Design Acceleration Response Spectrum

This module presents procedures for developing the design Acceleration Response Spectrum (ARS) for Caltrans bridges in accordance with the requirements of the Seismic Design Criteria (Caltrans, 2019), Version 2.0, with October 2019 Interim Revisions (SDC v2.0).

This module does not address the development of the design ARS for project sites that require a site-specific dynamic ground response analysis (DGRA) per Appendix B of the SDC v2.0.

Unless specified otherwise in a Project-Specific Seismic Design Criteria, Caltrans current practice is to use the Safety Evaluation Earthquake (SEE) design ARS developed per SDC v2.0 to characterize design ground motions for earth retaining structures, embankments, slopes, sign structures and other appurtenant highway facilities.

Design Ground Motion

Per SDC v2.0, the design ground motion at a bridge site due to earthquakes is characterized by the Design Spectrum in the form of the design ARS for 5% damping.

Unless otherwise requested by Structure Design, Geotechnical Services provides the SEE design ARS that characterizes the site horizontal ground motion at or near the ground surface with a 5% probability of exceedance in 50 years (i.e., 975 years return period). The SEE design ARS is evaluated based on the United States Geological Survey's (USGS) 2014 National Seismic Hazard Map (2014 NSHM) for 975 years return period (USGS, 2014, Peterson et al., 2014 and 2015). Modifications due to the basin-effects and/or near-fault effects are applied where necessary, per Appendix B of SDC v2.0.

In some cases, Structure Design may request the Functional Evaluation Earthquake (FEE) design ARS that characterizes the site horizontal ground motion with a 20% probability of exceedance in 50 years (i.e., 225 years return period). Except the return period, all other development requirements specified in Appendix B of the SDC v2.0 for the SEE design ARS are also applicable to the development of the FEE design ARS.

For bridge sites with low shear wave velocity, as specified in Appendix B of the SDC v2.0, a site-specific DGRA (i.e., numerical analysis of vertically propagating seismic shear waves from bedrock through the overlying subsurface soils to at or near the ground surface) is required to develop the final design ARS.

Unified Hazard Tool and ARS Online V3.0 Tool

The 2014 NSHM is the basis for developing the design ARS for Caltrans bridge sites. The USGS' Unified Hazard Tool (UHT) is used to obtain the 2014 NSHM ARS, and other required design ground motion and related seismic source parameters. Attachment 1 presents additional information regarding the 2014 NSHM and the UHT. It also briefly discusses the orientation-independent, rotated spectral acceleration definition used in the 2014 NSHM ARS, and the directionality of the component of the design ground motion acting on the horizontal plane as represented by the design ARS developed per SDC v2.0

Caltrans has developed the ARS Online v3.0 web tool (Caltrans, 2020) to conveniently determine the SEE design ARS and other related design ground motion parameters. For FEE design ARS, a procedure that utilizes both the UHT and ARS Online is discussed later in this document. In the future, the ARS Online will be updated to include FEE design ARS.

Design Ground Motion Parameters

The following information related to design ground motion is required in the foundation reports.

- Site coordinates (latitude and longitude in decimal degrees)
- Time-averaged shear wave velocity VS30 in feet /sec for the upper 100 feet (30 meters) of the design subsurface soil/rock profile(s)
- ARS
- Horizontal Peak Ground Acceleration (HPGA or PGA), in units of g, where g is the acceleration of gravity.
- Deaggregated mean earthquake moment magnitude (M or Mw) for the design PGA, and the
- Deaggregated mean site-to-source distance (R or Rrup, in km) for the 1.0 second period design spectral acceleration.

Site Coordinates

Site coordinates can be determined using a variety of tools, including Caltrans' Postmile Services, USGS' web-based Interactive Fault Map, and Google Earth.

Time-Averaged Shear Wave Velocity

The 2014 NSHM provides ARS for a site location based on time-averaged shear wave velocity (V_{S30}) for the upper 30 meters (100 feet) of the subsurface soil/rock profile.

To determine V_{S30}, the upper 100 feet (30 meters) of the subsurface soil/rock profile is divided into N number of layers based on the average layer shear wave velocity V_{Si} (i=1 to N). The equation used for calculating V_{S30} in feet/sec is:

$$V_{S30}\left(\frac{\text{feet}}{\text{sec}}\right)=\frac{100\ \text{feet}}{\left(\frac{D_1}{V_{S1}}\right)+\left(\frac{D_2}{V_{S2}}\right)+\cdots+\left(\frac{D_i}{V_{Si}}\right)+\ \ldots..+\left(\frac{D_N}{V_{SN}}\right)}$$

Where D_i and V_{Si} are the thickness in feet and average shear wave velocity in feet/sec, respectively, for the i^{th} layer (i=1 to N), and $\sum_{i=1}^{N} D_i = 100\ feet.$ Attention must be paid to the unit used for the soil/rock shear wave velocity since both feet/sec and meters/sec are widely used. For example, V_{S30} evaluated based on the above equation is in feet/sec, which must be converted to meters/sec unit for use with the ARS Online v3.0 or the UHT.

Design V_{S30} Profile(s)

For many bridge sites, the spatial variations in the subsurface soil/rock conditions within the upper 100 feet are not substantial to cause significantly different ground shaking at different support locations. In such cases, the design horizontal ground motion at all support locations can be represented by a single ARS evaluated based on a representative soil/rock profile or V_{S30} value for the entire site.

For a bridge site, where V_{S30} values differ drastically between support locations, more than one design ARS should be provided. In general, different design ARS should be provided if the “Soil Profile Type”, as defined in Figure B.10 of the SDC v2.0, differs between supports by one or more letters (e.g., Soil Profile Type C at abutments and Soil Profile Type D or E at intermediate supports). This does not consider any effects due to wave scattering, and thus may not apply to long bridges (e.g. >1000 feet). For such bridges the variations in the ground motions between supports due to wave-passage effects can be significant.

Field Testing for In-situ Shear Wave Velocity

Soil/rock shear wave velocity is best obtained by direct field or in-situ measurement methods such as those listed in Table 1.

Table 1. Common Test Methods for In-situ Measurements of Shear Wave Velocity

Test Methods	Brief Description, Advantages and Disadvantages
Seismic Cone Penetration Test (SCPT)	The SCPT uses a fixed source at the surface to generate seismic shear waves in the soils. Receivers (seismometers) are placed on the SCPT rod at locations near and above the cone tip. Soil shear wave velocities are determined at discrete depth intervals. No predrilled borehole is necessary. Simultaneously obtains soil stratigraphic information and other useful data for geotechnical interpretation and evaluation of the subsurface conditions and design analysis. SCPT can be used to reduce the numbers of boreholes to be drilled, or to verify and correlate with an adjacent borehole drilled as part of a regular geotechnical site investigation. SCPT is fast and suitable for developing multiple shear wave velocity profiles at project sites, where necessary. Data resolution reduces with depth.
Rayleigh Wave Inversion	Measurements are made at the surface. Several variations of this method are available, including Refraction Microtremor (ReMi), Multichannel Analysis of Surface Waves (MASW) and Spectral Analysis of Surface Waves (SASW). Non-destructive method requiring no boreholes. Measures shear wave velocities of larger volumes of soil/rock. Suitable for V_{S30} determination. Inversion analysis does not result in a unique solution.
P- and S-Wave (PS) Suspension Logging	Shear wave measurements are made in an uncased or thermoplastic-cased borehole. Source and receivers have a fixed separation and are both within the borehole. Localized shear wave velocities are measured at discrete depth intervals. Good quality boreholes and coupling between the casing, when used, and the surrounding grout and borehole wall soils are required to obtain reliable soil or rock shear wave velocity measurements. Requires coordination with drill crew at borehole completion. Data resolution remains the same with depth.
Downhole Seismic Logging	The seismic wave source is fixed at the surface, and shear wave measurements are made with the receiver placed in the uncased or open borehole at discrete depth intervals. Uses the same basic seismic principles as the SCPT with data resolution decreasing with depths. Good quality borehole is required to obtain reliable soil or rock shear wave velocities. Requires coordination with drill crew at borehole completion.

Depending on the types of field measurements and methods of data interpretation, soil/rock shear wave velocities may be presented either in terms of the average shear wave velocity (V_s) for each interpreted uniform soil/rock layer or simply as a near continuous function of depth (d). In the latter case, when appropriate, it may be convenient to divide the upper 30 m of the soil/rock profile into a fewer number of relatively uniform soil/rock layers and their average shear velocities (V_{Si}) calculated from the measured shear wave velocities. The total number of layers (N) and the thicknesses D_i (i=1,N) of the individual layers should be determined based on the type (e.g., sand, silt, clay etc.) and density or consistency of the soil/rock, and the variations in the measured shear wave velocity with depth. The greater the variations in the measured shear wave velocity with depth the smaller should be the layer thickness D_i.

Geophysical tests have their own limitations, and each test type has its own advantages and disadvantages compared with the others. Reliability of the shear wave velocities measured is dependent on many factors, including the equipment operator, test method or type used; the quality of the boreholes, when used, and the field measurements; the assumptions and the tools used for data analysis and interpretation, and the complexities of the actual subsurface conditions (Coe et al., 2018; NCHRP, 2006).

In conjunction with the typical geotechnical subsurface investigation, and where appropriate for use, SCPT is the preferred method for measuring soil shear wave velocities in the field for both V_{S30} determination and site-specific DGRA. It is also preferred when measurements at more than one locations are necessary at a project site due to spatial variability in the subsurface conditions.

Surface-based geophysical field tests (e.g., MASW) are preferred for V_{S30} determination at: (a) soil sites underlain by boulders, cobbles and/or significant fraction of coarse gravels or other obstructions, where SCPT data may not be reliable and/or refusal is anticipated at depths <30m, and (b) shallow rock sites, when shear wave velocity measurement is considered necessary.

PS Suspension Logging or Downhole Seismic methods may also be used for obtaining soil/rock shear wave velocities for both V_{S30} determination and site-specific DGRA. PS Suspension Logging should be used when shear wave velocity measurements need to extend significantly deeper than 30m. Table 1 provides additional information for each of the above field test methods.

Field measured shear wave velocity data is generally required for performing a site-specific DGRA. For these sites, the depth of measurements may need to extend to depths significantly greater than 100 feet (30 m) to reach bedrock whenever feasible. For deep soil deposits where it may not be feasible to reach bedrock, field measurements need to extend at least to the depth of very dense/hard soil (shear wave velocity > 1200 ft/sec or 360 m/sec). Field measurements should extend at least 10 to 20 feet into the very dense/hard soils to ensure that soil shear wave velocity is increasing with depth or at least not decreasing. For assistance in evaluating these situations, refer to an experienced seismic specialist.

Established empirical correlations for shear wave velocity, such as those included in Attachment 2, with other directly measured soil/rock parameters or properties, where available, may be used to estimate V_{S30} for preliminary evaluations. Use of empirical correlations for final design may be acceptable when:

- A site-specific DGRA is not required, and
- Additional subsurface field investigation is not considered necessary or planned for the preparation of the foundation report, or

- Subsurface field investigation at the project site will be performed but the V_{S30} is estimated to be at least 1000 ft/sec (300 m/sec) based on reliable information, and field measurement of shear wave velocity is considered not feasible. For such cases, an experienced seismic specialist may be contacted for further assistance.

When using empirical correlations, for clay soils those with directly measured undrained shear strength are preferred over CPT tip resistance. For sand and silts, the empirical correlations with CPT tip resistance are preferred. In general, for all soils, CPT tip based empirical correlations are preferred over those based on SPT blow counts.

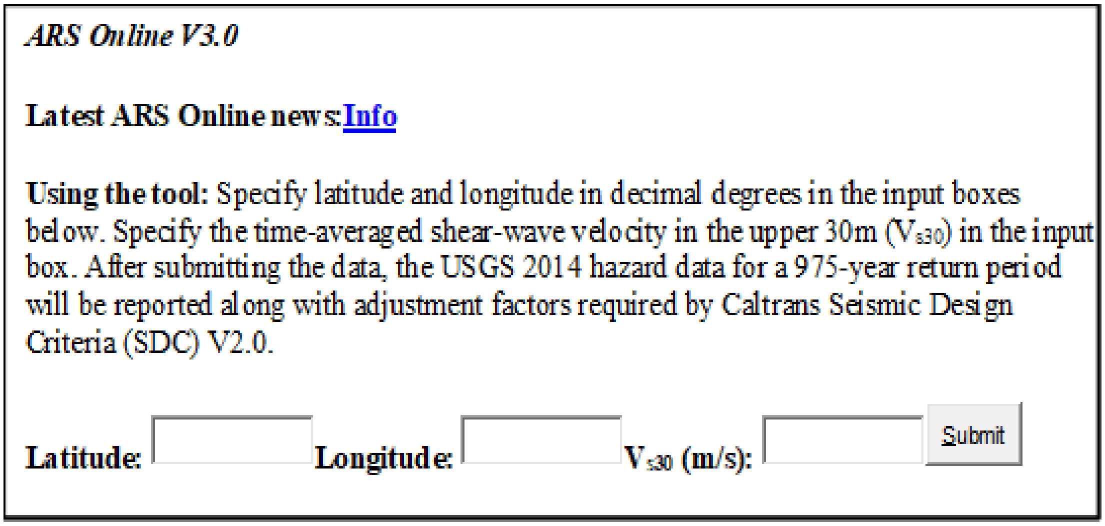
ARS Online v3.0 Tool

The ARS Online v3.0 tool develops the SEE design ARS by running the UHT tool in the background to obtain the 2014 NSHM ARS data for 975 years return period, and by applying, where required, the modifications factors due to near-fault and/or basin effects.

The following site input parameters are required to run the ARS Online v3.0 tool. The latest available version of ARS Online v3.0.x tool shall be used, here “x” indicates the latest updated version.

- Site coordinates (latitude and longitude in decimal degrees), and the
- V_{S30} (meters/sec) for the design soil/rock profile.

A screen shot of the ARS Online v3.0 tool input page is shown in Figure 1.



ARS Online V3.0

Latest ARS Online news: Info

Using the tool: Specify latitude and longitude in decimal degrees in the input boxes below. Specify the time-averaged shear-wave velocity in the upper 30m (V_{s30}) in the input box. After submitting the data, the USGS 2014 hazard data for a 975-year return period will be reported along with adjustment factors required by Caltrans Seismic Design Criteria (SDC) V2.0.

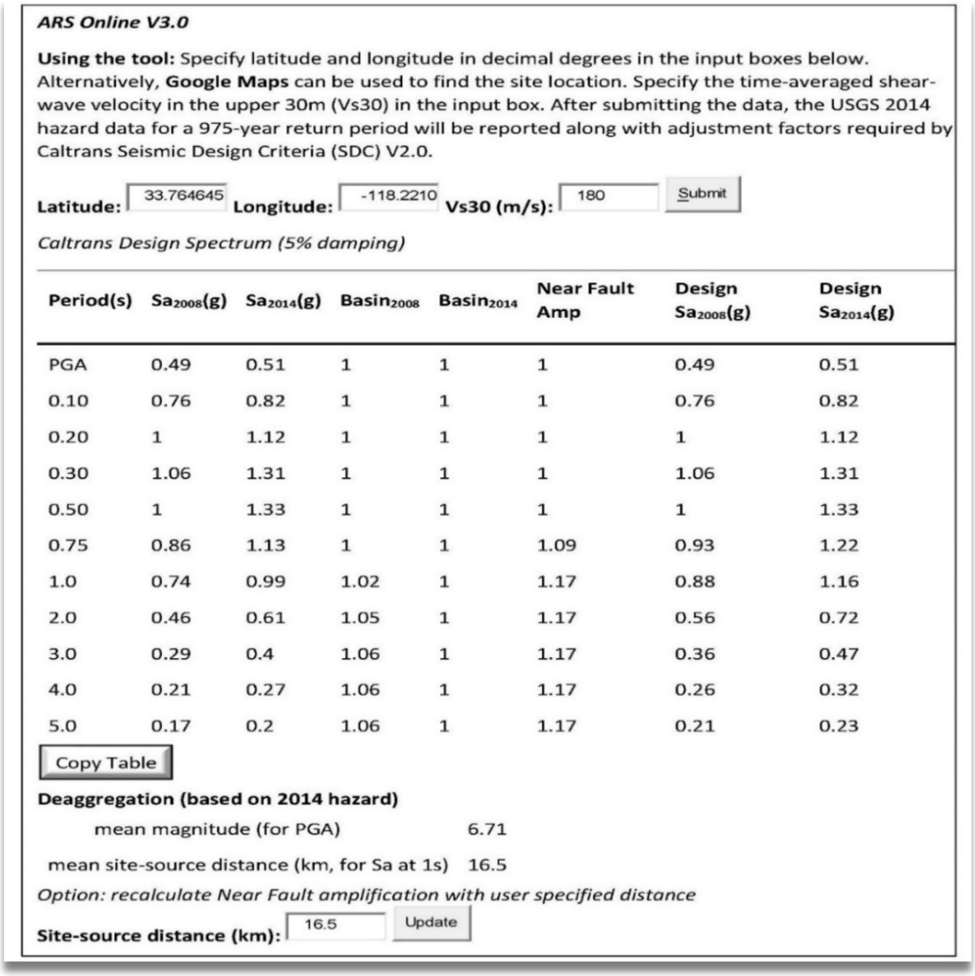
Figure 1: Input Page of the ARS Online v3.0 Web Tool

The 2014 NSHM provides hazards and ARS data for sites with $V_{S30} \geq 180$ meters/sec (590 feet/sec). For Caltrans project sites, the maximum value of the V_{S30} is limited to 1150 meters/sec. Therefore, when using the UHT for Caltrans project sites, the option for V_{S30}, that is the UHT “Site Class” input parameter, is limited to the following specific values only: 180, 259, 360, 537, 760 and 1150 meters/sec (590, 850, 1180, 1760, 2500, and 3775 feet/sec). These V_{S30} values are referred to hereafter in this document as the “Site Class” V_{S30}.

Additional input parameters, as discussed in Attachment 1, are necessary to run the UHT. For a site or support location with a design V_{S30} equal to one of the “Site Class” V_{S30}, the ARS Online v3.0 automatically enters the appropriate values for the additional input parameters required to run the UHT for 975 years return in the background.

For a site with V_{S30} not equal to one of the “Site Class” V_{S30} value, the ARS Online v3.0 determines the design ARS based on the interpolation of the two design ARS obtained for the two nearest bounding “Site Class” V_{S30} values, one higher and the other lower.

A screen shot of the ARS Online v3.0 result page for a site is shown in Figure 2.



ARS Online V3.0

Using the tool: Specify latitude and longitude in decimal degrees in the input boxes below. Alternatively, **Google Maps** can be used to find the site location. Specify the time-averaged shear-wave velocity in the upper 30m (Vs30) in the input box. After submitting the data, the USGS 2014 hazard data for a 975-year return period will be reported along with adjustment factors required by Caltrans Seismic Design Criteria (SDC) V2.0.

Latitude: 33.764645 **Longitude:** -118.2210 **Vs30 (m/s):** 180

Caltrans Design Spectrum (5% damping)

Period(s)	Sa$_{2008}$(g)	Sa$_{2014}$(g)	Basin$_{2008}$	Basin$_{2014}$	Near Fault Amp	Design Sa$_{2008}$(g)	Design Sa$_{2014}$(g)
PGA	0.49	0.51	1	1	1	0.49	0.51
0.10	0.76	0.82	1	1	1	0.76	0.82
0.20	1	1.12	1	1	1	1	1.12
0.30	1.06	1.31	1	1	1	1.06	1.31
0.50	1	1.33	1	1	1	1	1.33
0.75	0.86	1.13	1	1	1.09	0.93	1.22
1.0	0.74	0.99	1.02	1	1.17	0.88	1.16
2.0	0.46	0.61	1.05	1	1.17	0.56	0.72
3.0	0.29	0.4	1.06	1	1.17	0.36	0.47
4.0	0.21	0.27	1.06	1	1.17	0.26	0.32
5.0	0.17	0.2	1.06	1	1.17	0.21	0.23

Deaggregation (based on 2014 hazard)

mean magnitude (for PGA)	6.71
mean site-source distance (km, for Sa at 1s)	16.5

Option: recalculate Near Fault amplification with user specified distance

Site-source distance (km): 16.5

Figure 2: ARS Online v3.0 Result Page

Figure 2 shows the specified site input parameters followed by a tabular presentation of the structure periods (in secs) in the 1st column and the corresponding SEE design spectral accelerations as “Design S_{a2014}(g)” in the last column. The table also includes the 2014 NSHM base ARS spectral accelerations values as “S_{a2014} (g)”, and the corresponding basin amplification factors as “Basin_{2014}” and near-fault amplifications factors as “Near-Fault Amp” in the 3rd, 5th and 6th columns, respectively. The table also includes, for information and visual comparison only, ground motion parameters corresponding to the USGS’ 2008 NSHM for the same return period.

The required source parameters from hazard deaggregation, i.e., the mean M and R values for the PGA and 1.0 second period spectral acceleration, respectively, are presented in the ARS data table in Figure 2.

A “**Copy Table”** button is included to copy all the data in the table into the computer’s clipboard and paste in a spreadsheet for further processing and plotting. An additional option to calculate the near-fault amplification factors for any site based on a user specified R value is also included near the bottom of the result page.

Procedure for Developing SEE Design ARS

ARS Online v3.0 tool is used to determine the SEE design ARS. The recommended steps are:

STEP 1. Determine the site coordinates in terms of latitude and longitude (in decimal degrees)

STEP 2: Determine V_{S30} value(s) in meters/sec for the representative subsurface soil/rock profile(s) at the bridge support location(s). Evaluate if more than one design ARS is necessary at the site due to variations in the V_{S30}.

STEP 3: Determine if a site-specific DGRA is required to develop the final design ARS per Appendix B of the SDC v2.0. If not, continue with Step 4. Otherwise, contact an experienced seismic specialist for assistance.

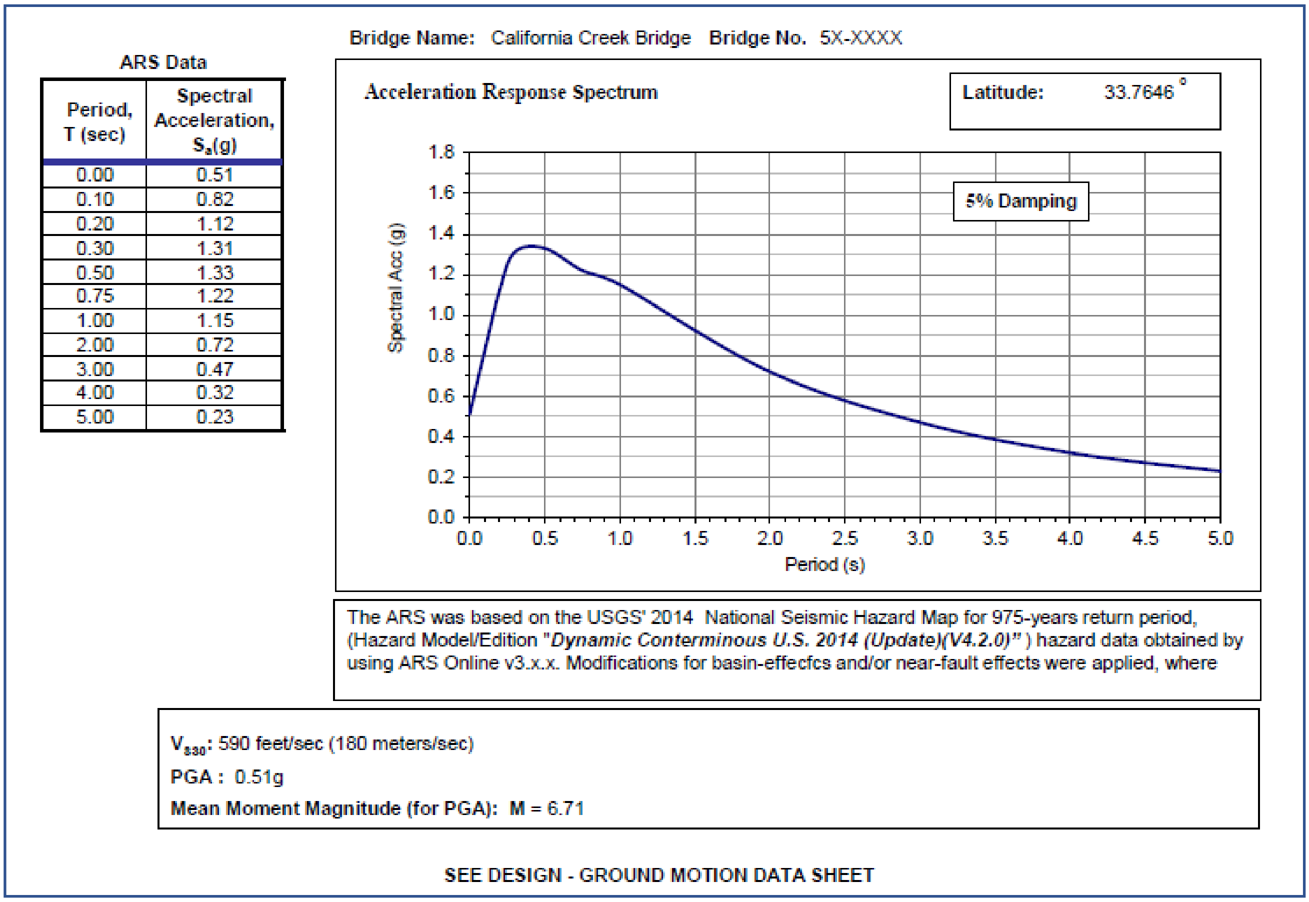
STEP 4: Open ARS Online v3.0 web tool available at https://arsonline.dot.ca.gov/. Enter the site latitude and longitude in decimal degrees and the design V_{S30} in meters/sec for the subsurface soil profile.

STEP 5: Click on the “Submit” button to run the tool. It may take a minute for the result page to show up.

STEP 6: Copy the ARS data table by clicking on the “Copy Table” button”.

STEP 7: Paste the copied ARS data table into the Ground Motion Data Sheet (or equivalent spreadsheet). Change the “PGA” in the “Period(s)” column to 0.0 sec.

STEP 8: Plot and present the SEE design ARS data points as shown in Figure 3. Present all information shown on the Ground Motion Data Sheet for the project.



Bridge Name: California Creek Bridge **Bridge No.** 5X-XXXX

ARS Data

Period, T (sec)	Spectral Acceleration, S_a(g)
0.00	0.51
0.10	0.82
0.20	1.12
0.30	1.31
0.50	1.33
0.75	1.22
1.00	1.15
2.00	0.72
3.00	0.47
4.00	0.32
5.00	0.23

The ARS was based on the USGS' 2014 National Seismic Hazard Map for 975-years return period, (Hazard Model/Edition ***"Dynamic Conterminous U.S. 2014 (Update)(V4.2.0)"***) hazard data obtained by using ARS Online v3.x.x. Modifications for basin-effecfcs and/or near-fault effects were applied, where

V_{S30}: 590 feet/sec (180 meters/sec)

PGA : 0.51g

Mean Moment Magnitude (for PGA): **M** = 6.71

SEE DESIGN - GROUND MOTION DATA SHEET

Figure 3: SEE Design - Ground Motion Data Sheet

Step by Step Procedure for Developing FEE Design ARS

The FEE design ARS is provided only if requested by the Structure Designer. The same site- and design ground motion parameters are required as for the SEE design ARS, except for 225 years return period. Until included in a future version of the ARS Online web tool, the following step by step procedure is recommended to develop the FEE design ARS:

STEP 1: Determine the site latitude and longitude (in decimal degrees).

STEP 2: Determine V_{S30} value(s) in meters/sec for the representative subsurface soil/rock profile(s) at the support location(s). Evaluate if more than one design ARS is necessary for the site due to variations in the V_{S30}.

STEP 3: Determine if a site-specific DGRA is required to develop the final design ARS per Appendix B of the SDC v2.0. If not, continue with Step 4. Otherwise, contact an experienced seismic specialist for assistance.

STEP 4: If the design V_{S30} is not equal to one of the “Site Class” V_{S30}, determine the nearest "Site Class" V_{S30}. The "Site Class" V_{S30} values are those that can be selected from the UHT "Site Class" drop-down menu. The "Site Class" V_{S30} values for Caltrans' project sites are 180, 259, 360, 537, 760 and 1150 meters/sec (Limit V_{S30} to 1150 meters/sec if site V_{S30}>1150 meters/sec).

As an example, the V_{S30} for a bridge project site was determined to be 205 meters/sec in Step 2. This V_{S30} is not equal to one of the "Site Class" V_{S30}. The nearest "Site Class" V_{S30} values are 180 meters/sec and 259 meters/sec. The average of these two nearest "Site Class" V_{S30} values 219.5 meters/sec. Since the site V_{S30} (205 meters/sec) ≤ 219.5 meters/sec, the nearest "Site Class" V_{S30} for this site is 180 meters/sec. For a different site, the design V_{S30} was determined to be 220 meters/sec in Step 2. For this site, since V_{S30} (220 meters/sec) >219.5 meters/sec, the nearest "Site Class" V_{S30} is 259 meters/sec.

STEP 5: Open the UHT: (https://earthquake.usgs.gov/hazards/interactive/).

STEP 6: Enter the input parameter options/values from Table 2.

STEP 7: Run hazard/ARS analysis by clicking on the "Compute Hazard" button that appears below the input parameter section. It may take a minute for the UHT to complete calculations and display results on the screen.

STEP 8: Once the results are shown, determine and record the ARS data points in a spreadsheet by clicking on the data symbols on the ARS plot. This ARS data set or (T, S_a) points correspond to the 2014 NSHM base ARS for 225 years return period. It is advantageous to keep open the UHT web page and the spreadsheet until all the steps are completed.

Table 2: UHT Input Options

Input Parameter	Option/Value
Edition	*Dynamic Conterminous U.S. 2014 (Update)(V4.2.0)*
Latitude	Site latitude (in decimal degrees) from Step 1
Longitude	Site longitude (decimal degrees) from Step 1
Site Class	"Nearest Site Class V_{S30}" from in Step 4
Spectral Period	Any one value of the available input options will work
Time Horizon (Return Period, yrs.)	225

STEP 9: Return to open UHT web page and select "Peak Ground Acceleration" (i.e., PGA) as the input for the "Spectral Period" parameter. Check and confirm that all other UHT input parameter options/values remained the same as those in Table 2.

STEP 10: Run hazard deaggregation for the PGA by clicking on the "Compute Deaggregation" button that appears below the hazard curves/ARS plot. UHT may take up to one minute to complete the calculations.

STEP 11: From the PGA hazard deaggregation results, find the value of the parameter "m" (magnitude) reported in the section under the "Mean (over all sources)" heading. This is the deaggregated mean earthquake moment magnitude M for PGA.

STEP 12: Return to the open UHT web page and select "1.0 Second Spectral Acceleration" option for the "Spectral Period" parameter. Check and confirm that all other UHT input parameter options/values remained the same as those in Table 2.

STEP 13: Run hazard deaggregation for the "1.0 Second Spectral Acceleration" by clicking on the "Compute Deaggregation" button.

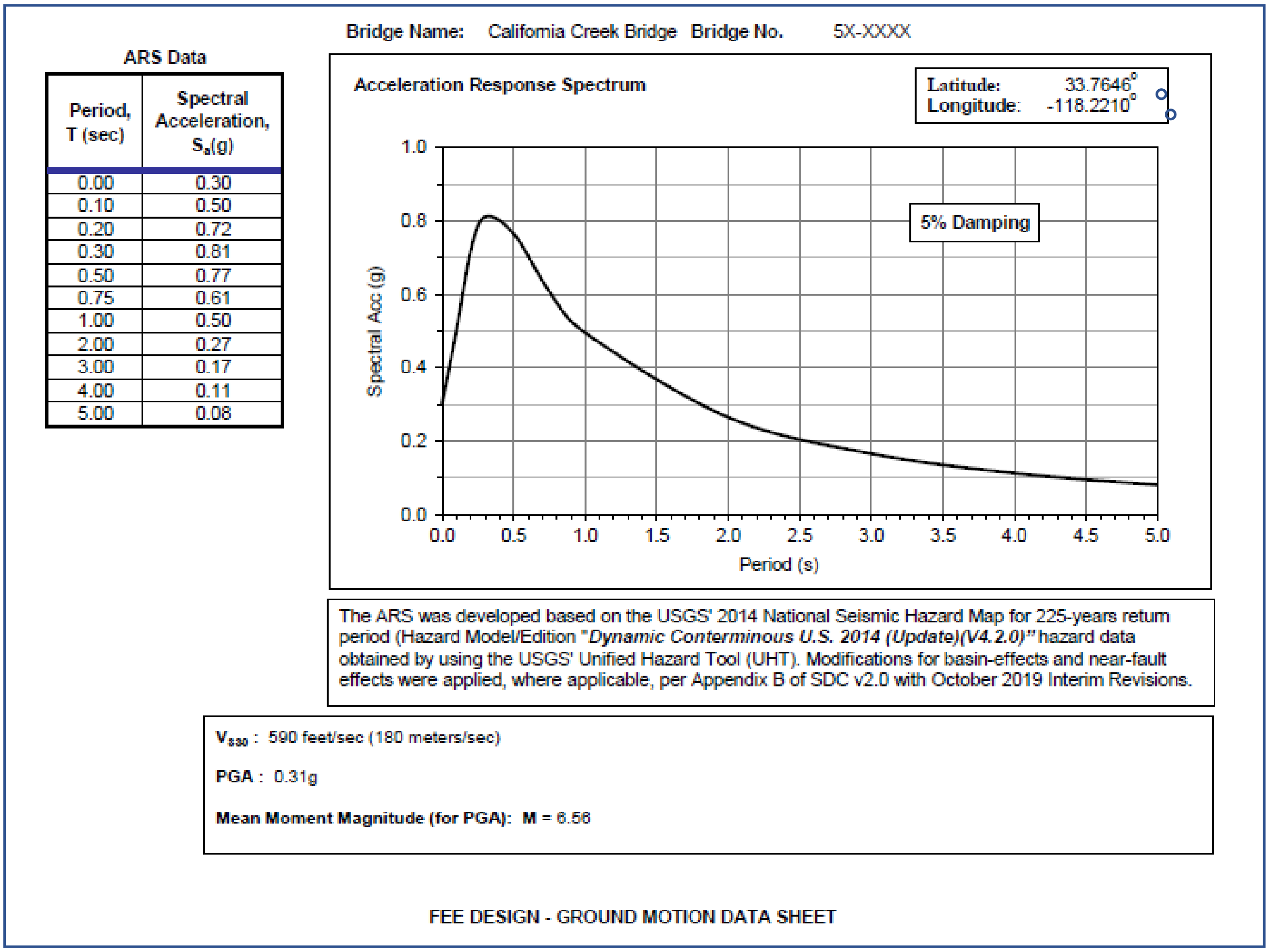
STEP 14: From the results of "1.0 Second Spectral Acceleration" hazard deaggregation analysis, find the value of the parameter "r" (distance, km) reported in the section under the "Mean (over all sources)" heading. This is the deaggregated mean site-to-source distance R (or R_{rup}) for 1.0 second period design spectral acceleration.

STEP 15: To determine the amplification factors for basin-effects, run ARS Online v3.0 for the site location (latitude and longitude from Step 1) and the nearest "Site Class" V_{S30} from Step 4. Copy the "$Basin_{2014}$" data column from the ARS data table (5th column) and paste this data in the spreadsheet next to the 2014 basic ARS data. Keep the ARS Online v3.0 result page open.

STEP 16: To determine the near-fault factors, return to the open ARS Online v3.0 result page and replace the "site-source distance (km)" input value equal with the mean site-to-source distance R (for 1.0 sec S_a) determined in Step 14. Click on the "update" button. Once the updated results are available, copy the "Near-Fault Amp" data column from the ARS data table (6th column) and paste in the spreadsheet next to the "Basin2014" data.

STEP 17: Determine the FEE ARS by multiplying the 2014 base ARS spectral acceleration values by the corresponding "$Basin_{2014}$" and Near-Fault Amp" factors.

STEP 18: Plot and present the FEE design ARS data points as shown in Figure 4. Include all data/information shown on the Ground Motion Data Sheet for the project site.



Bridge Name: California Creek Bridge **Bridge No.** 5X-XXXX

ARS Data

Period, T (sec)	Spectral Acceleration, S_a(g)
0.00	0.30
0.10	0.50
0.20	0.72
0.30	0.81
0.50	0.77
0.75	0.61
1.00	0.50
2.00	0.27
3.00	0.17
4.00	0.11
5.00	0.08

The ARS was developed based on the USGS' 2014 National Seismic Hazard Map for 225-years return period (Hazard Model/Edition "*Dynamic Conterminous U.S. 2014 (Update)(V4.2.0)*" hazard data obtained by using the USGS' Unified Hazard Tool (UHT). Modifications for basin-effects and near-fault effects were applied, where applicable, per Appendix B of SDC v2.0 with October 2019 Interim Revisions.

V_{s30} : 590 feet/sec (180 meters/sec)

PGA : 0.31g

Mean Moment Magnitude (for PGA): M = 6.56

FEE DESIGN - GROUND MOTION DATA SHEET

Figure 4: FEE Design - Ground Motion Data Sheet

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2014 National Seismic Hazard Map

The United Stated Geological Survey (USGS) developed the 2014 National Seismic Hazard Map (2014 NSHM) based on its 2014 long-term time-independent seismic hazard model (Peterson et al., 2015). This hazard model was developed utilizing the latest component models, data and methods available at the time for assessing earthquake-induced ground motion hazards.

The California portion of the 2014 NSHM is used as the basis to determine the design ARS for Caltrans project sites as specified in SDC v2.0. Detail information on the California portion of the 2014 NSHM, including the seismic source models, the fault source map, and the ground motion models (GMMs) or the ground motion prediction equations (GMPEs) used and other related documentation or references, can be found at https://earthquake.usgs.gov/hazards/hazmaps/conterminous/index.php#2014).

Orientation-Independent, Rotated Spectral Acceleration

With regard to the engineering applications, an important aspect of the 2014 NSHM is that the ground motion models used in its development no longer predict the spectral intensity of the horizontal ground motions in terms of the geometric-mean spectral acceleration, $(S_a)_{GM}$. The $(S_a)_{GM}$ is a scalar parameter and determined based on the spectral accelerations (S_a) of the two orthogonal components (field ground motion records are usually oriented at arbitrary azimuthal directions) of the horizontal ground motion.

The GMMs used predict the spectral intensity of the horizontal ground motions in terms of the recording instrument orientation independent, rotated single horizontal component spectral acceleration $(S_a)_{Rotxx}$, as defined by Boore (2010). Here, symbol “Rot” indicates that this spectral acceleration is calculated for a single horizontal ground motion component obtained by rotating the “as recorded”, two arbitrarily oriented orthogonal components of a horizontal ground motion event through all possible non-redundant rotation angles (0 to 180°). The symbol “xx” represent the percentile of the all the rotated spectral accelerations calculated for a horizontal ground motion record (orthogonal pairs).

These GMMs provide predictions of the mean $(S_a)_{Rotxx}$, designated as $(S_a)_{RotD50}$ and the associated standard deviation necessary for the development of the hazard curves. Here, the symbol “D” indicates that the rotation angle for the special acceleration is dependent on the structure period, and “50” indicates the 50th percentile of the spectral accelerations $(S_a)_{Rotxx}$ obtained for all non-redundant rotation angles.

Based on the above spectral intensity measure definition and the calculation procedure used, the $(S_a)_{Rotxx}$ for a horizontal ground motion ranges from a minimum of $(S_a)_{RotD00}$ to a maximum of $(S_a)_{RotD100}$, $(S_a)_{RotD50}$ being the median value (See Boore, 2010). The GMMs used in the development of the 2014 NSHM predict the median spectral acceleration $(S_a)_{RotD50}$ and the associated standard deviation.

Seismic Source Models for California

The seismic hazard model for the California portion of the 2014 NSHM is based on the Time-Independent Model (Field et al, 2014) component of the Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3). The UCERF3 model consists of three new and updated component models: fault source model, seismic deformation (slip rates) model and long-term earthquake rate model. The UCERF3 used updated seismic source models consisting of fault-based (system) and gridded seismicity-based (background) sources to estimate future earthquake hazards from known active fault sections and those from unknown or unidentified sources, respectively. It also considers rupture scenarios involving multiple fault segments.

Earthquakes from gridded seismicity-based (background) sources are represented as points or planar fault sources at the centers of evenly spaced grid cells that make up the UCERF3 forecast region. The UCERF3 forecast region cover the part of the State California where shallow crustal earthquakes occur. This includes most of the State, except the northwestern coastal region where the Cascadia subduction interface and deep subduction intra-slab earthquake events dominate the hazard. The gridded seismicity-based sources are used to predict future, distributed earthquake occurrences to account for the fact that many significant earthquakes do not occur on known, mapped faults.

Detail information on the UCERF3, including the fault-section database and the main report titled "Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3)-The Time-Independent Model (USGS OFR 2013-1165)", and the many appendices and supplemental information can be found at https://pubs.usgs.gov/of/2013/1165/.

The UCERF3 provides updated (relative to the 2008 USGS NSHM) estimates of earthquake magnitudes, locations and rates of earthquakes of moment magnitudes $M \geq 5.0$ from shallow crustal sources in California. In addition to UCERF3, the 2014 USGS NSHM also includes an updated source model for the Cascadia subduction interface and deep subduction intra-slab earthquake events for the northwest part of California.

Ground Motion Models for California

The California portion of the 2014 NSHM uses three categories of GMMs for predicting ground motion intensity depending on the tectonic settings.

For shallow crustal earthquake events from the UCERF3 source model, all five of the following NGA (Next Generation Attenuation) -West 2 GMMs are used. These include Bozorgnia et al (2013, 2014), Abrahamson et al (2013, 2014), Boore et al (2013, 2014, Campbell and Bozorgnia (2013, 2014), Chiou and Young (2103, 2014); and Idriss (2013, 2014) for the reference firm site conditions only (i.e., V_{S30}=760 meters/sec).

The GMMs used for the Cascadia subduction interface earthquake events include Atkinson and Boore (2003) global model, Atkinson and Macias (2009), Addo et al (2012), Zhao et al (2006), and BC Hydro (Addo et al, 2012)

The GMMs used for the Cascadia deep intra-slab earthquake events include Atkinson and Boore (2003) global model, Atkinson and Boore (2003) Cascadia model, Zhao et al (2006), and BC Hydro (Addo et al, 2012).

The use of the updated as well as new source models and GMMs, with the new definition of the spectral acceleration, resulted in differences between the probabilistic ground motions in the 2008 and 2014 NSHMs, which were used as the basis for the development of the design ARS per the SDC v1.7 and the SDC v2.0, respectively.

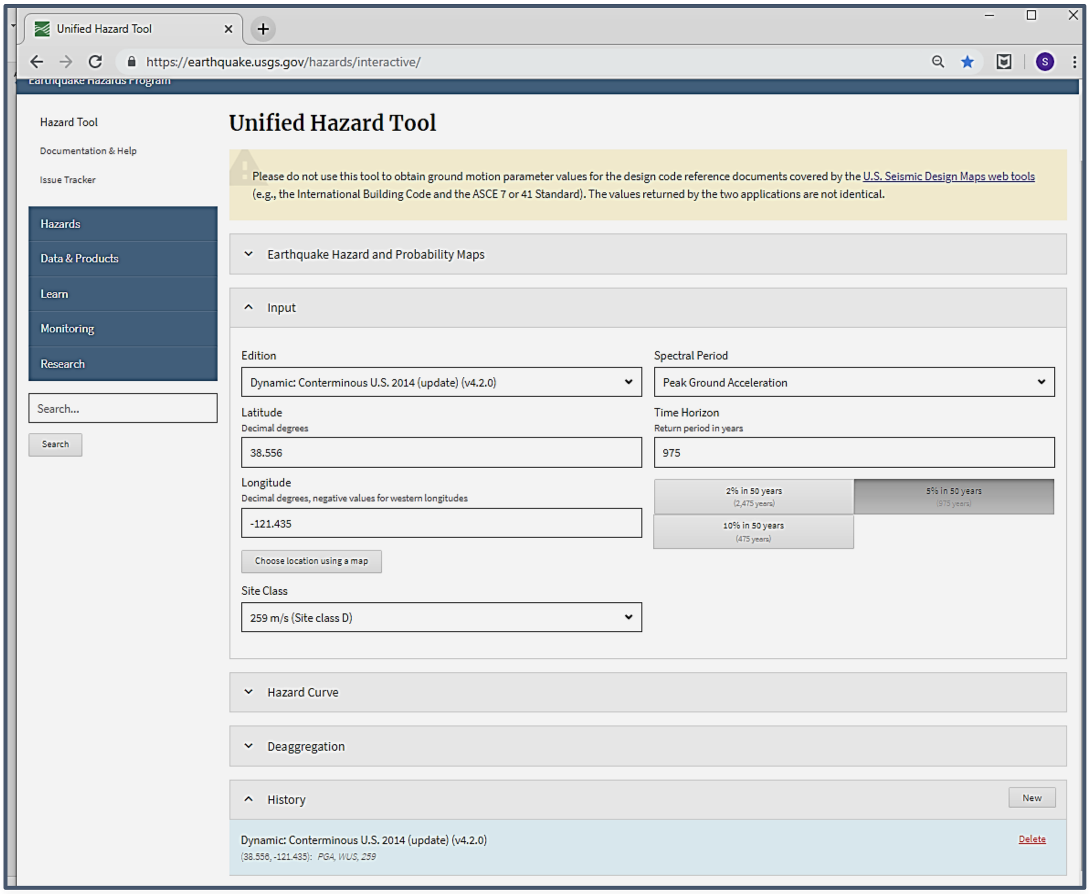
Unified Hazard Tool (UHT)

The web-based UHT is developed and made available by USGS for determining the ARS data and related information, including hazard deaggregation for selected periods, for various versions of the USGS' NSHMs. The UHT can be accessed at https://earthquake.usgs.gov/hazards/interactive/.

A screen shot of the UHT front page is shown in Figure A-1. The available options under each panel can be accessed by expanding it with a click on the down-arrow next to the panel title. The UHT provides 2014 NSHM ARS data or spectral accelerations for periods, T= 0.0 (PGA), 0.1, 0.2, 0.3, 0.5, 0.75, 1.0, 2.0, 3.0, 4.0 and 5.0 seconds.

As seen in the Figure A-1, the UHT input parameters include:

- "Edition" for the hazard model. For developing design ARS per SDC v2.0, the appropriate hazard model and edition is identified as *"Dynamic Conterminous U.S. 2014(Update)(V4.2.0)*" in the drop-down menu.
- Latitude" and "Longitude" (in decimal degrees) for the site location co-ordinates. The site latitude and longitude can be entered directly or by utilizing the "Choose location using a map" option.
- Site Class" for the site V_{S30} (meters/sec). The "Site Class" can be selected from one of the options available in the drop-down menu. For Caltrans project sites, the available option for the V_{S30} value includes 180, 259, 360, 537, 760, and 1150 meters/sec.



Unified Hazard Tool

Please do not use this tool to obtain ground motion parameter values for the design code reference documents covered by the U.S. Seismic Design Maps web tools (e.g., the International Building Code and the ASCE 7 or 41 Standard). The values returned by the two applications are not identical.

Edition: Dynamic: Conterminous U.S. 2014 (update) (v4.2.0)

Spectral Period: Peak Ground Acceleration

Latitude (Decimal degrees): 38.556

Time Horizon (Return period in years): 975

Longitude (Decimal degrees, negative values for western longitudes): -121.435

Site Class: 259 m/s (Site class D)

Dynamic: Conterminous U.S. 2014 (update) (v4.2.0)
(38.556, -121.435): *PGA, WUS, 259*

Figure A-1: UHT Front Page (Accessed on January 27, 2020 at https://earthquake.usgs.gov/hazards/interactive/)

- "Spectral Period" for a spectral acceleration corresponding to one of the period value from the following list: 0.0 (PGA), 0.1, 0.2, 0.3, 0.5, 0.75, 1.0, 2.0, 3.0, 4.0 and 5.0 seconds. For the hazard (or ARS) analysis only, any of the available "Spectral Period" option can be selected from the drop-down menu. To run the deaggregation analysis for a particular period-specific spectral acceleration, it must be the option entered by selecting from the drop-down menu.
- "Time Horizon (return period in years)" for the return period can be entered directly or, if available, by clicking on the corresponding button. To obtain the 2014 USGS NSHM ARS data for use in the development of the SEE design ARS, the "Time Horizon/Return period in years" must be 975 years. To determine 2014 NSHM ARS data for use in the development of the FEE design ARS, the "Time Horizon/Return period in years" must be 225 years.
- Once all the input parameter values are entered, the hazard analysis for the input return period is performed by clicking on the "Compute Hazard Curve" button that appears in the expanded "Hazard Curve" panel. Once the calculations are

completed, the results of the analysis are present on the screen as plots of the hazard curves for the site and the ARS curve for the input return period.

The exact values of the plotted ARS data points can be obtained by clicking once on the data point symbols. These ARS data points corresponds to the 2014 NSHM ARS for the specified input return period. Modifications to these ARS data points are applied, where necessary, for basin-effects and/or near-fault effects, as specified in Appendix B of the SDC v2.0.

Hazard deaggregation analysis for a period-specific spectral acceleration is performed by selecting it from the “Spectral Period” drop-down menu, making sure all other input parameters remained unchanged and then clicking on the “Compute Deaggregation” button available in the “Deaggregation” analysis panel below the ‘Input” panel. The results of the analysis are presented on the screen. The analysis must be repeated for each period-specific spectral acceleration for which the results of hazard deaggregation analysis are required.

Ground Motion Directionality

The azimuth direction of the design horizontal ground motion component represented by the USGS’ 2014 NSHM basic ARS at a site is random (i.e., equal probability of occurrence in any direction on the horizontal plane).

The design ARS determined per Caltrans SDC v2.0, which includes only the basin effects, where necessary, also represents the randomly oriented mean (or average) component of the design horizontal ground motion at the site. The design ARS obtained by applying near-fault effects represents the Fault-Normal (FN) component for near-fault sites.

Empirical Correlations for Estimating Shear Wave Velocity

In the absence of field measurements, the shear wave velocity Vs for most soil and soft sedimentary rock formation may be estimated based on established empirical correlations with other field and/or laboratory measured site and layer-specific soil/rock properties or index parameters, if available.

The geo-professionals should be aware of the limitations of the empirical correlations for Vs, including the soil/rock properties or parameters uses. For example, penetration of the SPT sampler in earth material may be limited or affected by the presence of large particles (e.g. gravel, cobbles, boulders or rock fragments). Correlations, in particular using SPT data, should only be used with test data and other related information that are reliable and representative of the actual site conditions. If established empirical correlations are not applicable (e.g. SPT correlation used in a thick, coarse gravel deposit) or not available, then in-situ measured shear wave velocities should be used.

For cohesive soil layers, empirical correlations with laboratory measured undrained shear strength (S_u) are preferred. For cohesionless soil layers, correlations with CPT (ASTM D 5778) tip resistance are preferred. In the absence of CPT tip resistance, SPT (Standard Penetration Test – ASTM D1586) blow count, N_{60} (blow counts corrected for hammer efficiency but not for overburden pressure) may be used to estimate V_S for cohesionless soil layers.

For young sedimentary rock deposits that display soil-like properties, established correlations with SPT blow counts may be used to estimate layer V_S values. For stronger rock, V_{S30} may be estimated based on the field measured V_S for nearby sites underlain by similar deposits; or based on published measured V_S or V_{S30} data or surface geology based V_{S30} maps available for, the same geographically and geologically-defined rock unit or formation and with similar intact rock and rock-mass characteristics. These characteristics include, but not limited to uniaxial compressive strength, small-strain modulus, Poisson’s ratio, RQD, hardness, degree of weathering, fracture density and conditions, ultrasonic seismic shear and/or compression wave velocities (Mayne et al., 2001).

Recommended empirical correlations are presented below. Other well-documented and established empirical V_S correlations specific to the earth material under consideration at the project site or the general area with similar earth material, may be used by experienced geo-professionals provided adequate justifications of their use and the pertinent references are included in the report.

Recommended Empirical Correlations

Wair et al (2012) compiled published correlations between layer shear wave velocity and common in-situ geotechnical test parameters and presented recommended correlations for various soil types. The empirical correlations recommended below are based on a review of this and other noted references.

Soil Layers

For the SPT based empirical corrections presented below, the parameter N_{60} is obtained by correcting the field measured SPT blow count (N_m) for variations from the ASTM Standard D1586, including the hammer energy, borehole diameter, rod length and sampler without liner (see *Liquefaction Evaluation* Module or Youd et al. 2001). No correction due to the current effective overburden stress (σ'_{vo}) is applied, and these correlations are valid for $3 \leq N_{60} \leq 100$.

Note that the recommended empirical correlation presented below provide estimates of the seismic shear wave velocity V_S in meter/sec at the depth of measurement of the correlated parameter (e.g., S_u or CPT tip resistance). Unless stated otherwise, the unit of *(σ'_{vo})* is kPa. Attention must also be paid to the specific units or definitions used for the other correlated parameters.

Cohesive Soil Layers

The following correlation by Dickenson (1994) based on the undrained shear strength (S_u) is recommended for cohesive soil layers:

$$V_s = 203 \left(\frac{S_u}{p_a}\right)^{0.475}$$

Where, p_a is the atmospheric pressure (same unit as S_u). The undrained shear strength (S_u) should be measured as a function of depth either in-situ by field vane shear test or in the laboratory by unconsolidated undrained (UU) tests, or as a function of the effective overburden stress (σ'_v) by consolidated undrained (CU) tests, on undisturbed samples.

In the absence of measured undrained shear strength data, the shear wave velocity for cohesive soils may be estimated by using the following empirical correlation with CPT tip resistance developed by Mayne and Rix (1995):

$$V_s = 1.75\,(q_t)^{0.627}$$

Where, q_t is the measured CPT tip resistance (kPa) corrected for water pressure effects due to unequal end area (See Robertson, 2016).

If S_u or CPT tip resistance (q_t) data are not available, the following correlation with the corrected SPT blow count (N_{60}) developed by Wair et al (2012) may be used to determine V_S for cohesive soil layers:

$$\mathrm{Vs} = 26\,(ASF)\,(N_{60})^{0.17}\,(\sigma'_{vo})^{0.32}$$

Here, ASF = Dimensionless Age Scaling Factor for geologic age of the soil deposit (=1.0 for Quaternary or 0.88 for Holocene, and 1.12 for Pleistocene, if known).

Cohesionless Soil Layers

The following correlation developed by Baldi et al (1989) is recommended to calculate V_S for uncemented cohesionless soil layers when using CPT data:

$$V_S = 277(q_t)^{0.13} (\sigma'_{vo})^{0.27}$$

Here, both q_t and σ'_{vo} are in MPa

In the absence of CPT data, the following correlations developed by Wair et al (2012) are recommended for cohesionless soil layers when using SPT data:

Silts

The SPT N_{60} correlation recommended above for cohesive soil layers is also recommended for silt layers.

Sands

$$\text{Vs} = 30\,(ASF)\,(N_{60})^{0.23}(\sigma'_{vo})^{0.23}$$

Where, ASF =1.0 for Quaternary or 0.9 for Holocene and 1.17 for Pleistocene.

Gravels

$\text{Vs} = 53(N_{60})^{0.19}(\sigma'_{vo})^{0.18}$ for Holocence

$\text{Vs} = 115(N_{60})^{0.17}(\sigma'_{vo})^{0.12}$ for Pleistocene

Young Sedimentary Rock Formations

Imai and Tonouchi (1982) reviewed over a hundred SPTs with corresponding field measured V_S in young sedimentary rocks (Tertiary deposits) and developed the following correlation for “Tertiary Sand/Clay”.

$$V_S = 109\,(N_{60})^{0.319}$$

If site-specific measured shear wave velocity data are not available, this empirical correlation may be used for young sedimentary rock deposits in California. Limit the maximum value of V_S obtained from this correlation to 560 m/sec.

Other Rock Formations

There are relatively few studies available that correlate seismic shear wave velocity to physical properties of other rock masses. Two notable studies that may be useful to geo-professionals in estimating approximate seismic shear wave velocities in rock, based on physical properties of rock masses are: (1) Fumal (1978), which correlated shear wave velocity to weathering, hardness, fracture spacing, and lithology based on data from 27 sites in the upland areas of the San Francisco (Bay Area) region, and (2) Fumal and Tinsley (1985). which extended the 1978 study to include 84 sites in the Los Angeles region. Some physical properties of the rock were more important than others depending on lithology, texture and hardness, but fracture spacing was found to be the most important factor affecting shear wave velocity. A thorough review of these studies will significantly aid geo-professionals in their estimations of the shear velocities in rock formations.

For Caltrans projects, the V_{S30} for rock sites should be limited to 760 meters/sec when in-situ measured $V_s(d)$ data are not available.

Estimating V_{s30} for Sites with Depth of Exploration 10 to 29m

The V_{S30} estimated based on the below extrapolation scheme should not be used to develop the final design ARS when the assessed site Soil Profile Type is D. This extrapolation scheme should not be used for project sites: (1) underlain by unusual soil profiles not used in its development, or (2) for which a site-specific DGRA may be required per Appendix B of the SDC v2.0.

For sites for which the subsurface information is available only for the upper 10 to 29 m, V_{S30} in meters/sec for assessment of the site “Soil Profile Type” as defined in Table B.10 of the SDC v2.0, may be estimated by extrapolation using the following empirical correlation developed based on Boore (2004):

$$V_{S30} = (1.45-0.015*d)V_{sd}$$

Where, V_{sd} (meters/sec) is the time-averaged shear wave velocity for the upper “d” meters of soil/rock for which subsurface information is available ($10 \leq d \leq 29$ meters). V_{sd} is calculated using the same equation as V_{S30}, except that the total depth of calculation is limited to “d” meters. This equation was developed based on the assumption that that shear wave velocity increases with depth and no significant abrupt changes in the subsurface conditions, particularly in the small-strain stiffness of the soil/rock, occur between the depths of 10 and 29 m.