Development of the Caltrans Deterministic PGA Map and Caltrans ARS Online

Tom Shantz, Division of Research and Innovation
Martha Merriam, Geotechnical Services

April 27, 2009

Introduction

This report describes the methodology employed in the creation of the Caltrans Deterministic PGA Map (2008) and the Caltrans ARS Online (V1.0) design spectrum tool. These two items are important design aids that assist the implementation of newly adopted criteria (see Caltrans Seismic Design Criteria, Appendix B) for the development of response spectra for design. Their development grew out of an effort to update the Caltrans Seismic Hazard Map (SHM). The Caltrans fault database had undergone numerous updates since the SHM was last produced in 1996, and the list of errata items had grown large and difficult to manage. Early in the update planning, however, it was recognized that the SHM update presented an opportunity to adopt recently developed Next Generation Attenuation (NGA) ground motion prediction equations (GMPE's) for the map. These equations were the result of an ambitious effort by the PEER-Lifelines Program, co-funded by Caltrans, and partner developer teams to develop state-of-the-art ground motion prediction models incorporating data from a number of recent large magnitude earthquakes.

The choice to adopt NGA GMPE's was followed by a major decision to include probabilistic criteria in the specification of the design spectrum. This decision eliminated any doubt that the past practice of relying on a deterministic PGA contour map and standard spectral curves would be insufficient to address the newly adopted probabilistic criteria as well as capture the additional complexity associated with implementing the NGA ground motion prediction models. This realization that a more powerful design tool was needed provided the impetus for the development of Caltrans ARS Online.

The added functionality of Caltrans ARS Online relegates the Deterministic PGA Map, which replaces the former SHM, to a secondary role. The Deterministic PGA Map, in conjunction with updated standardized spectral curves provided in SDC, Appendix B, enables rapid development of an approximate deterministic design spectrum, similar to recent Caltrans practice. Since this map is unable to capture site specific features to be discussed in later sections of this report, it should only be used for preliminary design purposes.

The development of the Deterministic PGA Map and Caltrans ARS Online (deterministic portion) are closely intertwined since they both rely on the same fault database and ground motion prediction equations. Furthermore, Caltrans ARS Online relies on and extends the basic methodology used for the development of the Deterministic PGA Map. Thus, the discussion below pertains to both tools unless indicated otherwise.

This report begins with a section on the development of the Caltrans Fault Database. This database represents a complete listing of planar seismic sources and their properties used in deterministic hazard calculations. Next, an overview of the adopted NGA GMPE's is presented, with primary focus on new features that will impact their implementation. A discussion of the development of the Deterministic PGA Map and Caltrans ARS Online follows. A final section presents the methodology used to implement the newly adopted probabilistic criteria.

2007 Caltrans Fault Database

1.1 Caltrans criteria for inclusion.

Caltrans defines a fault as active if it has ruptured within the past 700,000 years (late-Quaternary to present) (Jennings, 1994; Mualchin, 1996). This definition is broader than the definition used by most agencies, and as a result older faults included in the Caltrans fault database are often not as well studied as some of the more active faults in California. Because of this lack of study (as well as evidence of faulting being obscured over time), assumptions were made for some of the fault parameters. Active faults at least 10 km long are included in the database. Earthquakes occurring on faults shorter than this minimum length are not expected to result in ground motions higher than those predicted by the minimum spectrum in SDC.

1.2 Fault references

The Caltrans fault database was developed primarily from CGS and USGS databases (see *REFERENCES*). The USGS Quaternary Fault and Fold Database was a major source of fault parameters. CGS and USGS geologists as well as other geologists both in the private and public sectors made recommendations regarding faults to include and fault parameters. Since the database is considered dynamic in nature, comments are solicited regarding future inclusions or deletions.

Fault locations were taken in particular from the 2005 draft revision (v.2) of Jennings (1994) (CGS, 2005) that was simplified when necessary, two simplified databases (USGS 2002 and 2003), and a few other references for individual faults. Fault location accuracy in Caltrans ARS Online is assumed equivalent to that of a map with an approximate scale of 1:750,000 (1 inch = 12 miles), and is intended for use at that scale. While zooming in may enable users to distinguish various lines and patterns, it also can mislead people into thinking that the digital map is more precise than it really is. As such, the Caltrans Deterministic PGA map and Caltrans ARS Online are for ground motion estimation only. Uncertainties in these fault locations are on the order of $\pm$ 1 km. Accuracy in Google Maps is stated to be no more than 140 meters.

1.3 1996 vs. 2007 fault databases

The Caltrans Deterministic PGA Map (2008) and the Caltrans ARS Online (V1.0) design spectrum tool relied on the Caltrans fault database (2007) for deterministic source characterization. Additional changes since 2007 will be incorporated through the listing of errata. (Caltrans ARS Online provides a link to this errata file and a reference is included on the

Caltrans Deterministic PGA Map). These errata will be incorporated more fully in future updates of the map and design tool.

Changes in the Caltrans fault database from the 1996 to the 2007 version include the addition of more faults considered active in southern California (e.g., Puente Hills and San Joaquin Hills blind thrusts), and in northern California (e.g., Cascade and Silver Creek faults). Faults found to be older than the Caltrans criterion and removed from the database include the Antioch fault and many faults in the Sierran Foothills Fault System. Names of faults and fault sections are usually consistent with CGS nomenclature but not always with the 1996 database (e.g., the Wilmar Avenue fault is now included in the southern San Luis Range fault zone). Faults within a half a degree latitude and longitude of the California border are included in the database.

Comparison between the 1996 and 2007 Caltrans fault databases in terms of "number of faults" is difficult since the sections are not always equivalent between databases. For instance, the San Andreas Fault trace is represented by twice as many sections in the 2007 database as in the 1996 database. The 1996 fault database included a total of 270 fault sections; the 2007 fault database includes 428 sections. For similar reasons a simple comparison of 1996 MCE values and 2007 **M**Max values is difficult not only because of different methods used to develop the values but also because of different estimations of fault section lengths for the two different maps. For faults included in both databases, 2007 **M**Max values are on average about 3% larger than 1996 MCE values.

1.4 Additional seismic sources

An area source known as the Eastern California Shear Zone (Figure 1) is included per Wills et al, 2006 (see WGCEP 2008). This area is an apparent zone of distributed shear, treated as having the potential for a **M**Max of 7.6 on a strike-slip fault at a distance of 10 km. Other distributed shear zones (C zones in WGCEP, 2008) may be included in the errata or later editions of the fault database and Caltrans ARS Online.

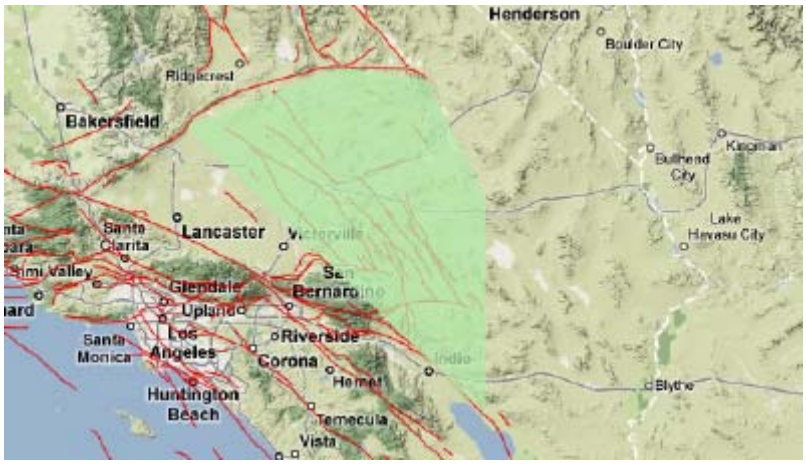

Figure 1. Zone of distributed shear in southern California (green) (simplified from WGCEP, 2008).

Attenuation Models

2.1 Selection of Campbell-Bozorgnia (2008) and Chiou-Youngs (2008) models

A key component of the revised Caltrans Seismic Design Criteria (SDC) is the adoption of recently developed "Next Generation Attenuation" (NGA) ground motion prediction equations for determination of the deterministic design spectrum. These models are the result of a multiyear effort by the PEER-Lifelines Program and five participating model development teams to update attenuation models for shallow crustal events incorporating new data from several recent large magnitude events. These events (1999 Hector Mine, 1999 Kocaeli and Duzce , 1999 Chi-Chi, 2003 and Nenana Mountain and Denali earthquakes) increased the number of large magnitude-near fault recordings considerably. Each team (selected by their prior development of attenuation models) worked collaboratively while independently developing their ground motion prediction model.

The schedule for the Seismic Hazard Map update was largely driven by the need to incorporate several faults not included in the original 1996 map, not the readiness of the various NGA models. During initial map development, two of the models (Campbell-Bozorgnia and Chiou and Youngs) were mature and well documented. The remaining three models' status ranged from nearly complete but poorly documented (the Boore-Atkinson model) to still under development (the Abrahamson-Silva and Idriss models). Coincidental to our selection of appropriate attenuation models for the SHM, the USGS was evaluating the NGA models for possible implementation in their 2008 release of an updated national hazard map. To aid their evaluation effort, the USGS assembled an advisory team of recognized experts in seismology and geotechnical engineering. Based on detailed and documented responses by each developer to questions posed by USGS earth scientists as well as available developer documentation, the advisory team recommended that the Campbell-Bozorgnia (2008) (CB) and Chiou-Youngs (2008) (CY) models be used for the national hazard mapping effort. The team recommended that previous versions of these models not be used (i.e. prior to NGA), and that the other three NGA models not be used due to either insufficient model maturity or documentation. Given the stature of the review team and their unanimous recommendation, the Caltrans SHM team decided to follow these recommendations and use the average of the CB and CY models. As the project was expanded to include Caltrans ARS Online the same models were used to ensure consistency between the Deterministic PGA Map and Caltrans ARS Online. A comparison of the average of the CB and CY models with other NGA models is shown in Figure 2.

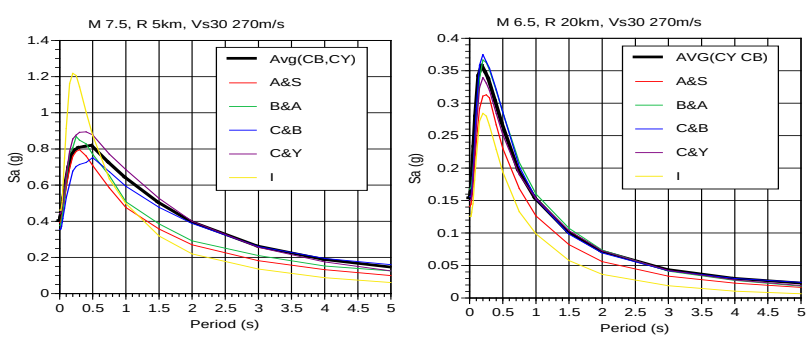

Figure 2: Comparison of CB & CY average with individual NGA models for 2 earthquake scenarios. A&S =Abrahamson and Silva, B&A = Boore and Atkinson, I = Idriss.

2.2 New features in the CB and CY attenuation models

There are several new features incorporated into the CB and CY models that impact their implementation within Caltrans.

V_{S30} Dependence

V_{S30} refers to the average shear wave velocity in the upper 30 meters of the soil/rock profile and is a measure of the near surface soil stiffness. In the past, NEHRP site classes were used to divide soil profiles into a handful of broad classes. V_{S30} offers the advantage of a continuous classification. Analysis of large numbers of measured velocity profiles suggests the following approximate relation between NEHRP soil classes and V_{S30}:

NEHRP Class	Vs_{30}(m/s)
B/C	760
C	560
D	270

Both the CB and CY models use V_{S30} in conjunction with soil nonlinearity effects to incorporate soil amplification in their ground motion prediction. This novel capability is in contrast to previous generations of attenuation models that were developed either for rock or generic soil conditions (or both). The built-in soil amplification of the CB and CY models (other NGA models share this capability as well) eliminate the need to perform site-specific response analysis in all but soft soil conditions. It should be cautioned, however, that if a profile includes very soft layers (Vs<120m/s), the depth and thickness of these layers strongly influence the response spectrum at the ground surface. In such cases a site-specific response analysis should be required. Both the CB and CY models limit use of their models to V_{S30} greater than 150 m/s.

Hanging Wall / Foot Wall Effects

Earthquake records show strong amplification (in excess of 50% at PGA) when a site is located on the hanging wall of a dipping fault. This effect is captured in both the CB and CY models through the use of multiple distance parameters (R_{rup}, R_{JB}, and in the case of the CY model R_x). Figure 3 provides a pictorial description of key fault geometry factors including these three distance measures. Using these distance measures, both models are able to capture the essential geometrical influences of the hanging wall/foot wall (HW/FW) effect.

It must be noted that the HW/FW effect is most prominent at high frequencies. Thus, the Deterministic PGA Map, being a map of PGA, is strongly influenced by this effect. Standard spectral curves (as explained below) are based on non-HW situations since, given a specific PGA level, the spectral curve will be higher at longer periods. When faced with a fault dipping in the direction of a particular site, an attenuation model spreadsheet should be used instead of the

standard spectral curves since the standard spectral curves, being referenced to a PGA value that has been increased due to the HW effect, could over-predict spectral values at longer periods.

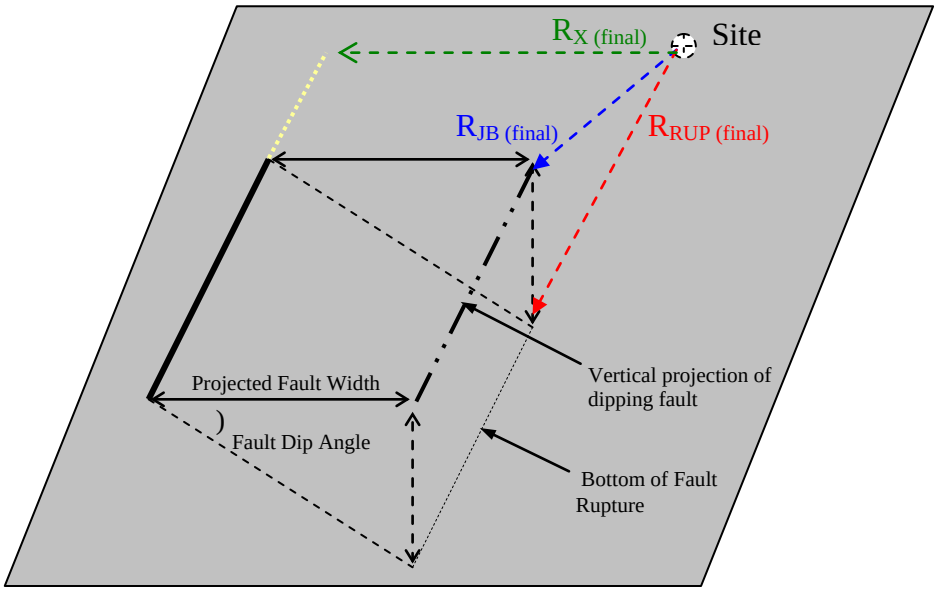

Figure 3: Illustration of the three distance measures used by the CB and CY models. R_{rup} is the closest distance from the site to any point on the fault plane. R_{JB} (the "Joyner-Boore" distance) is the distance from the site to the closest surface projection of the fault plane. R_x is the perpendicular distance from the site to the surface projection of the top of fault.

Basin Effect

Earthquake records from deep sedimentary sites such as the LA basin tend to have elevated spectral values at long period relative to non-basin sites. In order to capture this effect, both the CB and CY models include a term for "depth to bedrock." The CB model uses the parameter $Z_{2.5}$, or depth to a shear wave velocity of 2.5 km/s. The CY model has a similar term, $Z_{1.0}$, or depth to 1.0 km/s. In both models, these effects result for example in a 20-50% increase in spectral values at 3 seconds for a typical LA basin site. To enable implementation of this aspect of the CB and CY models, contours of $Z_{1.0}$ and $Z_{2.5}$ were developed for regions with large enough Z values to result in amplification. These contours are shown in SDC Appendix B, Figures B.5 to B.11. The development of these contours is discussed in detail in a later section of this report.

It should be noted that both the CB and CY models also predict a deamplification at sites with shallow rock (small Z). Implementation of this aspect of these models would require statewide knowledge of shallow rock depth, information that is not currently available. As a result, only amplification due to large Z is currently considered in SDC.

2.3 Subduction zone model

All of the NGA models (including CB and CY) were developed for application to shallow crustal events. All but one of the seismic sources considered in California hazard analysis represent

shallow crustal fault mechanisms. The one exception is the Cascadia Subduction Zone which is a large shallow dipping thrust fault zone in northwestern California, Oregon, and Washington. For this fault zone, a separate attenuation model is required. Unfortunately, attenuation models for subduction events have not advanced as far as that of shallow crustal models and there is large disagreement between different models. For application to the Deterministic PGA Map and Caltrans ARS Online (deterministic portion), two subduction models were considered: Youngs et al. (1997) and Atkinson and Boore (2003). Distance versus PGA using these two relationships is plotted in Figure 4. Also plotted for comparison is the average of the CB and CY shallow crustal models with their hanging wall adjustment terms set to zero for the comparison. Note that the Atkinson and Boore (2003) model is significantly lower than the other models. In 2002, the USGS national hazard mapping team (see Frankel, 2002), concerned about the much lower prediction of ground motion at short distance by subduction attenuation models, recommended that where Youngs (1997) is less than the shallow crustal prediction (based at that time on Sadigh 1997), the two predictions should be averaged. This approach is recommended in SDC, Appendix B, and is implemented in the Deterministic PGA Map and Caltrans ARS Online (deterministic portion), using the average of CB and CY as the shallow crustal prediction.

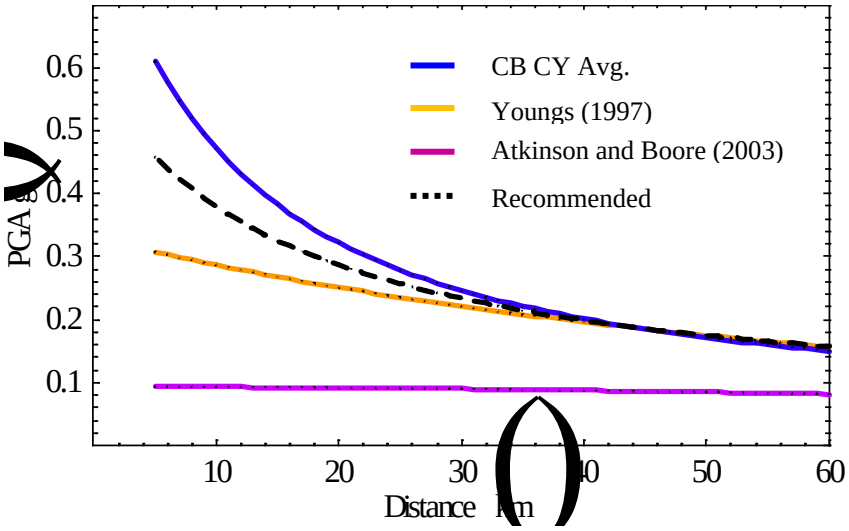

Figure 4: Recommended attenuation model for subduction zone earthquakes

2.4 Near fault effects

Past studies of earthquake recordings from sites located near a rupturing fault demonstrate elevated levels of shaking, particularly at periods longer than 0.5 to 1 second. Theoretical considerations as well as simulation studies suggest several mechanisms contribute to this phenomenon. Key mechanisms include constructive wave interference, radiation pattern effects, and static fault offset (fling). As a practical matter, these mechanisms are commonly combined into a single “near-fault” adjustment factor. The CB and CY models currently do not consider potential near-fault effects. Previous Caltrans practice has been to apply a 20% increase to spectral periods greater than 1 second (tapering to zero increase at 0.5 second) at all locations within 15 km (9.4 miles) of a fault. Preliminary findings from on-going studies of near-fault effects suggest that elevated levels of ground motion may extend to distances larger than 15 km.

Until these studies are completed and more definitive recommendations can be made, it is recommended that the previous Caltrans near-fault adjustment be modified to include an extended distance taper as shown in Figure 5.

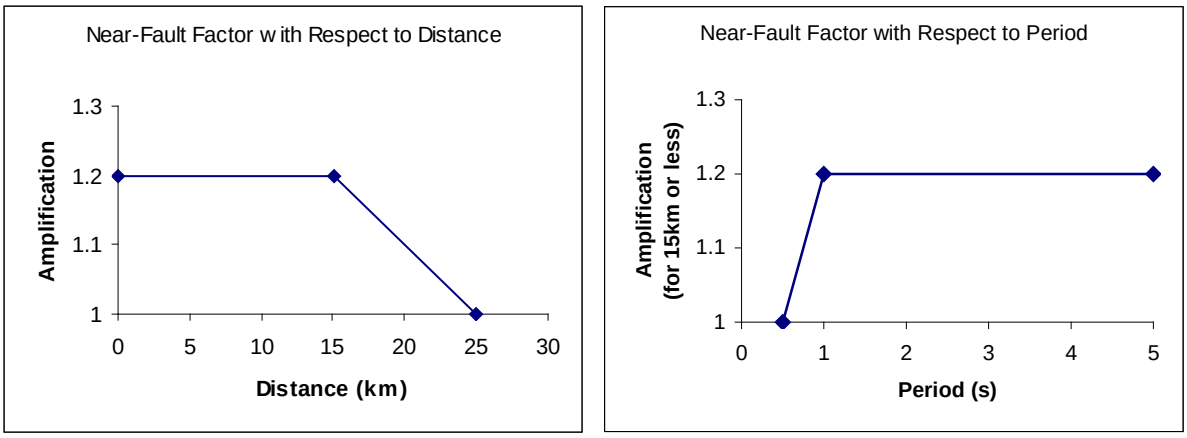

Figure 5: Near-fault adjustment factor as a function of distance and spectral period. The distance measure is based on the closest distance to any point on the fault plane.

Development of Deterministic PGA Map and Caltrans ARS Online

3.1 Treatment of nonlinear fault traces

Each fault or fault section was defined by a sequence of linear segments. Each segment was then treated as a separate subfault with the prescribed magnitude and dip of the overall fault system, as shown in Figure 6. Where adjacent subfault planes diverged, they were connected using a conical surface. While this approach is reasonable, there is currently no consensus in the earth science community regarding how to define fault planes given nonlinear fault traces. While other assumptions can be made, the approach implemented here has a significant advantage in that distance calculations can be performed with simple hand calculations. Overall, the sensitivity to this choice is small in most cases. The calculation R_x is insensitive to this choice since it is surface fault based. The calculations of R_{rup} and R_{JB} are affected for locations on the hanging wall side of the fault. Where fault strike is linear or where the fault is vertically dipping, R_{rup} and R_{JB} are unaffected by different assumptions.

3.2 Caltrans Deterministic PGA Map

The Caltrans Deterministic PGA Map was constructed by using the CB and CY GMPE's to calculate median PGA on a two kilometer grid throughout the State. The PGA values were developed for a "soft-rock" condition based on a V_{S30} of 760 m/s (2500 fps). The basic methodology employed at each grid point was to (1) identify all possible faults within a distance of 80 km from the grid point; (2) for each identified fault, determine which fault segment (or subfault plane) is closest to the grid point (i.e. minimum R_{rup}) and calculate R_{rup}, R_{JB}, and R_x; (3) use the CB and CY attenuation models to calculate a median estimate of PGA based on the three distance measures in step 3 and the fault characteristics specified in the Caltrans fault database; and (4) assign the maximum PGA value from all the identified faults to that grid point.

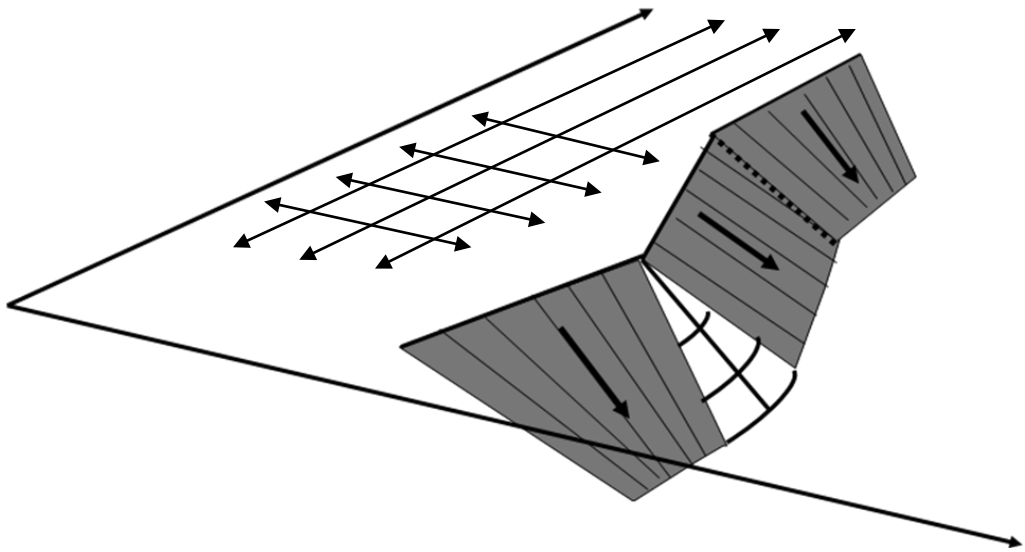

Figure 6: Fault plane approximation used for distance calculations.

The program SURFER was used to generate contours of the gridded PGA data. While SURFER's contouring algorithms worked reasonably well at distances 5 to 10 km beyond a fault, closer in the algorithms struggled to conform to the long quasi linear shapes of the fault traces. Furthermore, regions with high fault density (e.g. many regions in Southern California) resulted in complex contours that were often difficult to interpret and, at times, incorrect. Extensive data interpretation and GIS hand work was required, making the map development a labor intensive process. Future updates to the map will likely require significant labor as well.

3.2 Standard spectral curves for use with Deterministic PGA Map

Utilization of the Deterministic PGA Map for preliminary design requires standardized spectral curves so that an entire spectrum can be estimated from a single PGA value. Here, the term "standardized" is used to reflect a spectrum that has a specific PGA value (typically 0.1g, 0.2g, etc.). Typically, standardized spectral curves are provided for a number of different magnitude and soil profile combinations. Since both the CB and CY models require a large number of input parameters (more than previous generations of attenuation models), considering all possible ranges of values in all possible combinations is impractical. The strategy employed here was to perform parametric evaluation of the models and use combinations of parameters that lead to the largest (most conservative) standardized spectral curve, with the only caveat being that the combination of parameters had to be "reasonable" and not an odd combination that would be exceedingly rare. Fortunately, the parametric study led to parameter combinations that were both realistic and common.

The parametric study found that up to values of 0.5 g PGA, vertical strike-slip faults that ruptured to the surface gave the largest standardized spectral curves. A sample set of curves for the case of **M**Max of 7 and V_{S30} of 560 m/s is given in Figure 7. For standardized spectral curves corresponding to PGA values greater than 0.5g (i.e., 0.6 g, 0.7 g, and 0.8 g) a different range of parameter values had to be considered since vertical strike-slip faults can't produce

median values of PGA much larger than 0.5 g, even at large magnitudes and short distances from the fault. To obtain PGA's on the order of 0.6 g or larger, one has to consider dipping reverse faults since sites on the fault hanging wall receive significant amplification at high frequencies, resulting in high PGA's. This amplification does not extend to long period, however. In fact, at longer periods dipping reverse faults tend to have spectral values below their vertical fault counterpart. The consequence is that at long period, the standardized spectral curves corresponding to a vertical strike-slip fault at 0.5 g will exceed even that of a dipping reverse fault with a PGA of 0.8 g.

For the development of standardized spectral curves, only the case of a 45 degree dipping fault rupturing to the surface was considered for PGA values exceeding 0.5g. Other possible scenarios were evaluated and the case of a 45 degree dipping fault was found to be reasonably representative of the wide range of possible scenarios. The resulting plots are given in SDC, Appendix B, Figures B.13 to B.24.

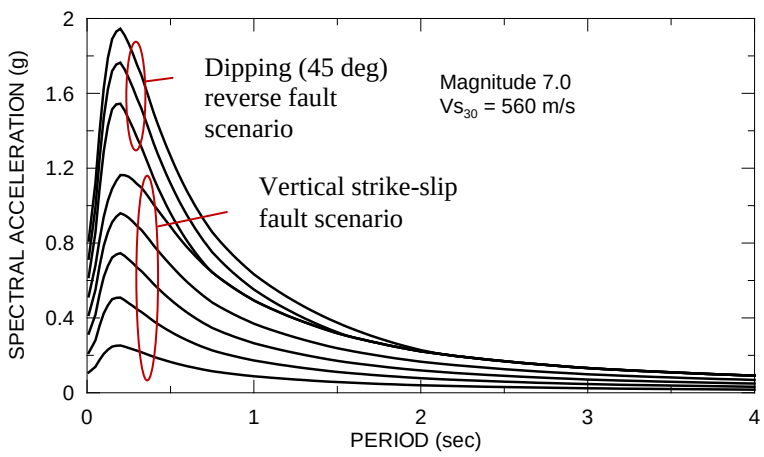

Figure 7: Example standardized spectral curves for the case of a M_w 7 event with a soil profile V_{S30} of 560 m/s

3.3 Caltrans ARS Online

Caltrans ARS Online is a web based design tool that operates through a web browser and enables the user to calculate a design response spectrum subject to the criteria described in Appendix B of Caltrans Seismic Design Criteria (SDC). The basic operation is depicted in Figure 8. The user selects a site location using a Google Maps interface, inputs a V_{S30} for the site, and Caltrans ARS Online returns the controlling deterministically derived response spectrum, a probabilistically derived response spectrum, and the design spectrum (an envelope of the two spectra). The methodology employed in this application is rooted in that used to create the Deterministic PGA Map, but also extends that methodology in many important ways. These extensions will be discussed in separate sections below:

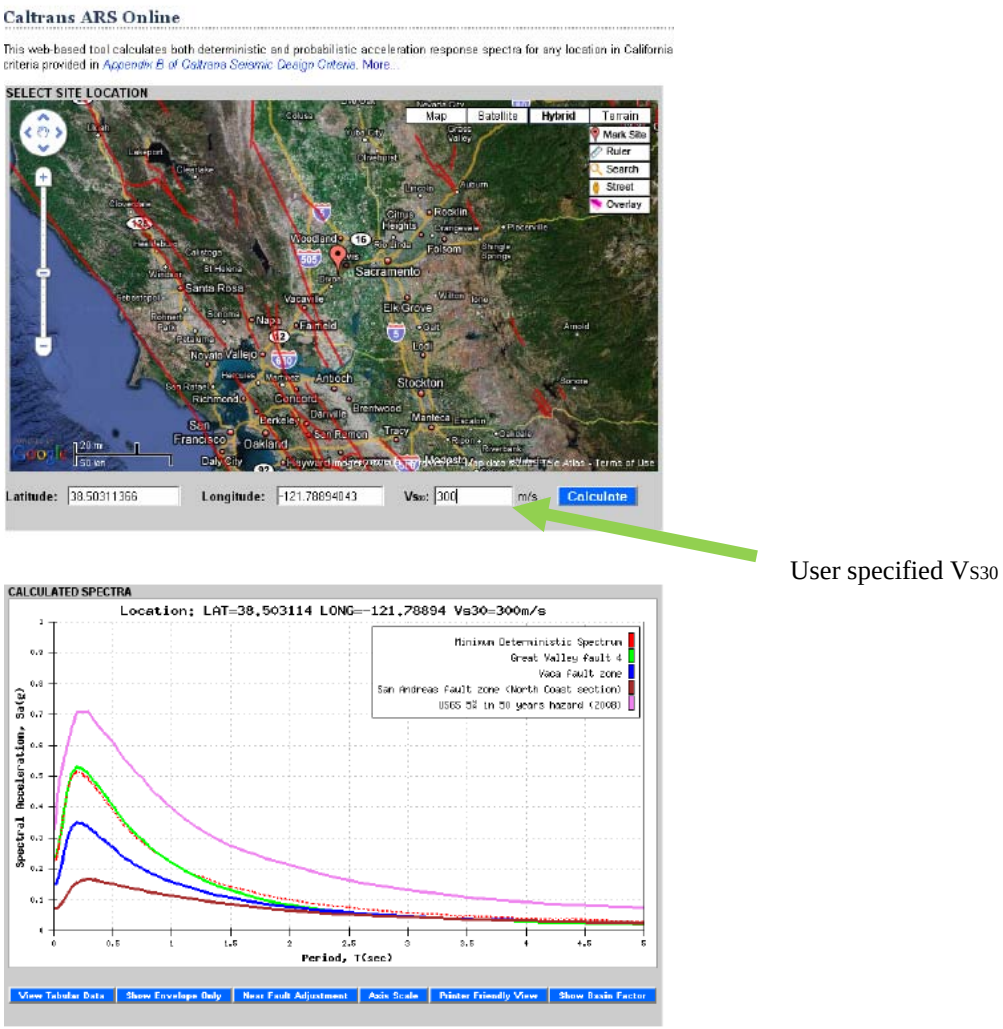

Figure 8: Top: Caltrans ARS Online input screen. Bottom: Caltrans ARS Online output screen

Grid Files

Caltrans ARS Online must be able to identify which fault and which segment along the fault trace results in the maximum response spectrum, and because it is an interactive tool, it must do so quickly. To enable a fast calculation, the program relies on pre-calculated "grid" files. A grid file specifies the controlling fault and the three distance measures (R_{rup}, R_{JB}, and R_x) for every grid point in the state. Having this information in advance allows the program to quickly calculate the deterministic spectrum and focus on making the many possible adjustments detailed below.

Multiple grid files are needed because more than one fault might be responsible for controlling (maximum) spectral values. It is common, for example, for a smaller magnitude fault that is closer to the site to control at shorter periods while a more distant larger magnitude fault may control at larger distances. In order to ensure that all relevant faults are considered, grid files are

calculated at five period ranges (0.01, 0.3, 0.7, 1.2, and 3 seconds). When a grid point is selected, all files are checked and all faults identified are used to determine the deterministic spectrum.

To complicate things a bit further, the determination of the controlling fault is also affected by the user specified site V_{S30}. A fault that controls a rock site might not control if that same site is on soil (which tends to amplify longer periods). Thus to ensure that the correct controlling fault is identified, a set of five grid files (i.e. for five different periods) is calculated for each of five different V_{S30} values (making 25 grid files total). When the user selects a site V_{S30}, the five grid files with the closest reference velocity are then used to determine the controlling faults.

Interpolation

Using the grid files described in the previous section, one can quickly determine the controlling fault(s) and corresponding distance measures for the four grid points that surround any site location. With this information, one can use linear interpolation to better estimate the distance measures at the site location. A complexity is that the four grid points that surround the site location may not be controlled by the same fault. If this is the case, special interpolation schemes are employed that rely on only two or three points. If only one grid point is controlled by a particular fault, interpolation of distance measures is impossible and the values for that grid point are used. With site distance measures now known, a response spectrum can be calculated using the CB and CY GMPE's. The maximum spectral ordinates are obtained after considering all the possible controlling faults that make up the deterministic spectrum.

Sometimes a site is located very close to a fault and some of the surrounding grid points may fall on opposite sides of the fault. In this case, simple linear interpolation of distance measures would lead to an erroneous result. To address this case, special interpolation schemes are used. While these schemes are fairly sophisticated and can provide excellent interpolation accuracy, they do not apply to locations that extend beyond the end of the fault trace. In that case, a simpler, more approximate approach is employed.

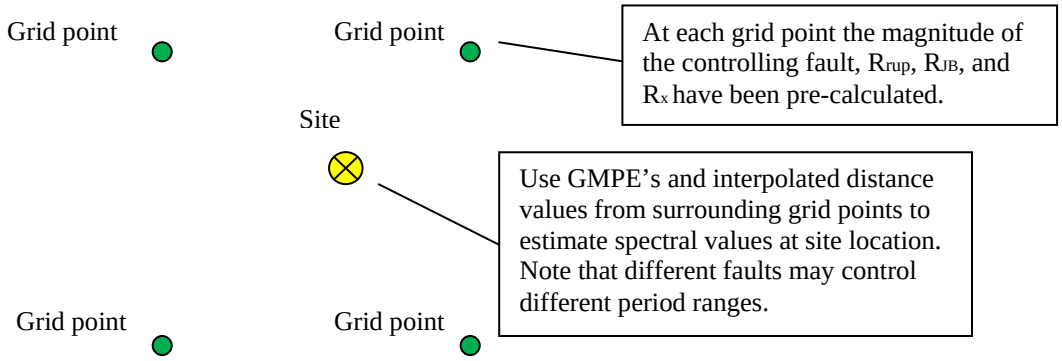

Figure 9: Use of distance measures at surrounding grid points to estimate distance measures at the project site.

The need for different interpolation schemes results more from the evolution of the program routines than a fundamental requirement of the Caltrans ARS Online methodology. While the use of interpolation schemes can lead to inaccuracies in the deterministic spectrum, it is rare for

those inaccuracies to exceed more than a few percent. The minor shortcomings of the current method will be addressed in a future update of Caltrans ARS Online.

Basin Amplification

Analysis of earthquake records clearly demonstrates additional ground motion amplification at sites located in deep sedimentary structures. Both the CB and CY models address this issue using the depth to rock parameter Z. CB uses a depth to hard rock reference, with hard rock being defined by a shear wave velocity of 2500 m/s. This parameter is referred to as $Z_{2.5}$. CY chooses to use a softer rock reference defined as a shear wave velocity of 1000 m/s. This parameter is referred to $Z_{1.0}$. The CB basin amplification model initiates at a $Z_{2.5}$ of 3000 meters. The CY basin amplification model initiates at a $Z_{1.0}$ of approximately 400 meters. A plot of amplification as a function of depth to rock for the two models is shown in Figure 10. (This same figure is presented in SDC, Appendix B, as Figure B.4.) Amplifications can approach a 60% increase at the deepest sites.

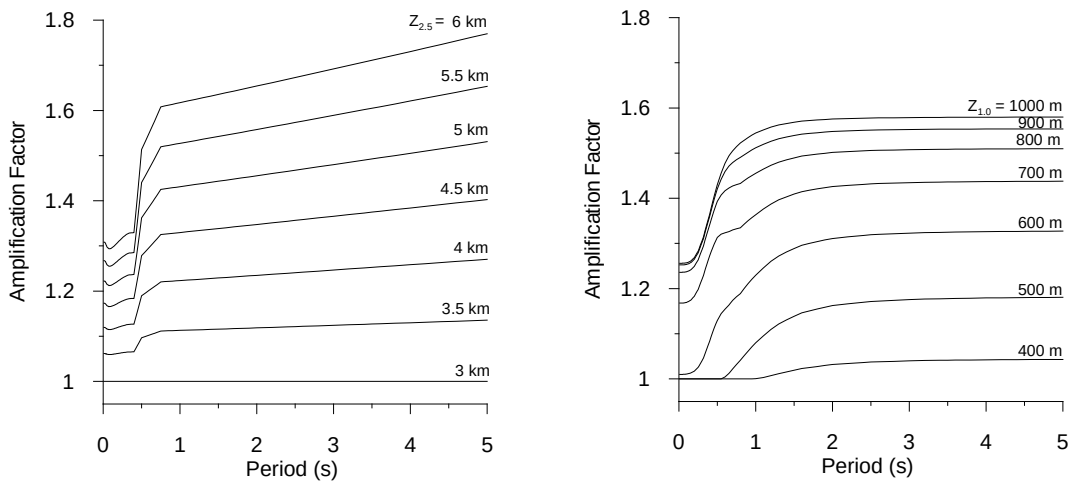

Figure 10. Basin amplification factors for the Campbell-Bozorgnia (2008) and Chiou-Youngs (2008) ground motion prediction equations. Curves may be slightly conservative at periods less than 0.5 seconds.

In order to implement basin effects in Caltrans ARS Online, a means to determine $Z_{1.0}$ and $Z_{2.5}$ was required. In Southern California, $Z_{1.0}$ and $Z_{2.5}$ were determined using data from the Community Velocity Model (CVM) Version 4 (http://www.data.scec.org/3Dvelocity/). Using the CVM data, contours of $Z_{1.0}$ and $Z_{2.5}$ were created and are shown in Appendix B of SDC, Figures B.5 to B.10. The creation of contours included a modest level of smoothing of the velocity data and some simplification of more complex basin structures. At some locations more than one $Z_{2.5}$ could be obtained since the CMV predicts harder rock overlying softer rock. An example of such a case from the Imperial Valley is shown in Figure 11. In these instances the smallest $Z_{2.5}$ was used.

Developing depth to rock contours in Northern California was more challenging since the availability of velocity data was limited. The lack of data led to the determination that development of a reliable $Z_{1.0}$ contour map was not currently feasible. For the development of

$Z_{2.5}$ contours, the primary data source was a tomography study of Northern California by Thurber et al (2009). This study used tomography data on a 10 to 20 km grid to develop P-wave

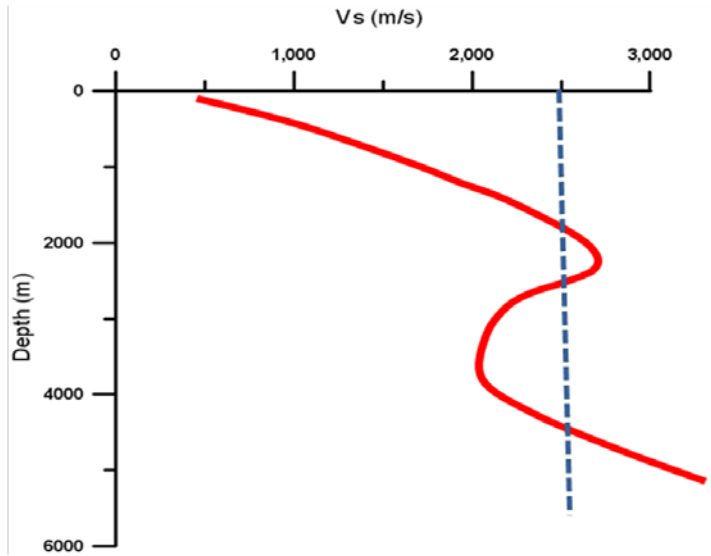

Figure 11: Example of a velocity profile with multiple $Z_{2.5}$'s (in this case from Imperial Valley). The smallest $Z_{2.5}$ was used to define $Z_{2.5}$ contours.

velocity estimates at several depth horizons. Of the various depths considered in the study (1, 4, 8, and 16 km), only the 4 km horizon data was of use to this study since the 8 and 16 km horizon rock is stiffer than that considered by the CB basin amplification model, and the 1 km horizon is too poorly constrained for creation of reliable $Z_{1.0}$ contours. Since the Thurber et al (2009) study estimated P-wave velocity, we relied on correlation models from Brocher (2005) and Boatwright (2004) to estimate corresponding shear wave velocity (V_s) from P-wave velocity (V_p). Both correlations suggest the CB reference V_s of 2.5 km/s corresponds to a V_p of about 4.2 km/s.

The construction of the $Z_{2.5}$ contours consisted of the following steps and assumptions:

- Since the Thurber et al (2009) tomography data was available at 4 km depth, all P-wave velocities at that depth equal to 4.2 km/s were used to define the 4 km contour.

- To create contours at depths other than 4 km, a P-wave velocity gradient was assumed. We utilized results from Brocher (2005, Figure 13a) that showed for Central Valley sediments V_p increased about 600 m/s for every 1000 meter increase in depth.

- Using the assumption above, we argue that a V_p of 4.8 km/s at 4km depth would correspond to a V_p of 4.2km/s at 3 km depth since we can expect, on average, that V_p will decrease by 0.6 km/s with a 1 km decrease in depth. Thus, V_p values of 4.8 km/s in Thurber et al's 4 km depth horizon were used to define the 3 km contour. This process is graphically depicted in Figure 12. In a similar manner, a 3.5 km deep contour was defined using V_p=4.5 km/s data points. Since no data points were significantly less than V_p=4.2 km/s, no contours deeper than 4 km were required.

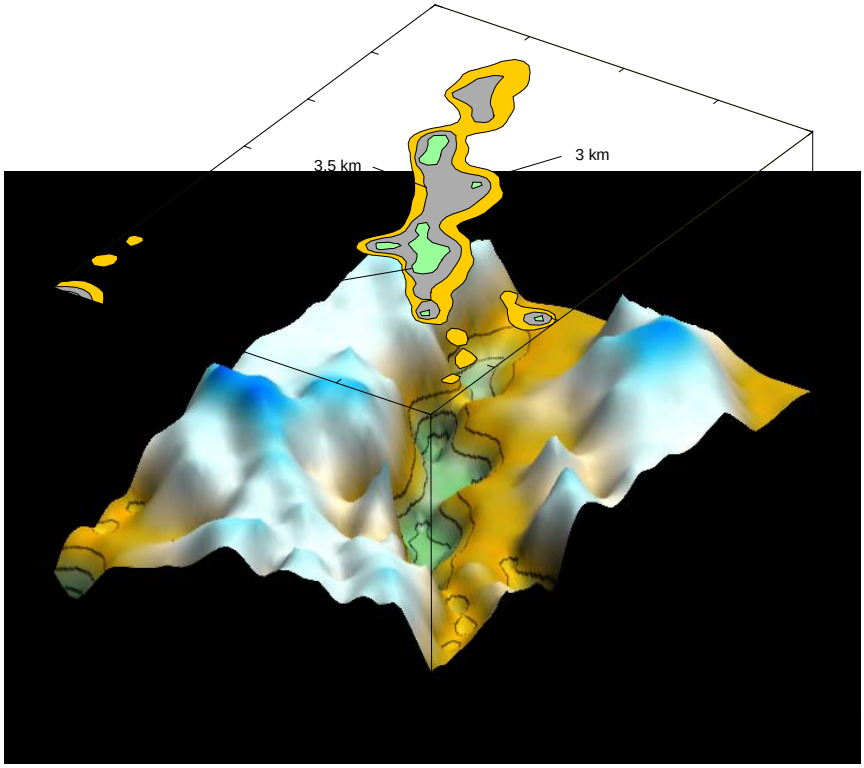

Figure 12: Construction Northern California $Z_{2.5}$ contours. Surface plot (bottom) of P-wave velocity at 4 km depth (Thurber et al, 2009). Contour plot (top) represents corresponding $Z_{2.5}$ contours.

While the Northern California $Z_{2.5}$ contours should be considered approximate given the coarse-grid tomography data they are based on as well as the assumption of P-wave velocity gradient, the resulting contour locations correspond reasonably well with estimates of very deep basement rock in the Central Valley (Downey and Clinkenbeard, 2005).

Basin contours in Caltrans ARS Online

For Caltrans ARS Online to incorporate $Z_{1.0}$ and $Z_{2.5}$ basin depths into the calculation of response spectra, it must be able to quickly determine (1) whether a given site location falls within a basin,

$$Z_{site} = Z_1 + \left(Z_2 - Z_1\right) * \left(\frac{r_{site} - r_1}{r_2 - r_1}\right)$$

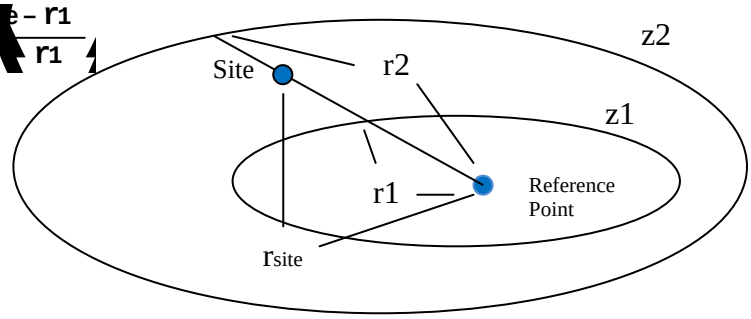

Figure 13: Diagram depicting use of polar coordinates to define contours and use of radii to perform interpolation between contours.

and (2) perform an interpolation of basin depth between contours to improve the basin depth estimate as well as avoid discontinuity in basin depth over small distances. The basic approach employed was to define each contour in polar coordinates, with each basin having a common reference point. For contours with simple oval shapes this is a very efficient and effective technique. Interpolation between contours is handled through simple interpolation of radii (at a common angle) as shown in Figure 13. While interpolation ideally should be performed along a path of maximum gradient between contours, the simpler approach used here provides sufficient accuracy, particularly when one considers the approximate nature of the contours.

Unfortunately, only a minority of the contours had simple enough shapes to employ the method above directly. Several extensions to this basic approach were employed to handle the more common case of irregularly shaped contours. These methods consisted of the following techniques:

- use of a functional transformation of one of the contour coordinates to create a simpler shape that can be tackled by the basic polar coordinate approach
- use of multiple reference points to define the contour
- breaking contours into smaller overlapping contours

While employing these techniques proved at times to be complex, successful solutions were found in all cases. As basin velocity models improve with time, an effort should be made to find a more comprehensive approach to efficiently modeling them.

A final note on terminology, when a soil site incurs basin amplification, the increased level of shaking will in general result in an increase in soil amplification as well. Caltrans ARS Online follows the convention when reporting basin amplification factors that the reported basin amplification is relative to the non-basin condition. Any additional soil amplification that occurs due to increased basin response is considered part of the overall basin amplification. This convention is somewhat at odds with the ground motion prediction models, where basin amplification is implicitly considered to be relative to a rock condition.

Probabilistic Design Spectrum

4.1 Utilization and modification of USGS hazard data

For creation of the probabilistic spectrum, Caltrans ARS Online relies on 5% in 50 year hazard data provided at 11 spectral periods by the USGS (see Petersen, 2008). This data assumes a soft rock condition (V_{S30} = 760 m/s) and is provided on a 0.05 deg grid spacing (approximately 5 km). The USGS hazard data is based on a slightly more recent fault database than the 2007 Caltrans fault database. To improve the estimate of spectral values at a particular site, a four-point linear interpolation scheme is used. While this interpolation is effective in most cases, at locations near a fault, the hazard may be underestimated due to the limited resolution of the data. While this under prediction is theoretically possible at any distance less than 5 km, as a practical matter, significant differences are most likely to occur at distances less than 2 to 3 km.

Since the USGS hazard data is applicable only to soft rock conditions, Caltrans ARS Online must apply a soil amplification factor to extend application to a broader range of site conditions. Since the USGS hazard data was developed using an equal weighting of the Boore-Atkinson (2008), Chiou-Youngs (2008), and Campbell-Bozorgnia (2008) ground motion prediction equations, Caltrans ARS Online applies the average soil amplification from these three models. In cases where a site is located within a basin, a basin amplification factor will be applied as discussed in the previous section. The basin amplification for the probabilistic spectrum may be slightly different than that of the deterministic spectrum since basin amplification includes a component of additional soil amplification that is amplitude dependent, and the amplitude of the probabilistic and deterministic spectra may not be the same. Caltrans ARS Online gives the user the option to apply near-fault adjustment factors to the probabilistic spectrum, as required by SDC, Appendix B. Since the near-fault adjustment is distance dependent, a deaggregation analysis should generally be performed to determine the applicable distance.

4.2 Limitations of the Caltrans ARS Online Probabilistic Spectrum

During the creation of Caltrans ARS Online, USGS hazard data was available only for soft rock conditions. As discussed above, in order to create the probabilistic spectrum at soil sites, soil amplification factors are applied to the soft rock spectrum. While this approach usually leads to a close approximation of the "true" probabilistic spectrum, the more correct approach is to incorporate site amplification directly into the hazard calculation. Recently, USGS has made results from this more accurate hazard calculation available through an updated deaggregation tool (currently in beta testing at http://eqint.cr.usgs.gov/deaggint/2008/index.php). Generally, the soil modified rock hazard that Caltrans ARS Online employs results in a small under-prediction of the USGS soil hazard. However, in cases of softer soil conditions, moderately worsened by increased shaking level, the USGS probabilistic spectral values may exceed that of Caltrans ARS Online by as much as 20% or more, depending on period. Figure 14 presents the results of a comparison study that determined threshold curves of V_{S30} as a function of PGA for three spectral periods. Points on or below these curves will result in an under-prediction of the probabilistic spectral value(s) of at least 10%. In such cases, use of the USGS deaggregation tool for determination of the probabilistic spectrum should be considered.

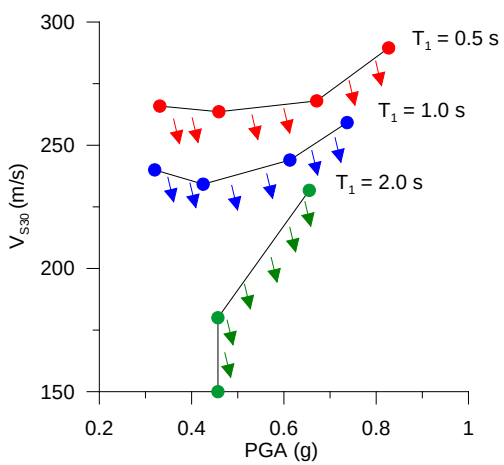

Figure 14: Threshold values of V_{S30} as a function of PGA for spectral periods of 0.5, 1, and 2 seconds. V_{S30} -PGA combinations that fall below the curve (side with arrows) will result in an under-prediction of the probabilistic spectrum by Caltrans ARS Online of more than 10%.

Concluding Comments

Although the Deterministic PGA Map and Caltrans ARS Online design tool have undergone extensive review for accuracy (more than 100 locations were checked by hand), the history of software development suggests errors are inevitable. While the Deterministic PGA Map will be used for preliminary design only and occasional errors maybe tolerable, errors in Caltrans ARS Online of more than 10% are considered intolerable. Thus, it is recommended that for an initial period (perhaps six months to one year), Caltrans ARS Online results should be checked by hand and verified. If the reported error rate decreases to an acceptably low level, the requirement for verification can then be removed.

The Deterministic PGA Map and Caltrans ARS Online design tool were created to aid in the development of response spectra that meet design criteria specified in SDC, Appendix B. While these criteria are expected to remain relatively static over time, it is also expected that occasional updates will be required as the state of knowledge evolves. A good example of this pertains to the issue of near-fault effects. This issue is a topic of active research and improved design criteria may be possible in the not too distant future. In a similar vein, knowledge of seismic hazards will continue to advance. A sustained effort is necessary to track and update seismic hazard information. Periodic updates will be needed and a listing of errata should be made available to identify important changes between updates. While the final responsibility for the design spectrum rests with the geo-engineering professional, every effort should be made to keep the map and online tool accurate and up to date.

References

2007 Working Group on California Earthquake Probabilities (WGCEP 2008), 2008, The Uniform California Earthquake Rupture Forecast, Version 2 (UCERF 2): USGS Open-File Report 2007-1437/CGS Special Report 203/SCEC Contribution #1138, 96 pp and Appendices (http://pubs.usgs.gov/of/2007/1437)

Applied Technology Council, 1996, Improved Seismic Design Criteria for California Bridges: Resource Document, Publication 32-1, Redwood City, California.

Atkinson, G., Boore, D., Empirical ground-motion relations for subduction zone earthquakes and their application to Cascadia and other regions., *Bulletin of the Seismological Society of America* (August 2003), 93(4):1703-1729

Boatwright, J., Blair, L., Catchings, R., Goldman, M., Perosi, F., and Steedman, C. (2004), Using twelve years of USGS refraction lines to calibrate the Brocher and others (1997) 3D velocity model of the Bay area, *U.S. Geol. Surv. Open-File Rept. 2004-1282*, 34 pp.

Boore, D., and Atkinson, G., 2008, Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s: Earthquake Spectra, Vol.24, pp.99-138.

Brocher, T., M, 2005, A regional view of urban sedimentary basins in Northern California based on oil industry compressional-wave velocity and density logs: Bull. Seism. Soc. Am., v.95, 2093-2114.

Bryant, W.A. compiler, 2005, Digital Database of Quaternary and Younger Faults from the Fault Activity Map of California, Version 2.0 (July 2005): http://www.consrv.ca.gov/CGS/information/publications/QuaternaryFaults_ver2.htm

California Geological Survey (CGS), 1997 (rev.2008), Guidelines for evaluating and mitigating seismic hazards in California: Special Publication 117, 74 pp. http://www.conservation.ca.gov/cgs/shzp/webdocs/Documents/sp117.pdf

Caltrans, 2008a, Seismic Design Criteria (*SDC*): http://www.dot.ca.gov/hq/esc/techpubs/manual/othermanual/other-engin-manual/seismic-design-criteria/sdc.html

Campbell, K., and Bozorgnia, Y., 2008, NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD, and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s.: Earthquake Spectra, Vol.24, pp.139-172.

Chiou, B., and Youngs, R., 2008, An NGA model for the average horizontal component of peak ground motion and response spectra: Earthquake Spectra, Vol.24, pp.173-216.

Downey, C., Clinkenbeard, J., An Overview of Geologic Carbon Sequestration Potential in California, CGS Special Report 183, September 30, 2005.

Frankel, A.D., Petersen, M.D., Mueller, C.S., Haller, K.M.,Wheeler, R.L., Leyendecker, E.V., Wesson, R.L., Harmsen,S.C., Cramer, C.H., Perkins, D.M., Rukstales, K.S., 2002,Documentation for the 2002 update of the National SeismicHazard Maps: U.S. Geological Survey Open-File Report2002–420, 39 p.

Jennings, C., compiler, 1994, Fault activity map of California and adjacent areas: CGS Geological Data Map No.6, scale 1:750,000 ("Jennings Map").

Petersen, Mark D., Frankel, Arthur D., Harmsen, Stephen C., Mueller, Charles S., Haller, Kathleen M., Wheeler, Russell L., Wesson, Robert L., Zeng, Yuehua, Boyd, Oliver S., Perkins, David M., Luco, Nicolas, Field, Edward H., Wills, Chris J., and Rukstales, Kenneth S., 2008, Documentation for the 2008 Update of the United States National Seismic Hazard Maps: U.S. Geological Survey Open-File Report 2008–1128, 61 p.

Thurber,C., Zhang, H., Brocher, T., and Langenheim, V., 2009, Regional three-dimensional seismic velocity model of the crust and uppermost mantle of northern California: *J. Geophys. Res.*, 114, B01304.pp.

Southern California Basin Models (Community Velocity Model V.4) http://www.data.scec.org/3Dvelocity/

SURFER Golden Software, Golden Colorado

USGS Custom Mapping and Analysis Tools (US 2002 version – simplified fault traces): http://earthquake.usgs.gov/research/hazmaps/interactive/index.php

USGS Hazmap documentation, April 2003 (received 11/01/2005 via email from Ken Rukstales, USGS).

USGS Probabilistic Seismic Hazard Analysis http://earthquake.usgs.gov/research/hazmaps/

Youngs, R.R., S.J. Chiou, W.J. Silva, and J.R. Humphrey (1997). Strong ground motion attenuation relationships for subduction zone earthquakes, *Seism. Res. Letts.*, v. 68, no. 1, pp. 58-73.