2012.

Dickinson, W.R., Ducea, M., Rosenberg, L.I., Greene, H.G., Graham, S.A.,Clark, J.C.,Weber, G.E., Kidder, S., Ernst, W.G.,and Brabb, E.E., 2005, Net Dextral slip, Neogene San Gregorio-Hosgri Fault Zone, coastal California: Geologic evidence and tectonic implications: Geologic Society of America Special Paper, 391, 43 p.

Hall, N.T., Hunt, T.D., and Vaughan, P.R., 1994, Holocene behavior of the San Simeon Fault Zone, south- central coastal 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. 167–189.

Hanson, K.L., Kelson, K.L., and Wesling, J.R., 1990, Neotectonics of the south-central coastal California: Friends of the Pleistocene, Pacific Cell, 1990 Fall Field Trip Guidebook, p. 91-138.

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., eds., 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 coastal 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. 45–71.

Hanson, K.L., Lettis, W.R., McLaren, M.K., Savage, W.U., and Hall, N.T., 2004, Style and rate of Quaternary deformation of the Hosgri Fault Zone, offshore southcentral California: U.S. Geological Survey Bulletin 1995-BB, 33 p.

Hanson, K.L., 2012, Hosgri-San Simeon Fault Zone Geologic Slip Rate, Diablo Canyon SSHAC workshop, Nov. 7, 2012.

Johnson, S.Y., and Watt, J.T., 2012, Influence of fault trend, bends, and convergence on shallow structure and geomorphology of the Hosgri strike-slip fault, offshore central California, Geosphere, dec. 2012,; vol. 8;no 6; p. 1632-1656.

Johnson, S.Y., and Watt, J.T., 2012, Influence of fault trend, bends, and convergence on shallow structure and geomorphology of the Hosgri strike-slip fault, offshore central California, Diablo Canyon SSHAC workshop, Nov. 7, 2012.

Johnson, S.Y., and Watt, J.T., 2012, Influence of fault trend, bends, and convergence on shallow structure and geomorphology of the Hosgri strike-slip fault, offshore central California, Geosphere, dec. 2012,; abst. AGU fall meeting.

Lettis, W.R., DiSilvestro, L., Hanson, K.L., and Shiller, G.I., 1990, The San Simeon/Hosgri pull-apart basin; implications for late Quaternary activity on the Hosgri Fault Zone, *in* Lettis, W.R., Hanson, K.L., Kelson, K.I., and Wesling, J.R., eds., Neotectonics of the south-central coastal California: Friends of the Pleistocene, Pacific Cell, 1990 Fall Field Trip Guidebook, p. 91–138.

Lettis, W.R., and Hall, N.T., 1994, Los Osos Fault Zone, 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. 73–102.

Lettis, W.R., Hanson, K.L., Unruh, J.R., McLaren, M.K., and Savage, W.U., 2004, Quaternary tectonic setting of southcentral coastal California: U.S. Geological Survey Bulletin 1995-AA, 21 p.

McCaffrey, 2005, Block kinematics of the Pacific-North American plate boundary in the southwestern United States from inversion of GPS, seismological, and geologic data: Journal of Geophysical Research, v. 110, 27 p.

Meade, B.J., and Hager, B.H., 2005, Block models of crustal motion in southern California constrained by GPS measurements: Journal of Geophysical Research, v. 110, 19 p.

Murray, J., Svarc, J., Hearn, E., Thatchter, W., 2012, Regional deformation and kinematics from GPS data, presented by Murray, J. at Diablo Canyon SSHAC workshop, Nov. 7, 2012.

NUREG, 2007, A Performance-Based Approach to Define The Site-Specific Earthquake Ground Motion, Regulatory Guide 1.208, U.S. Nuclear Regulatory Commission, p.53.

PG&E, 1990, Response to RAI GSG Q13-2, Piedras Blancas antiform, assessment or orientation, rates and sense of vergence.

Rockwell, T., Vaughn, P.R., Bickner, F., and Hanson, K.L., 1994, Correlation and age estimates of soils developed in marine terraces across the San Simeon fault zone, central 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. 151-166.

Simpson, G, D., and Lettis, W.R., 1999, Slip rate and earthquake history of the northern San Gregorio Fault, Half Moon Bay to Moss Beach, CA, AAPG bul., April , 83 (4):701

Sorlien, C., 2012, Late Cenozoic kinematic model for transfer of strain along the California margin, Diablo Canyon SSHAC workshop, Nov. 7, 2012.

Weber, G. E.,Nolan, J.M, and Zinn, E.K., 1995, Determination of Late Pleistocene-Holocene slip rates along the San Gregorio fault zone, San Mateo Co., CA: U.S. Geological Survey Final Technical Report, National Earthquake Hazard Reduction Program, 52 p.

Weber, G. E., 1990, Late Pleistocene slip rates on the San Gregorio fault zone at Point Ano Nuevo, San Mateo County, California, in Griggs, G. B. and Weber, G. E., eds., Coastal Geologic Hazards and Coastal Tectonics, Northern Monterey Bay and Santa Cruz/San Mateo County Coastlines, Field Trip Guide: Association of Engineering Geologists, March 3, 1990, p. 64-79.

Weber, G. E., 1990, Late Pleistocene slip rates on the San Gregorio fault zone at Point Ano Nuevo, San Mateo County, California, in Geology and tectonics of the Central California coast region, San Francisco to Monterey, Volume and Guidebook, Garrison, R. E., and others (eds.), Pacific Section, Am. Assoc. Pet. Geol., p. 193-204.

Titus, S.J., Dyson, M., DeMets, C., Tikoff, B., Rolandone, F., and Burgmann, R., 2011, Geologic versus geodetic deformation rates adjacent to the San Andreas Fault, central California: Geological Society of America Bulletin, v. 123, p. 794–820, doi:10.1130/B30150.1.

Underwood, M.B., Laughland, M.M., Shelton, K.L., and Sedlock, R.L., 1995, Thermal-maturity trends within the Franciscan rocks near Big Sur, California: Implications for offset along the San Gregorio-San Simeon-Hosgri fault zone, Geology, v.23; no. 9; p. 839-842.

U.S. Geological Survey (USGS), 2008, NAMSS: National Archive of Marine Seismic Surveys: http://walrus.wr.usgs.gov/NAMSS/ (January 2012).

U.S. Geological Survey (USGS), 2009, California Seafloor Mapping Program: http://http://walrus.wr.usgs.gov/mapping/csmp/ (January 2012).