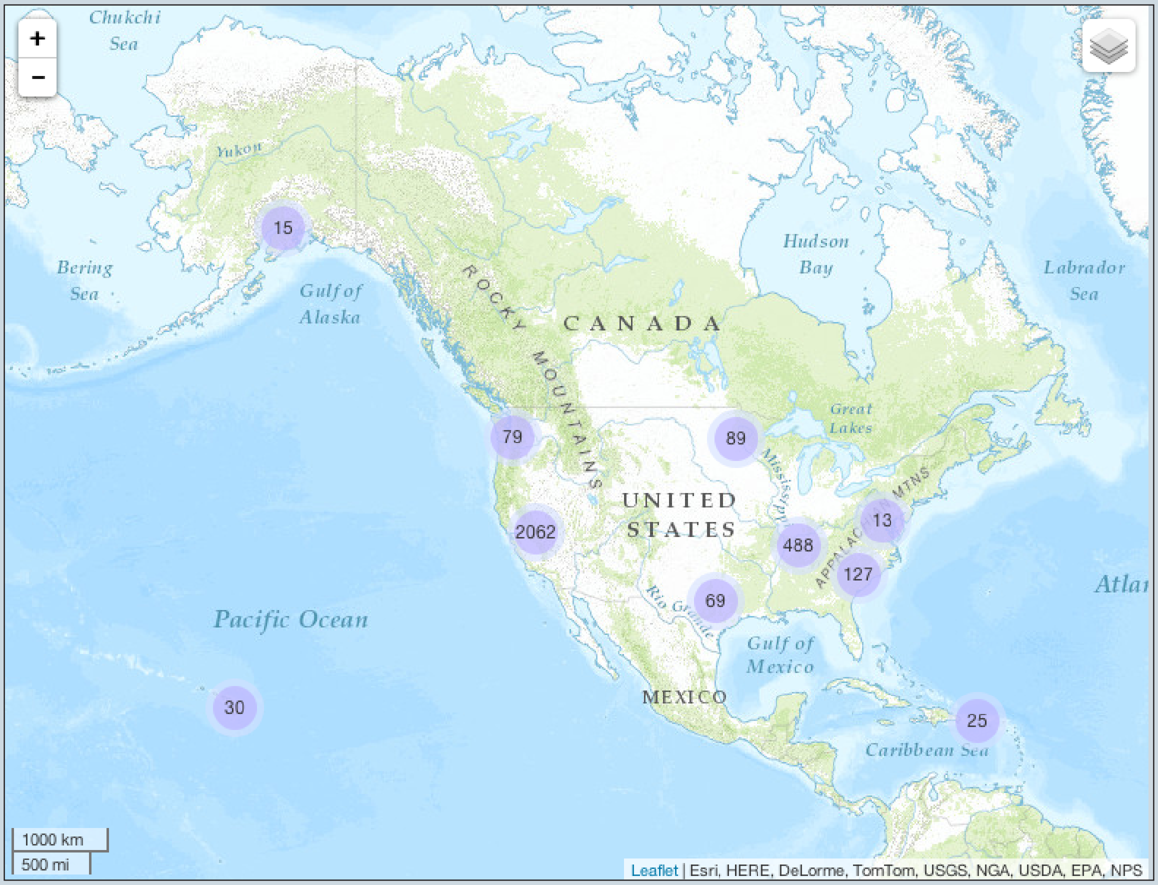
Compilation of V_{S30} Data for the United States



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Cover. Map showing a compilation of time-averaged shear-wave velocity values in the upper 30 meters (V_{S30}) at various locations in the United States. Map taken from the U.S. Geological Survey Earthquake Hazards Program Web site at http://earthquake.usgs.gov/research/vs30/.

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Abstract

V_{S30}, the time-averaged shear-wave velocity (V_S) to a depth of 30 meters, is a key index adopted by the earthquake engineering community to account for seismic site conditions. V_{S30} is typically based on geophysical measurements of V_S derived from invasive and noninvasive techniques at sites of interest. Owing to cost considerations, as well as logistical and environmental concerns, V_{S30} data are sparse or not readily available for most areas. Where data are available, V_{S30} values are often assembled in assorted formats that are accessible from disparate and (or) impermanent Web sites. To help remedy this situation, we compiled V_{S30} measurements obtained by studies funded by the U.S. Geological Survey (USGS) and other governmental agencies. Thus far, we have compiled V_{S30} values for 2,997 sites in the United States, along with metadata for each measurement from government-sponsored reports, Web sites, and scientific and engineering journals. Most of the data in our V_{S30} compilation originated from publications directly reporting the work of field investigators. A small subset (less than 20 percent) of V_{S30} values was previously compiled by the USGS and other research institutions. Whenever possible, V_{S30} originating from these earlier compilations were crosschecked against published reports. Both downhole and surface-based V_{S30} estimates are represented in our V_{S30} compilation. Most of the V_{S30} data are for sites in the western contiguous United States (2,141 sites), whereas 786 V_{S30} values are for sites in the Central and Eastern United States; 70 values are for sites in other parts of the United States, including Alaska (15 sites), Hawaii (30 sites), and Puerto Rico (25 sites). An interactive map is hosted on the primary USGS Web site for accessing V_{S30} data (http://earthquake.usgs.gov/research/vs30/).

Introduction

V_{S30}, the time-averaged shear-wave velocity (V_S) to a depth of 30 meters (m), is commonly used to account for site effects when developing empirical ground-motion relations, known collectively as attenuation relations or ground-motion prediction equations (GMPE; Abrahamson and Shedlock, 1997; Abrahamson and others, 2008; Gregor and others, 2014). Introduced by Borcherdt (1994) to unambiguously describe site classes and site coefficients for the 1994 United States National Earthquake Hazards Reduction Program (NEHRP) (Martin and Dobry, 1994), V_{S30} was first applied as a smoothed version of the NEHRP site class in a GMPE developed by Boore and others (1997). Before the introduction of V_{S30}, most GMPEs accounted for site conditions by applying either geological (soft, deep, or shallow soil; rock) or geotechnical (firm or very firm soil; soft or firm rock) categories (Abrahamson and Silva, 1997; Campbell, 1997; Sadigh and others, 1997; Spudich and others, 1997). Since the adoption by Boore and others (1997), V_{S30} has been accepted as the main site parameter in almost all modern GMPEs (Abrahamson and others, 2008; Gregor and others, 2014).

V_{S30} is defined as the time-averaged shear-wave velocity $\overline{V}_S(d)$ from the surface to a depth d of 30 m and is computed by (Boore, 2004b):

$$\overline{V}_S(d) = \frac{d}{tt(d)}, \qquad (1)$$

where travel-time $tt(d)$ is defined as:

$$tt(d) = \int_0^d \frac{dz}{V_S(z)}. \qquad (2)$$

In equation (2), $V_S(z)$ is velocity as a function of depth below ground surface, z.

Borcherdt (1994) proposed the use of V_{S30} based on correlations derived from borehole logging data and ground-motion recordings in California. Borehole (downhole) approaches require drilling, which is an expensive operation, and permits for such invasive approaches can often be difficult to obtain. About the time V_{S30} was introduced (Borcherdt, 1994), a depth of about 30 m was often only achieved after a full day of drilling. Noninvasive approaches (body- and surface-wave methods), however, only require minimal disturbance of the surface material, and fieldwork typically consumes a fraction of a day at a site. Both invasive and noninvasive approaches record waveforms generated from local energy sources (active sources: hammer strike, weight drop, rifle or shot-gun, vibroseis, downhole acoustic sources) or ambient noise (passive sources: traffic, ocean waves). The relative ease and simplicity of noninvasive approaches led to the recent increase of sites with measured V_{S30} values (Louie, 2005, 2007; Louie and others, 2011; Odum and others, 2013; Yong and others, 2013).

All approaches for deriving V_{S30} have uncertainties, and studies that address these concerns can be readily found in the literature (Wills, 1998; Williams and others, 2003; Foti and others, 2007; Moss, 2008; Comina and others, 2011). Moreover, V_{S30} does not capture all the underlying physics that control site amplification; thus, use of this parameter to describe site response has been the subject of debate (Anderson and others, 1996; Boore, 2004a; Mucciarelli and Gallipoli, 2006; Bragato, 2008; Castellaro and others, 2008; Lee and Trifunac, 2010). As a result, recent studies proposing new methods to account for site conditions have been published (Lee and Trifunac, 2010; Ghofrani and Atkinson, 2014). Until a new method is accepted, the engineering community will continue to use V_{S30} for the foreseeable future (Abrahamson and Shedlock, 1997; Abrahamson and others, 2008; Boore and others, 2011; Gregor and others, 2014).

The purpose of the project described in this report is to present a compilation of V_{S30} measurements made throughout the United States. The main product of this project is a U.S. Geological Survey (USGS) Web site showing this compilation (http://earthquake.usgs.gov/research/vs30/; fig. 1). We provide V_{S30} derived from a variety of techniques or combinations thereof. Most of the data in the compilation reflect the V_{S30} of

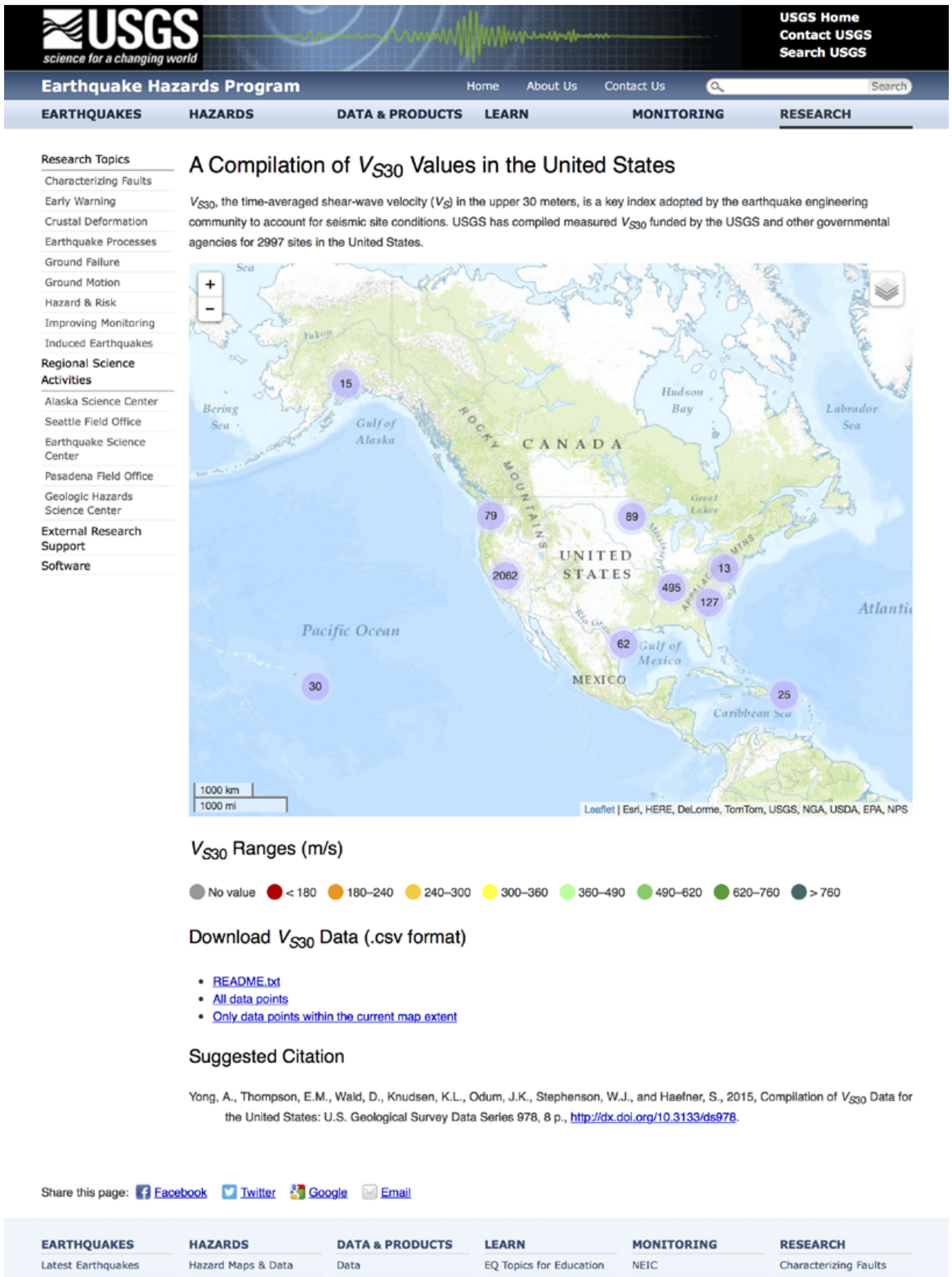

Figure 1. Screenshot of the U.S. Geological Survey Web site for data about V_{S30} (time-averaged shear-wave velocity to a depth of 30 meters; http://earthquake.usgs.gov/research/vs30/).

sites in the western contiguous U.S. (2,141 sites), whereas 786 V_{S30} values are provided for sites in the Central and Eastern United States; in addition, 70 V_{S30} sites are in Alaska (15 sites), Hawaii (30 sites), and Puerto Rico (25 sites) (fig. 1). We will continue to update the Web site by adding V_{S30} measurements as new data become available.

Figure 1 shows the main Web site for accessing V_{S30} data. The terrain base map is the default display for the map interface. Other base maps—that is, street, gray-scale or satellite-themed maps—are selectable by the user. Ranges of V_{S30} values are color-coded using the coding scheme developed by Allen and Wald (2009; figs. 1 and 2). Options to download region-specific V_{S30} data (fig. 2) or the complete compilation are also available on this USGS Web site.

V_{S30} data and the associated metadata are provided in tabular form based on a comma-separated-value (.csv) format at http://earthquake.usgs.gov/research/vs30/. Appendix A lists sources of geologic information used by site investigators when compiling V_{S30} data (Excel file available online only at http://dx.doi.org/10.3133/ds978). The current compilation consists of 2,997 rows of data (one row for each measurement) that are associated with 15 columns of attributes (including the V_{S30} value in meters per second, m/s). The data and associated metadata are described in the following sections.

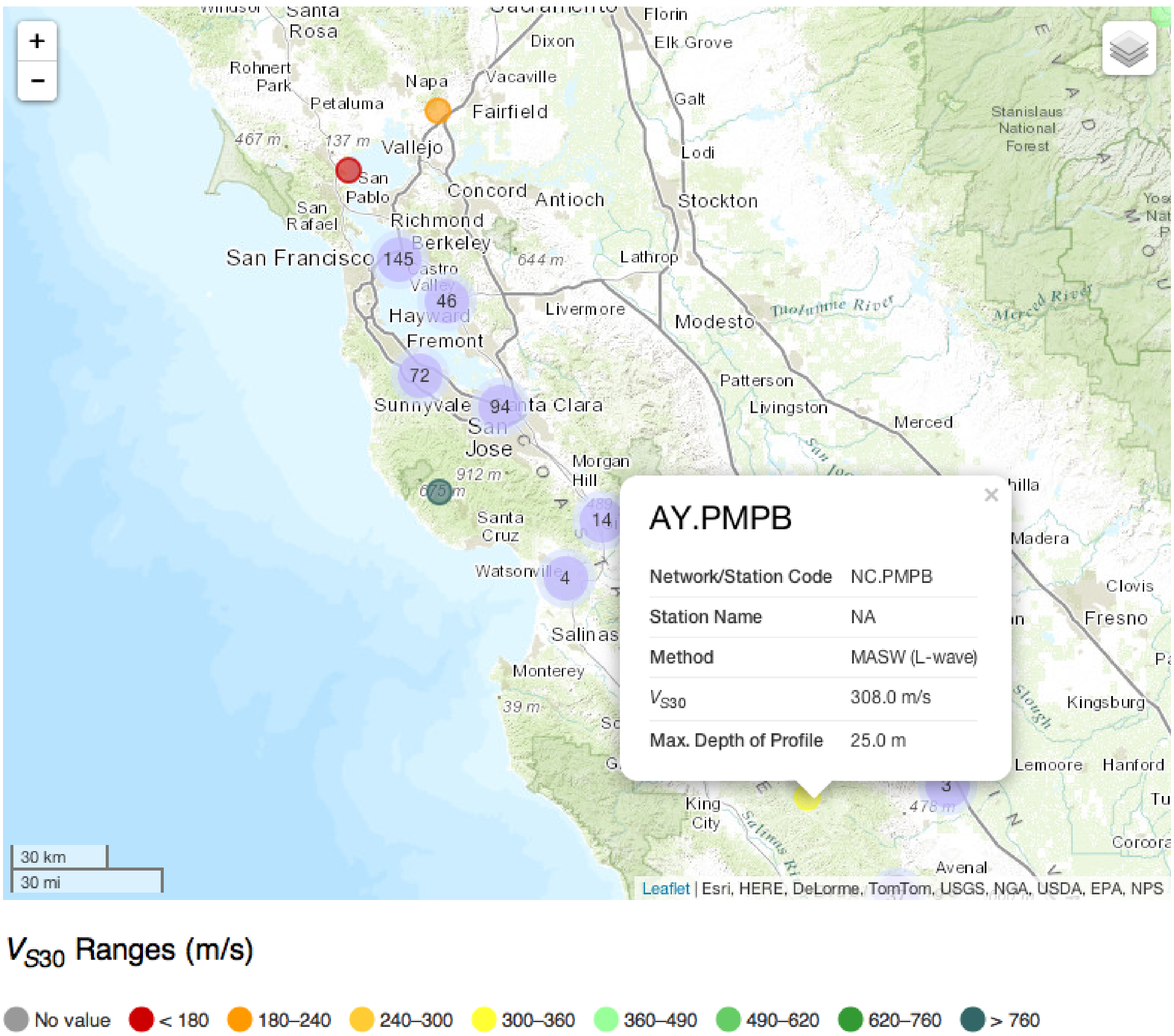

Figure 2. Screenshot of pop-up window on U.S. Geological Survey Web site for data about V_{S30} (time-averaged shear-wave velocity to a depth of 30 meters, m; http://earthquake.usgs.gov/research/vs30/). Window displays selected site information, including Network/Station Code, Station Name, Method, V_{S30} and Maximum Depth of Profile. Ranges of V_{S30} values (in meters per second, m/s) are color-coded using the coding scheme of Allen and Wald (2009). See V_{S30} Metadata section for additional details. NA, not applicable; km, kilometers; mi, miles.

V_{S30} Data

Our V_{S30} compilation includes V_{S30} and other pertinent site information (see V_{S30} Metadata section) that were reported by or obtained from site investigators. These reports were typically published in scientific journals or released by governmental agencies as technical reports or open-file reports. These investigators were funded by the USGS and other governmental agencies. In a few cases, USGS researchers had a primary role in carrying out the investigations (Williams and others, 2003; Stephenson and others, 2009; Odum and others, 2013; Yong and others, 2013).

A small subset (less than 20 percent) of our V_{S30} compilation was previously compiled by the USGS and other research institutions. These earlier compilations consist of online compendiums or archives that were assembled by USGS researcher David M. Boore (Boore, 2003; http://www.daveboore.com/data_online.html, accessed April 2, 2015), University of Nevada Las Vegas professor Barbara Luke (http://agc.unlv.edu/lv_archives/index.html, accessed April 2, 2015), the Utah Geological Survey (MacDonald and Ashland, 2008; http://geology.utah.gov/ghp/consultants/geophysical_data/shear-wave_velocity.htm, accessed April 2, 2015), and the Network for Engineering Earthquake Simulations consortium (http://nees.org/dataview/spreadsheet/sasw, accessed April 2, 2015). A subset of our V_{S30} data can also be found in the earlier Site Database (SDB) assembled by GMPE developers and other members from the Pacific Earthquake Engineering Research (PEER) Institute (Seyhan and others, 2014). Data in the SDB are limited only to V_{S30} at seismographic-station sites where strong-motion observations were recorded (Chiou and others, 2008; Seyhan and others, 2014). Whenever possible, we have crosschecked these earlier compiled V_{S30} values against reports published by the original investigators. Figure 3 shows the distribution of V_{S30} values presented in our compilation.

V_{S30} values were derived from a variety of geophysical or geotechnical approaches—active or passive source, invasive or noninvasive, or combinations of approaches (Odum and others, 2013; Yong and others, 2013). Geophysical approaches include active-source borehole logging techniques such as downhole P- and S-wave velocity logging and cross-hole methods; the frequency of each method in our database is tabulated in table 1. Noninvasive geophysical approaches include both active- and passive-source body and surface wave techniques, such as:

- Seismic reflection or refraction (P- and S-wave methods) (Liu and others, 1988; Odum and others, 2013),

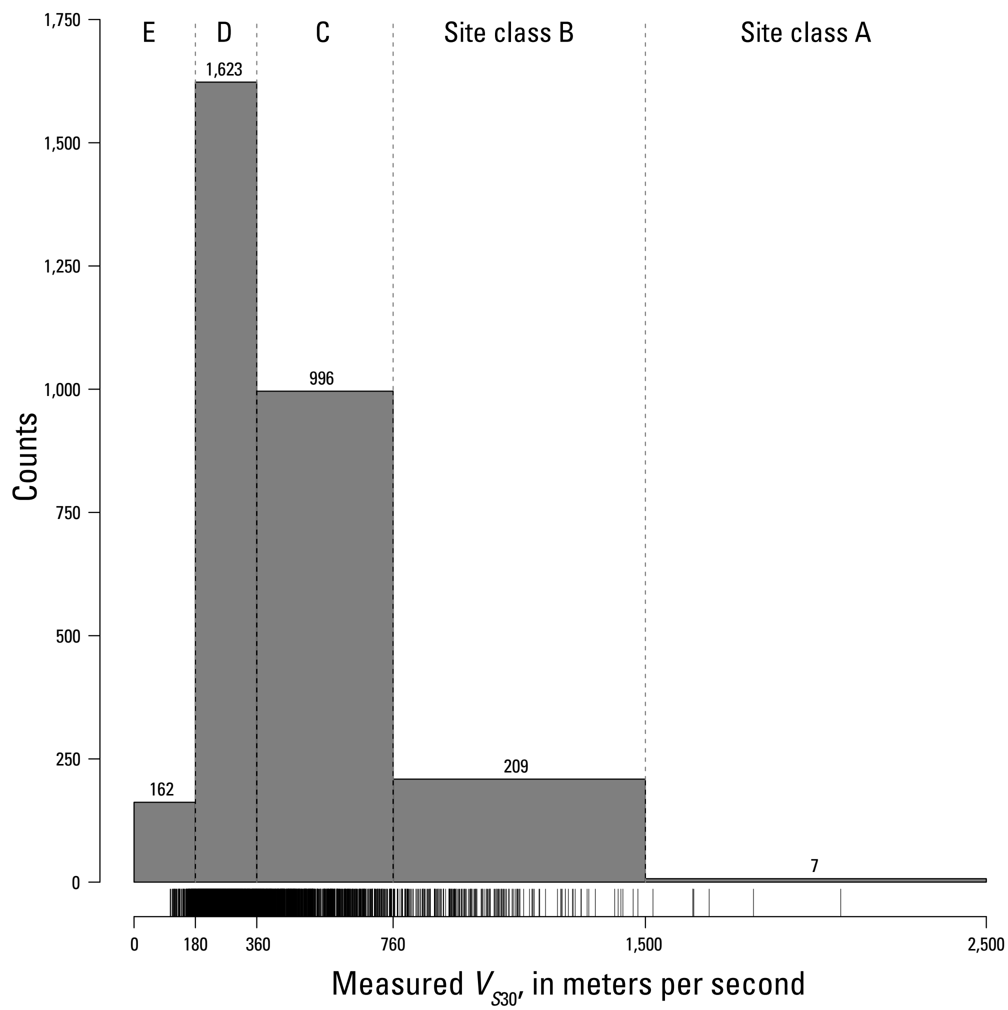

Figure 3. Histogram of measured-V_{S30} (time-averaged shear-wave velocity to a depth of 30 meters) values binned by National Earthquake Hazards Reduction Program (NEHRP) site classes. The number of measurements with respect to the NEHRP site class is also provided. Tick marks at bottom of histogram indicate the number of V_{S30} measurements in each site class.

- Spectral Analysis of Surface Waves (SASW) (Stokoe and others, 1988),
- Multi-channel Analysis of Surface Waves (MASW; Love and Rayleigh wave) (Park and others, 1999; Safani and others, 2005),
- Interferometric Multi-channel Analysis of Surface Waves (iMASW; Rayleigh wave) (O'Connell and Turner, 2011),
- Array Microtremor (AM, or Microtremor Array Method, MAM) (Lacoss and others, 1969; Capon, 1969; Kawase and others, 1998),
- Spatial Autocorrelation (SPAC and derivative approaches) (Aki, 1957; Asten, 2006; Stephenson and others, 2009),
- Horizontal-to-Vertical-Spectral-Ratio (HVSR) (Nogoshi and Igarashi, 1971; Nakamura, 1989),
- Refraction Microtremor (ReMi) (Louie, 2001), and
- Controlled-source measurement of surface wave dispersion (CXW) (Poran and others, 1996).

The geotechnical approach is based on the Seismic Cone Penetrometer Test (SCPT) (Holzer and others, 2005) (table 1), which uses invasive active-source seismic methods to derive V_{S30}.

To verify the reported V_{S30} values, V_S profiles were randomly selected, and V_{S30} was calculated for each profile using equations 1 and 2. The selected V_{S30} values were found to be accurate in all cases tested. However, some reports did not include data from the site V_S profile, in which case we attempted to collect the missing

Table 1. Geophysical and geotechnical measurement technique or combinations of techniques (description as recorded in compilation) and the frequency of the technique or combination of techniques used to derive V_{S30}.

[For 3 sites the surface wave technique(s) used to derive V_{S30} are not available (NA). AM, array microtremor; CXW, continuous surface wave; MASW, multichannel analysis of surface waves; iMASW, interferometric multichannel analysis of surface waves; ReMi, refraction microtremor; SASW, spectral analysis of surface waves; SCPT, seismic cone penetration testing]

Technique or Combination of Techniques	Frequency
AM	14
AM, ReMi	17
AM, SASW, ReMi	5
AM, Seismic Refraction (P-wave)	1
CXW	15
Downhole	318
Downhole-crosshole	1
iMASW	31
MASW (L-wave)	31
MASW (L-wave), MASW (R-wave)	7
MASW (R-wave)	117
MASW (R-wave), AM, seismic refraction (P-wave)	4
MASW (R-wave), AM, Seismic Refraction (P-wave), HVSR	17
MASW (R-wave), AM, Seismic Refraction (P-wave), Seismic Refraction (S-wave)	5
MASW (R-wave), AM, Seismic Refraction (P-wave), Seismic Refraction (S-wave), HVSR	20
MASW (R-wave), AM, Seismic Refraction (P-wave), Seismic Refraction (S-wave), HVSR, Downhole (PS-logging)	1
MASW (R-wave), ReMi	2
MASW (R-wave), SASW	23
MASW (R-wave), Seismic Refraction (P-wave), Seismic Refraction (S-wave)	1
ReMi	886
SASW	330
SASW (active and passive)	11
SASW, ReMi	3
SCPT	989
Seismic Refraction (P-wave)	5
Seismic Refraction (P-wave), Seismic Refraction (S-wave)	1
Seismic Refraction (S-wave)	55
Seismic Refraction (S-wave), ReMi	25
Seismic Refraction/Reflection (SH-wave)	32
Surface wave dispersion (R-wave)	27
NA	3

profile information and any missing metadata (see V_{S30} Metadata section) directly from the primary investigators. We found the reported V_S profiles described in various forms, which include analog or digital tables and figures. Although V_S profiles are not presented in this compilation, profile information may be available in subsequent updates.

V_{S30} Metadata

The metadata associated with the V_{S30} values include 15 attributes. Values of "NA" are applied wherever values are not available either from reports or through direct communication with the site investigators. As for V_S profiles, we contacted the investigators and requested information when we encountered missing metadata (for example, maximum depth of investigation, site coordinate system, site coordinates) in the reports. However, complete metadata are not available for all V_{S30} data compiled herein. The definitions of each attribute are as follows:

- *Id.*—Unique identifier/code associated with each row describing the reported V_{S30}. Each identifier/code is separated by a period (.). The alphabetic characters, prepended to the period mark, represent the initials of the name of the principal investigator (see Reference attribute) or primary contact (see Contact attribute). The numeric characters appended to the period mark are sequentially assigned (starting with 1) to the reported V_{S30} as obtained from the principal investigator or primary contact in the order presented in their publication.

- *Latitude and Longitude.*—In decimal degrees reflecting the coordinate location of the V_{S30} measurement. The precision of the value is the same as reported by the investigator(s). Location accuracies may vary by source and are not always represented by the number of significant figures reported.

- *Datum.*—Coordinate system as defined by the V_{S30} compilation. For sites where the reported coordinate systems do not conform to the 1984 World Geodetic System (WGS 84), latitude and longitude values were converted to the WGS 84 system.

- *Network/Station Code.*—Seismographic network and station codes as reported by the investigator(s). The distance between the associated seismographic station and V_{S30} measurement by the investigator(s) were not evaluated for this complication.

- *Station Name.*—Name of seismographic station or measurement location as reported by the investigator(s) where measurement was for the purpose of characterizing seismic site conditions.

- *Method.*—See V_{S30} Data section and table 1.

- V_{S30} *(*m/s*)*.—The time-averaged shear-wave velocity to a depth of 30 m from the surface. Values are converted to units of meters per second (m/s) when necessary.

- *Max Depth (of Profile,* m*)*.—Maximum depth of investigation as reported by the investigator(s).

- *Contact.*—Primary contact, principal investigator or lead author of published report.

- *Reference.*—Citation information.

- URL.—Universal resource locator for online access to reports and/or data source.

- *Geologic Map Unit(s)/Material(s).*—Geologic map unit name(s) or material(s) as reported by the investigator(s). Where available, the assigned names of the Geologic Map Units, as reported by the investigator(s), are provided at the main Web site (http://earthquake.usgs.gov/research/vs30/) and in appendix A (http://dx.doi.org/10.3133/ds978).

- *Geologic Data Source.*—Citation information for Geologic Map Units(s)/Material(s).

- *Comments.*—Notes and additional information.

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