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ABSTRACT

The San Diego County Water Authority (Water Authority) is undertaking a raise of the existing San Vicente Dam to provide both emergency and carryover storage to increase local reservoir supplies in San Diego County, California, USA. The emergency storage is required in case of a disruption to the imported water transmission system from floods or earthquakes and the carry-over storage would be utilized to store water during “wet” seasons to carry-over to seasons of drought. The existing San Vicente Dam is a 220 foot (67 m) high concrete gravity dam completed in 1943 with 90,063 acre-feet of storage. The raised San Vicente Dam will be about 337 feet (102.3 m) high, creating an approximately 247,000 acre-foot reservoir. The dam raise will be constructed using the roller compacted concrete (RCC) method.

This paper presents details of the seismic hazard evaluation that formed the basis for development of strong ground motions that were considered in final design of the dam raise. The dam is under the jurisdiction of the California Department of Water Resources, Division of Safety of Dams (DSOD) which requires the use of deterministic ground motions for design. However, the earthquake ground motions at the site are largely controlled by background (or random) earthquakes, which cannot be adequately addressed using deterministic methods alone. This prompted the development of supplemental seismic design ground motions based on a probabilistic seismic hazard analysis (PSHA). The PSHA was performed incorporating the latest information on seismic sources and recently developed Next Generation of Attenuation (NGA) relationships. Based on the results of the PSHA, ground motion parameters (response spectra and time histories) were developed for final design of the dam raise. Comparisons of the deterministic and probabilistic ground motions are provided. Application of the NGA relationships resulted in lower estimates of peak ground accelerations than what were obtained based on the previous attenuation relationships due to the use of the site-specific shear wave velocities of the foundation materials.

INTRODUCTION

It is planned to raise the existing San Vicente Dam to provide both emergency and carryover storage to increase local reservoir supplies in San Diego County, California, USA. The existing San Vicente Dam is a 220 foot (67 m) high concrete gravity dam completed in 1943 with 90,063 acre-feet of storage. The raised San Vicente Dam will be about 337 feet (102.3 m) high, creating an approximately 247,000 acre-foot reservoir. The dam raise will be constructed using the roller compacted concrete (RCC) method.

The San Vicente dam site is located on the western flank of the Peninsular Ranges physiographic province, northeast of San Diego, California. The Peninsular Ranges have a batholithic granitic core and are characterized by northwest-trending faults and geomorphic features. The dam and reservoir lie within a broad contact zone between the Tertiary-age sedimentary rock formations and the Cretaceous-age intrusive batholith. The contact zone includes north-northwest trending belts of older rocks, including Jurassic-age metavolcanic rocks and igneous plutonic bedrock from the Late Jurassic/Early Cretaceous.

SEISMOTECTONIC SETTING

The seismotectonic setting of San Diego County is influenced by plate boundary interaction between the Pacific and North American lithospheric plates. This crustal interaction occurs along a broad belt of northwest-trending, predominately right-slip faults that span the width of the Peninsular Ranges and extend into the offshore Intercontinental Borderland province.

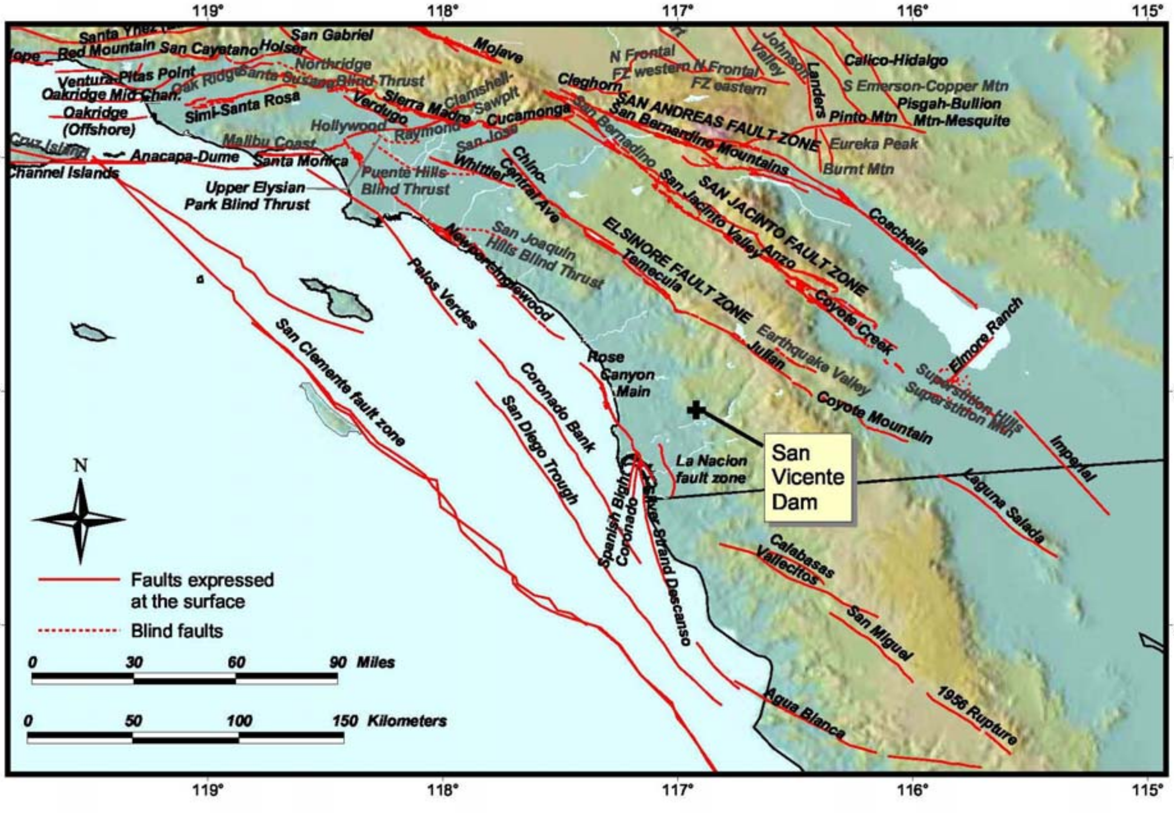

Fig. 1. Active Faults in southwestern California

The potential for large earthquakes is high as the plates slip past each other. The locations of significant faults in southern California are shown in Fig. 1.

The active and potentially active seismogenic faults shown on Fig. 1 are considered to be seismic sources significant for design of the dam raise in terms of strong ground shaking. Seismic source parameters for the most significant faults are listed in Table 1. The three most important faults, nearest to the dam site, for consideration in design were: the Elsinore, La Nacion and Rose Canyon faults.

Elsinore Fault

The nearest segment of the Elsinore fault (Julian segment) is located approximately 36 km east of the site (Fig. 1). The Elsinore fault is a 250-km-long, right-lateral strike-slip fault that is a significant part of the San Andreas fault system. It strikes northwest and runs west of the Salton Trough near the Mexican border to Corona where it branches into the Whittier and Chino faults (Fig. 1). The central part comprises several segments, separated by step-overs, which include, from north to south, Glen Ivy, Temecula, Julian, and Coyote Mountain segments. The Laguna Salada fault extends from the southern end of the Elsinore fault into Mexico.

There have been no historical surface-rupturing earthquakes on most segments of the Elsinore fault. Given the lack of paleoseismic data regarding displacement, maximum magnitude estimates for hazard assessments must come largely from empirical area-magnitude relationships. The 2002 California Geological Survey (CGS)/U.S. Geological Survey (USGS) maximum magnitudes ($\mathbf{M}_{\max}$) range from moment magnitude (**M**) 6.8 to 7.1 for individual segments of the Elsinore fault (Cao et al., 2003).

The slip rate on the Elsinore fault is about 5 mm/yr. The Julian segment is in two strands and has a late Quaternary slip rate of 3 to 6 mm/yr based on soil chronostratigraphy (Vaughan and Rockwell, 1986; Petersen and Wesnousky, 1994). The slip rates of the other segments are listed in Table 1.

La Nacion Fault

The La Nacion fault is located about 20 km west of the site and is the closest mapped potentially active fault to the project (Fig. 1). The fault is a 25 to 30 km long zone of down-to-the-west normal faults that forms the eastern boundary of the San Diego Embayment, a Pliocene-Pleistocene nested graben that is bounded on the east by the La Nacion fault and on the west by the east-side-down Point Loma fault, west of San Diego Bay (Marshall, 1989). Artim and Pinckney (1973) mapped the La Nacion fault from just south of Alvarado Canyon (near San Diego State University) to near the U.S.-Mexico border. Artim and Pinckney (1973) suggest a total vertical offset of 500 m, a Pleistocene offset of 120 m and a possible 1m displacement of Holocene alluvium. However, radiocarbon dating of unfaulted alluvium by Hart (1974) and Elliot and Hart (1977) shows that the most recent movement on the La Nacion fault is older than Holocene. Based on these relationships, it is likely that the fault last moved in the late Pleistocene, making this fault potentially active and it was therefore included in the seismic source model (Table 1).

The preferred slip rate in the seismic source model is based on the vertical offset of the Lindavista terrace south of Sweetwater Canyon. There, the geologic map of Kennedy and Tan (1977) shows that the Lindavista terrace is vertically offset 43 to 55m across the La Nacion fault. The preferred age of the Lindavista terrace is 855 ka (Kern and Rockwell, 1992), yielding the preferred slip rate in the seismic source model of 0.05 mm/yr (Table 1). Artim and Pinckney (1973) suggest that the total offset of Pleistocene sediments across the La Nacion fault system could be as much as 120 m, which gives a similar slip rate of 0.07 mm/yr. The upper-bound of the slip rate is estimated from the 500 m total offset of Artim and Pinckney (1973) since the Miocene (5.3 Ma), yielding a slip rate of 0.09 mm/yr. In the seismic source model, this is rounded to 0.10 mm/yr to be consistent with the upper bound slip rate estimate of Anderson et al. (1989). The lower estimate of the slip rate is taken from their published minimum rate and is 0.02 mm/yr. The preferred maximum magnitude for the La Nacion fault is estimated from using the Wells and Coppersmith (1994) regression for surface rupture length and magnitude, yielding **M** 6.7 as the preferred maximum magnitude (Table 1).

Table 1. Seismic Source Parameters

Fault Name/ GEOMORPHIC AREAS	Rupture Length (km)	Slip Rate (mm/yr)	Sense of Slip	Downdip Width (km)	Rupture Top (km)	Rupture Bottom (km)	Dip (degrees)	Preferred M_{max} ± 0.3
Elsinore Fault Zone								
Laguna Salada	67 ± 7	3.5 ± 1.5	rl-ss	15 ± 2	0	15	90	7.0
Elsinore-Coyote Mountain	39 ± 4	4.0 ± 2.0	rl-ss	15 ± 2	0	15	90	6.8
Elsinore-Julian	76 ± 8	5.0 ± 2.0	rl-ss	15 ± 2	0	15	90	7.1
Earthquake Valley	20 ± 2	2.0 ± 1.0	rl-ss	15 ± 2	0	15	90	6.5
Elsinore-Temecula	43 ± 4	5.0 ± 2.0	rl-ss	15 ± 2	0	15	90	6.8
Elsinore-Glen Ivy	36 ± 4	5.0 ± 2.0	rl-ss	15 ± 2	0	15	90	6.7
Elsinore-Whittier	38 ± 4	2.5 ± 1.0	rl-ss	15 ± 2	0	15	75 NE	6.8
Chino -Central Ave.	28 ± 3	1.0 ± 1.0	rl-r-o	17 ± 2	0	15	65 SW	6.7
SAN DIEGO AREA								
Newport-Inglewood (offshore)	66 ± 7	1.5 ± 0.5	rl-ss	13 ± 2	0	13	90	7.0
La Nacion	25 ± 5	0.02, 0.05, 1.0	n	10 ± 2	0	10	70W	6.7
Rose Canyon Fault Zone								
Rose Canyon (from offshore Oceanside south to include Silver Strand fault)	70 ± 10	1.5 ± 0.5	rl-ss	13 ± 2	0	13	90	7.2
Descanso (International Border to Punta Salsipuedes)	55 ± 10	1.5 ± 0.5	rl-ss	13 ± 2	0	13	90	7.1
Floating (Random) Earthquake		1.5 ± 0.5	rl-ss	13 ± 2	0	13	90	7.0

Notes:

a. rl-ss denotes right-lateral strike-slip faulting.
b. rl-r-o denotes right-lateral reverse-oblique faulting.
c. n denotes normal faulting.

The geologic evidence shows that the La Nacion fault is dominantly a normal fault with down-to-the-west displacements. However, the seismic source model used gives some weight (0.10) to the fault being a right-lateral strike-slip fault. In the present tectonic regime, northwest-trending faults within the continental borderlands, including the Rose Canyon fault zone, are dominantly right-lateral strike-slip faults that presently accommodate between 10% to 14% of the total plate boundary motion. The La Nacion fault, which trends north-northwest, is subparallel to the trend of the Rose Canyon fault zone and may accommodate a small fraction of right-lateral shear in the region due to its orientation relative to the present stress regime. Although the geologic evidence shows only evidence of normal faulting, if dextral faulting is present, it could be masked (Kahle, 1988), with insufficient expression in the existing geomorphology to resolve small amounts of right-lateral faulting. Due to this uncertainty, some weight (0.10) was given that the La Nacion fault is a right-lateral fault.

Rose Canyon Fault System

The Rose Canyon fault zone (RCFZ) is a complex zone of north- to northwest-trending right-lateral strike-slip fault segments extending from offshore of Oceanside, though La Jolla, into San Diego Bay, then continuing south into the offshore area west and south of Tijuana, Mexico (Fig. 1). The onshore portion of the RCFZ extends along the northeast flank of Mount Soledad and continues southward along the eastern margins of Mission Bay (Kennedy et al., 1975). Between Mission Bay and San Diego Bay, the zone appears to widen and diverge. Within San Diego Bay, the RCFZ appears to branch into three principal faults extending across Coronado and beyond to the south. These faults are the Spanish Bight, Coronado, and Silver Strand faults (Fig. 1). To the south of San Diego Bay, the southern reach of the Silver Strand fault appears to step to the west to the Descanso fault, which is mapped offshore of Rosarito Beach, Mexico (Legg and Kennedy, 1979) (Fig. 1). The Silver Strand fault lies closer to and is essentially subparallel to the RCFZ trend, and therefore its length is included in the approximate 70 km length of the RCFZ. The slip rate of about 1.5 mm/year is based on detailed trenching along the main trace of the Rose Canyon Fault in Rose Creek (Rockwell et al., 1991) (Table 1).

The Descanso fault appears to be a continuation of the RCFZ into the offshore area west of Rosarito Beach, Mexico. The southern reach of the Silver Strand fault appears to step westward to the Descanso fault at the latitude of the U.S./Mexico International Border. From this area, the Descanso fault continues southward to offshore of Punta Salsipuedes (just north of Ensenada), where the fault appears to merge with the offshore Agua Blanca fault. The Descanso fault extends approximately parallel to the shoreline for a distance of about 55 km. The location and trend of the Silver Strand Fault suggests a close structural association with the Descanso fault; therefore, the fault was modeled as a major segment of the RCFZ. The slip rate is assumed to be the full rate of slip along the RCFZ (i.e., about 1.5 mm per year).

The maximum magnitude of earthquakes that the RCFZ can generate is about **M** 7.2 ± 0.3 based on its rupture length (Table 1). Smaller events are possible, however, given the segmented nature of the fault.

HISTORICAL SEISMICITY

The historical seismicity of the San Diego area is characterized by a moderate level of activity with no large (**M** > 7) earthquakes having been reported in historical times. In contrast, the region to the northeast has experienced a higher rate of seismic activity with many, moderate to large earthquakes having occurred along the Elsinore, San Jacinto, and San Andreas faults (Fig. 2).

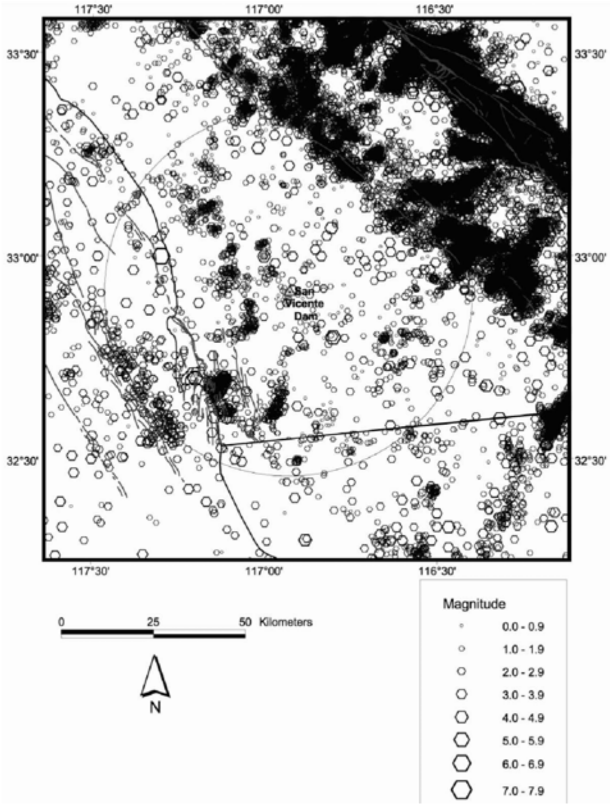

Fig. 2. Historical Seismicity of southwestern California, 1769 to 2004

San Diego has experienced strong shaking and minor damage from several local and distant earthquakes, but none has been very destructive (Agnew et al., 1979; Toppozada et al., 1981). Most of these earthquakes apparently originated at long distances from San Diego, generally from locations in the Imperial Valley or northern Baja California. Earthquakes in 1800, 1862 and 1892 are believed to have produced the strongest intensities in the San Diego area.

Background Seismicity

Fig. 2 illustrates that the dam is in an area where background (floating or random) earthquakes have been recorded that are not associated with the known or mapped faults. In most of the western U.S., the maximum magnitude for earthquakes not associated with known faults usually ranges from **M** 6 to 6½. Repeated events larger than these magnitudes probably produce recognizable fault- or fold-related features at the earth's surface (e.g., Doser, 1985; dePolo, 1994). For final design of the dam raise, a value of **M** 6.5 ± 0.3 was adopted for background earthquakes in southern California and Baja California. The best estimate value and one-sigma uncertainties are weighted in a logic tree similar to M_{max} for the faults.

To address the hazard from background seismicity, two approaches were used: 1) an areal source zone with uniformly distributed seismicity and 2) a gridded source zone in which seismicity varies from grid cell to grid cell. These two models of background seismicity are weighted equally. For the areal source zone, recurrence parameters "b" and "a" were adopted from Stein and Hanks (1998) although it is recognized that their parameters are appropriate for all seismicity in southern California, fault-related and background. The impact on the hazard is probably conservative.

In the second approach, Gaussian smoothing was used to address the hazard from background earthquakes in southern California. A historical catalog of independent mainshocks in the study region from 1852 to 2004 was compiled from various databases. Ranges in seismogenic crustal thickness were assumed for the background earthquakes to be identical to the range used for the faults. In the Gaussian filter approach (Frankel, 1995), the historical background seismicity was smoothed to incorporate a degree of stationarity, using a spatial window of 10 km. A slope of the recurrence curve (b-value) of 0.95 was also used in the Gaussian smoothing.

GROUND MOTION HAZARD ANALYSES

The dam is under the jurisdiction of the California Department of Water Resources, Division of Safety of Dams (DSOD). Planning studies for the dam raise were focused on developing ground motions for the site using a deterministic approach as required by DSOD. However, DSOD also suggested that consideration should be given to a higher level of performance in light of the probable short return period for the design earthquake. A preliminary probabilistic seismic hazard analysis (PSHA) indicated that the ground motions at the site are likely controlled by background (or random) earthquakes, which cannot be adequately addressed using deterministic methods (Wong et al., 2001). This prompted the development of seismic design ground motions based on a PSHA. The PSHA incorporated the latest information on seismic sources and recently developed ground motion attenuation relationships (Next Generation of Attenuation [NGA] models). In addition to the PSHA, deterministic seismic hazard analyses were performed for the two most significant active faults to the damsite, the Elsinore and La Nacion faults, using previous attenuation relationships and the NGA models.

Probabilistic Seismic Hazard Analysis

The PSHA approach used in this study is based on the model developed principally by Cornell (1968). The occurrence of earthquakes on a fault is assumed to be a Poisson process. The Poisson model is widely used and is a reasonable assumption in regions where data are sufficient to provide only an estimate of average recurrence rate. When there are sufficient data to permit a real time estimate of the occurrence of earthquakes, the probability of exceeding a given value can be modelled as an equivalent Poisson process in which a variable average recurrence rate is assumed. The occurrence of ground motions at the site in excess of a specified level is also a Poisson process if: 1) the occurrence of earthquakes is a Poisson process, and 2) the probability that any one event will result in ground motions at the site in excess of a specified level is independent of the occurrence of other events.

The calculations were made using the computer program HAZ38 developed by Norm Abrahamson. The program has been validated in the Pacific Earthquake Engineering Research (PEER) Center's "Validation of PSHA Computer Programs" project and qualified for use by the U.S. Department of Energy.

Seismic Source Input. Seismic source characterization is concerned with three fundamental elements: 1) the identification, location, and geometry of significant sources of earthquakes; 2) the maximum size of the earthquakes associated with these sources; and 3) the rate at which these earthquakes occur. The source parameters for the significant faults in the site region (generally within about 100 km) were characterized for input into the PSHA.

Table 1 provides the fault parameters for the three most significant faults in the analyses. These parameters, and those used for the other faults considered in the PSHA, consists largely of the parameters from the 2002 CGS/USGS model (Cao et al., 2003) although the uncertainties in each parameter have been explicitly incorporated through the use of logic trees. The 2002 CGS/USGS seismic source model was used in the development of the California portion of the National Hazard Maps (Petersen et al., 2008). Important departures from the 2002 CGS/USGS model were characterizations of the southern San Andreas, San Jacinto, and Elsinore faults. Much more segment rupture variability (multi-segment and nonsegmented behavior) was incorporated in this model as compared to the 2002 CGS/USGS model. Offshore faults such as the San Clemente and San Diego Trough fault zones (Legg et al., 2004) and faults in Baja California were also characterized as part of this study. The La Nacion fault, which is not included in the CGS/USGS database, was also added to the model.

In the model developed for the Elsinore fault, a total weight of 0.3 was included so that multi-segment ruptures can occur versus single-segment rupture. These multi-segment ruptures are allowed to "float" up and down the fault and are not constrained to correspond to specific fault segments.

In the analyses, all faults were modeled as single, independent, planar sources extending the full extent of the seismogenic crust. Thus, fault dips are averages estimated over the seismogenic crust. For all seismic sources, the seismogenic crust was assumed to range from 12 to 15 ± 2 km thick based on well-located contemporary seismicity, although local variations were accounted for in the model.

A lack of reliable paleoseismic data means that the recurrence rates for many of the faults within the southern California and Baja California region are either poorly understood or unknown. Fault activity is therefore expressed as an average annual slip rate in mm/yr rather than recurrence intervals. The uncertainty in the slip rates and the other input parameters are accommodated in the PSHA through the use of logic trees.

Uncertainties in determining recurrence models can significantly impact the hazard analysis. The maximum-magnitude and characteristic recurrence models were considered in the analysis. Observations of historical seismicity and paleoseismic investigations along faults in the western U.S. (e.g., San Andreas fault) suggest that characteristic behavior is more likely for individual faults (Schwartz and Coppersmith, 1984). Therefore, the characteristic model for all fault sources (weight of 0.70) was generally favored while the maximum magnitude model was weighted 0.30.

Ground Motion Attenuation Input. To characterize the attenuation of ground motions in the hazard analyses, empirical attenuation relationships appropriate to southern California and Baja California were used. All relationships provide the attenuation of peak ground acceleration and response spectral acceleration for 5% damping. Weighting of these attenuation relationships varies for the faults depending on their tectonic settings.

For southern California and Baja California, where faulting is due to transpressional stresses and where the style of faulting is generally both strike-slip and reverse, the recently released attenuation relationships were used. These new models developed as part of the NGA Project sponsored by the Pacific Earthquake Engineering Research (PEER) Center Lifelines Program have been published in the journal "Earthquake Spectra" and are available on the PEER website. The NGA models have a substantially better scientific basis than previous relationships (e.g., Abrahamson and Silva, 1997) because they are developed through the efforts of five selected attenuation relationship developer teams working in a highly interactive process with other researchers who have: 1) developed an expanded and improved database of strong ground motion recordings and supporting information on the causative earthquakes, the source-to-site travel path characteristics, and the site and structure conditions at ground motion recording stations; 2) conducted research to provide improved understanding of the effects of various parameters and effects on ground motions that are used to constrain attenuation models; and 3) developed improved statistical methods to develop attenuation relationships including uncertainty quantification. The relationships have benefited greatly from a large amount of new strong motion data from large earthquakes (**M** > 7) at close-in distances (< 25 km). Data include records from the 1999 **M** 7.6 Chi Chi, Taiwan, 1999 **M** 7.4 Kocaeli, Turkey, and 2002 **M** 7.9 Denali, Alaska earthquakes. Review of the NGA relationships indicate that, in general, ground motions particularly at short-periods (e.g., peak acceleration) are significantly reduced, particularly for very large magnitudes (**M** ≥ 7.5), compared to current relationships.

The models used in the PSHA were those of Chiou and Youngs (2008), Boore and Atkinson (2008), and Campbell and Bozorgnia (2008). A measured V_S30 (average shear wave velocity in the top 30 m) of 1830 m/sec for the hard rock foundation beneath the dam was adopted from site-specific geotechnical investigations and was used in the equations.

PSHA Results. The results of the PSHA are presented in terms of ground motion as a function of annual probability of exceedence. This probability is the reciprocal of the average return period. Fig. 3 shows the mean, median, 5th, 15th, 85th, and 95th percentile hazard curves for peak horizontal ground acceleration (PGA).

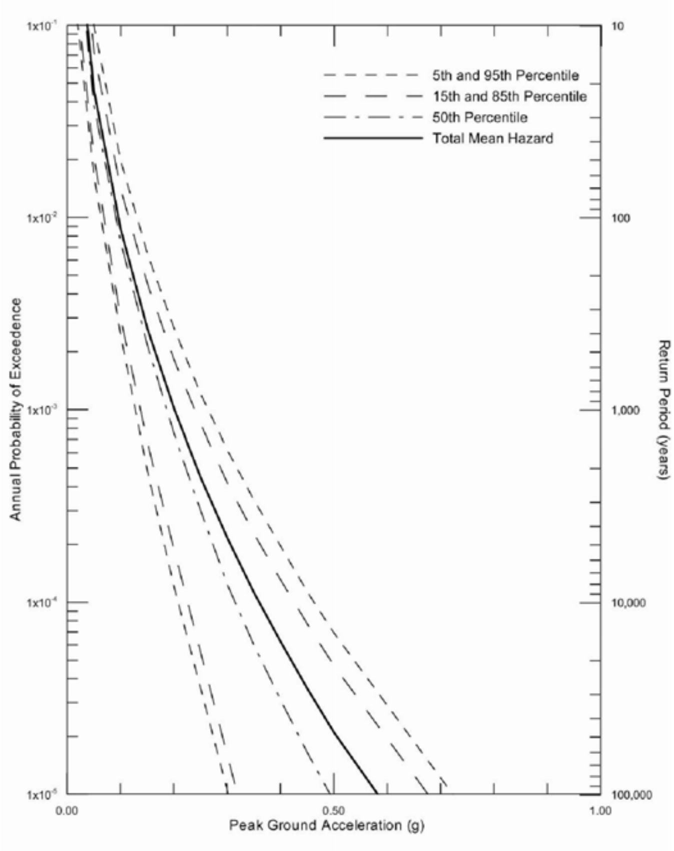

Fig. 3. Seismic Hazard Curves for PGA

The mean hazard curve was used to develop the final design ground motions. The probabilistic PGA, and 1.0 second spectral accelerations (SA) are listed in Table 2 for return periods of 500, 2,500, and 3,000 years (annual probabilities of exceedence of 2.0×10^{-3}, 4.0×10^{-4} and 3.3×10^{-4}, respectively). The natural period of the raised dam is estimated to be about 0.3 second.

Table 2. Probabilistic Ground Motions

Return Period (years)	PGA (g)	One Second Spectral Acceleration (g)
500	0.16	0.09
2,500	0.26	0.14
3,000	0.27	0.15

DSOD does not currently have any established guidelines in selecting a return period for dam safety evaluations. However, the United States Society on Dams, formerly the U.S. Committee on Large Dams (1998), recommends that return periods of 3,000 to 10,000 years be considered for design of moderate to high hazard dams. It was the consensus of the design team after consultation with DSOD that the seismic design of the dam raise project should consider a return period of 3,000 years. The seismic design also considered a Maximum Credible Earthquake using the previous attenuation relationships.

The hazard at the site is moderate with a 3,000-year return period PGA of 0.27g. Coincidently, this is similar to the deterministic PGA approved by DSOD for the "Minimum Earthquake", and lower than what had originally been anticipated from a nearby background earthquake based on an earlier study. The lower than anticipated PGA is primarily due to use of the recently published NGA relationships which incorporate site-specific shear wave velocities of the foundation materials.

The contributions of the various seismic sources to the mean PGA are shown on Fig. 4. At all return periods, the background areal source zone dominates the PGA hazard at the site. Also contributing to the PGA hazard is the Elsinore fault at short return periods. The gridded background seismicity is contributing very little to the site PGA hazard because there are very few observed earthquakes (with **M** $\geq$ 5) near the site.

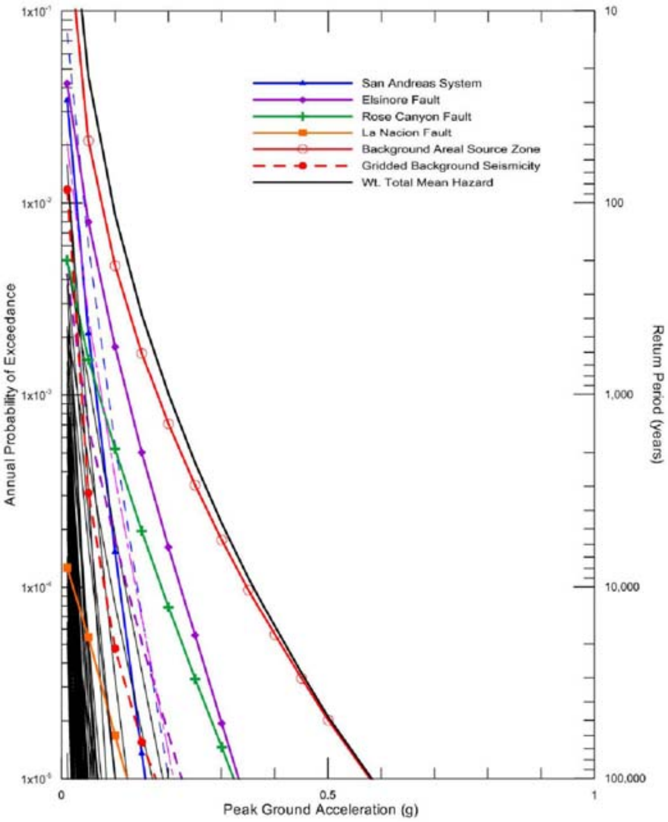

Fig. 4. Seismic Source Contributions to PGA Hazard

By deaggregating the mean PGA hazard, Fig. 5 illustrates the contributions by events. The PGA hazard at the site is controlled by background earthquakes of **M** 5.0 to 6.5 at distances less than 20 km. The Elsinore fault is evident as shown by the events of **M** 6.5 to 7.5 from 25 to 40 km away.

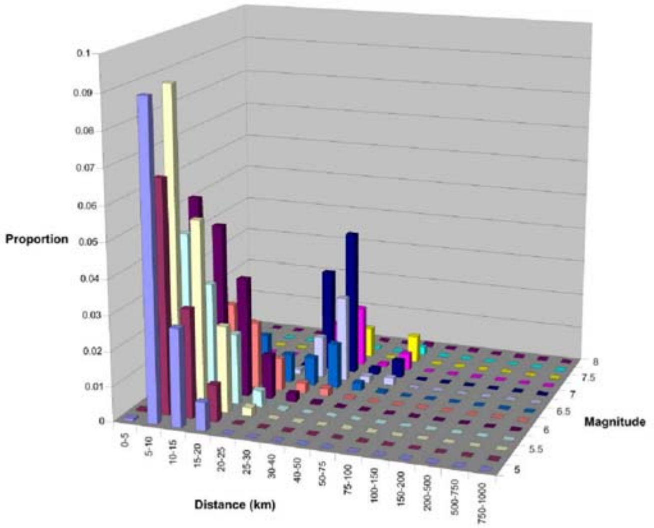

Fig. 5. Magnitude and Distance Contributions to PGA Hazard for a 3,000-year Return Period

Fig. 6 illustrates the sensitivity of the mean PGA to the choice of attenuation relationships.

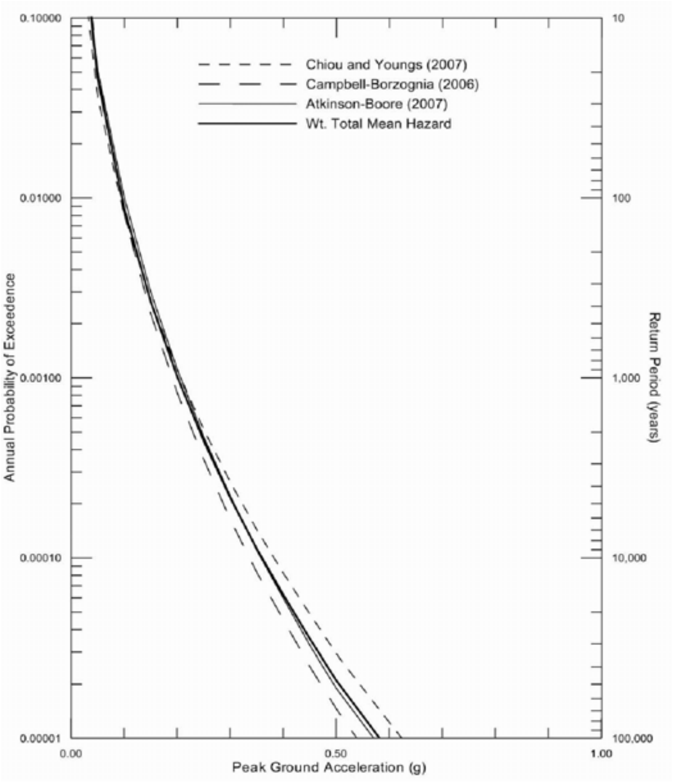

Fig. 6. PGA Hazard Sensitivity to Attenuation Relationship

Each hazard curve is labeled with one of the three attenuation relationships calculated using only that relationship. The PGA hazard is not particularly sensitive to the choice of NGA models since they all gave similar results. However, at 1.0 second SA hazard, the Chiou and Youngs (2008) and Campbell and Bozorgnia (2008) models resulted in fairly different hazard results.

Comparison with National Hazard Maps. In 1996, the USGS released a "landmark" set of national hazard maps for earthquake ground shaking (Frankel et al., 1996), which was a significant improvement from previous maps they had developed. These maps were the result of the most comprehensive analyses of seismic sources and ground motion attenuation ever undertaken on a national scale. The maps are the basis for the NEHRP Maximum Considered Earthquake maps, which are used in the International Building Code. The 2002 maps are for NEHRP site class B/C (firm rock) and a V_S30 (average shear wave velocity in top 30 m) of 760 m/sec, although the V_S30 of the maps is probably closer to 620 m/sec. The NGA models were not used in the 2002 maps (the 2008 maps had not been completed at the time of this study).

To compare the results of this study with the 2002 National Hazard Maps, the PSHA for a V_S30 of 620 m/sec was also calculated. The differences in hazard due to differences in V_S30 were quite significant across all spectral frequencies. For a 2,500-year return period, the 2002 maps indicate a firm rock peak horizontal acceleration of 0.36g for the site (Frankel et al., 2002) identical to the site-specific value for the PSHA incorporating firm rock. For hard rock (Vs30=1830 m/sec), the site-specific value is 0.26g.

Deterministic Seismic Hazard Analyses

Planning studies for the dam raise were focused on developing ground motions for the site using a deterministic approach as required by DSOD. DSOD approved the use of the ground motions presented in ECI (2005) for use in final design. These ground motions consisted of:

- Peak horizontal and vertical accelerations equal to 0.26g and 0.22g, respectively, at the San Vicente site caused by the Maximum Credible Earthquake (MCE) of **M** 6.7 on the La Nacion fault, located 20 km from the dam.
- Peak horizontal and vertical accelerations equal to 0.21g and 0.17g, respectively, at the San Vicente site caused by the MCE of a **M** 7.5 on the Julian segment of the Elsinore fault, located 36 km from the dam.

The peak acceleration values provided above represent the arithmetic mean of the 84th percentile values calculated using the pre-NGA attenuation relationships of Abrahamson and Silva (1997), Sadigh et al. (1997), and Boore et al., (1997). Response spectra were also calculated using these models. The relations of Abrahamson and Silva (1997) and Campbell and Bozorgnia (2003) were used to calculate the vertical spectra.

The seismic performance of the dam was checked in final design using time histories developed for the deterministic earthquakes. The La Nacion fault rupture style is highly uncertain and strike-slip faulting was assumed in this analysis, which results in higher ground motions consistent with the conservative nature of a deterministic approach.

Time histories were developed for the La Nacion MCE by spectrally matching the 84th percentile deterministic spectrum shown in ECI (2005).

For comparison, the three NGA attenuation relationships that were used in the PSHA were also used to calculate the deterministic ground motions. A V_S30 of 1830 m/sec was used in the models. The PGA values from the La Nacion and Elsinore fault maximum earthquakes are 0.18 and 0.16g, respectively.

CONCLUSIONS

It was recognized that the ground motion hazard at the site of the San Vicente Dam Raise project may not be controlled by earthquakes on known faults but rather by background (or random) earthquakes, which cannot be adequately addressed using deterministic methods alone. This prompted the development of supplemental seismic design ground motions based on a PSHA. The PSHA was performed incorporating the latest information on seismic sources and recently developed NGA relationships. Based on the results of the PSHA, ground motion parameters (response spectra and time histories) were developed for final design of the dam raise. Deterministic ground motions calculated using previous attenuation relationships were very similar to probabilistic ground motions using the NGA relationships. Use of the NGA relationships did lower the PGAs by about 25% to 30% from what had been obtained with the previous attenuation relationships.

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