WJE ENGINEERS ARCHITECTS MATERIALS SCIENTISTS

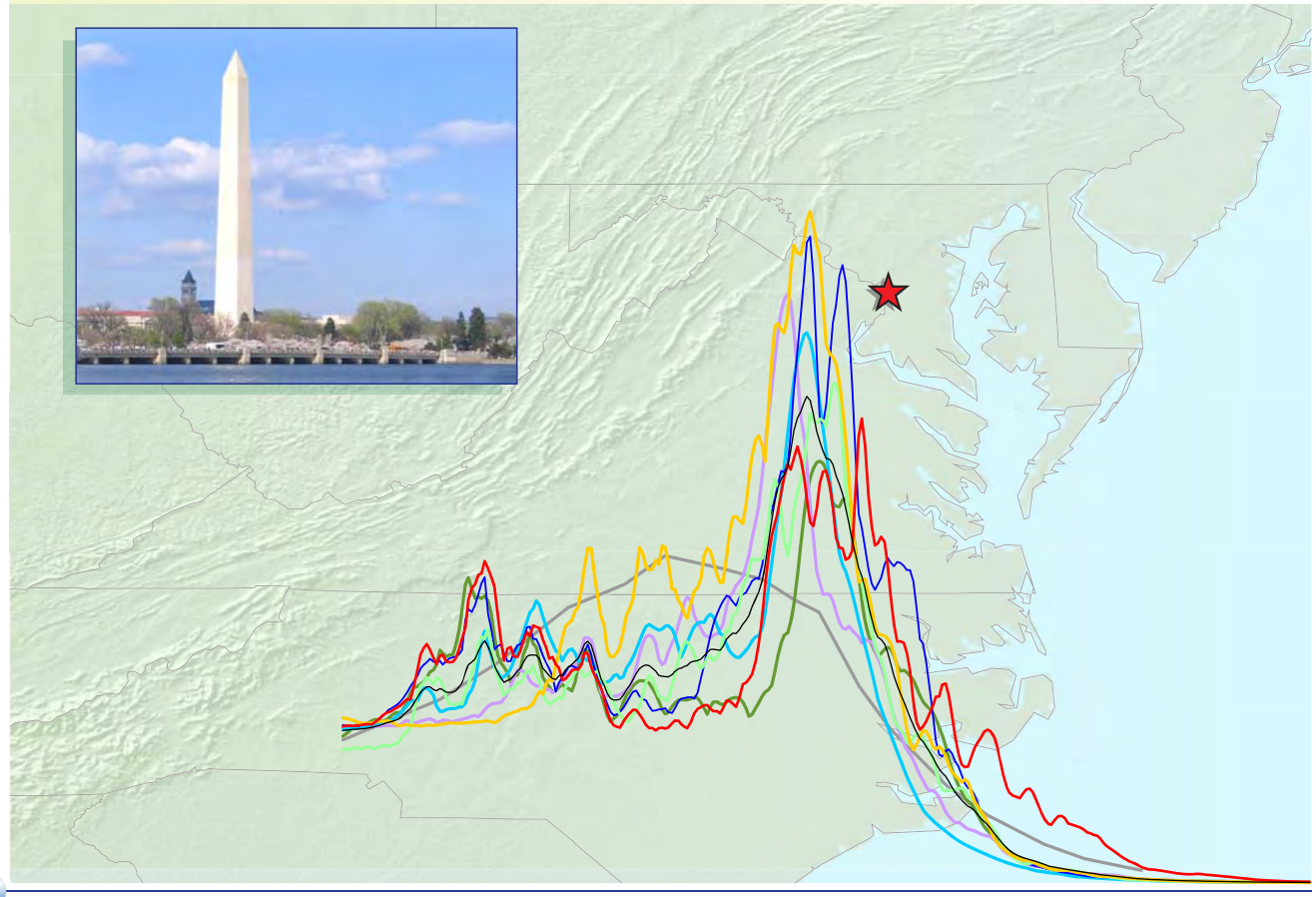
TIPPING MAR STRUCTURAL ENGINEERING

Appendix A: Ground Motion Hazard and Geotechnical Evaluation

Ground Motion Hazard & Geotechnical Assessment

Washington Monument

Washington, District of Columbia



Prepared for:

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May 2012

May 31, 2012
Project OD12162670

Terrence Paret
Wiss, Janney, Elstner Associates
2000 Powell Street Suite 1650
Emeryville, California 94608

Subject: **Ground Motion Hazard and Geotechnical Assessment**
Washington Monument
Washington, District of Colombia

Dear Mr. Paret:

AMEC Environment & Infrastructure, Inc. (AMEC) is pleased to submit this report for our ground motion hazard and geotechnical assessment conducted in support of seismic evaluations of the Washington Monument in Washington, D.C.. This assessment was undertaken in accordance with our proposal dated March 15, 2012.

If you have any questions about this report, please do not hesitate to call any of the undersigned. We appreciate the opportunity to work with you on this project.

Sincerely yours,
AMEC Environment & Infrastructure, Inc.

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GROUND MOTION HAZARD AND GEOTECHNICAL ASSESSMENT
Washington Monument
Washington, District of Columbia

1.0 INTRODUCTION

This report presents the results of a site-specific earthquake ground motion hazard and geotechnical assessment performed by AMEC Environment & Infrastructure, Inc. (AMEC) for Wiss, Janney, Elstner Associates, Inc. (WJE) in support of seismic evaluations of the Washington Monument (WAMO) in Washington, DC (Figure 1). We understand that WJE is working under subcontract to Tipping Mar and the National Park Service to perform a structural analysis of the WAMO. AMEC has conducted this ground motion hazard and geotechnical evaluation consistent with the scope of work in our proposal (dated March 15, 2012) and subcontract with WJE dated March 16, 2012. The purpose and scope of work are described in Section 1.1. A brief description of the project is presented in Section 1.2. The organization of the report is described in Section 1.3, and the project team and acknowledgments are listed in Section 1.4.

1.1 PURPOSE AND SCOPE OF WORK

The purposes of this study are to assess the ground shaking at WAMO from the August 2011 Mineral, Virginia, earthquake and other significant historical earthquakes, develop response spectra and a suite of earthquake time histories representing selected ground shaking levels at the foundation level of the WAMO, and develop geotechnical foundation parameters and recommendations for use in structural evaluation of the WAMO conducted by WJE.

Our scope of services to accomplish the above-stated purposes, as outlined in our proposal dated March 15, 2012, included the following tasks:

- Compile ground motions records and other information regarding the Mineral, Virginia, earthquake in August 2011 to assess the ground shaking at the monument resulting from that event;
- Perform a site-specific probabilistic seismic hazard analysis (PSHA) and develop site-specific ground motion response spectra representing selected ground shaking levels;
- Select and develop suites of seven sets of three orthogonal-component time histories representing ground shaking at the foundation level of WAMO from the 2011 Mineral, Virginia, earthquake and the maximum considered earthquake (MCE) that is defined for the site by the probabilistic ground motion hazard corresponding to a 2,475-year return period (2% probability of exceedance in 50 years);
- Review subsurface data for the area of the monument and develop geotechnical information, parameters, and recommendations for the foundation-soil system to use in structural evaluations of the monument; and
- Prepare of this report.

1.2 PROJECT DESCRIPTION

The Washington Monument, built to commemorate the first President of the United States, is located near the west end of the National Mall in Washington, D.C., and is one of the most widely recognized structures in the United States and the world. The monument is an obelisk constructed of marble, granite, and gneiss that stands 555 feet (169 m) tall and is 55 feet (16.8 m) wide at the base. Details of the construction and performance of the monument are well documented in several publications, including National Park Service (1983), U.S. Army Corps of Engineers (1984), Briaud et al. (2009), and WJE-Tipping Mar (2011). A summary of information regarding construction and performance of WAMO from these publications is presented below.

Construction of WAMO took place over a period of several decades, with the original foundation laid in 1848. From 1848 to 1854 construction of the shaft continued, reaching a height of about 180 feet (55 m). Although construction continued slowly for about four years, work was essentially halted from 1854 until 1878 due to a lack of funding, political turmoil within the Washington Monument Society, and the American Civil War. In 1878, construction resumed under the direction of the U.S. Army Corps of Engineers. Due to concerns regarding the bearing capacity of the original stone foundation, the monument was underpinned with a larger concrete foundation to provide greater bearing capacity. Construction of the shaft and capping pyramidion continued from 1878 until it was completed in 1884.

Settlement of the WAMO occurred both during construction and subsequently over time, continuing to the present. The estimated settlement during construction was about 4.5 inches. Post-construction surveys indicate an additional 2.5 inches of settlement has occurred at a relatively uniform rate from 1886-1992 (Briaud et al., 2009).

The August 23, 2011, moment magnitude (M_W) 5.8 earthquake was centered near Mineral Virginia, about 130 km south-southwest of Washington, D.C (Figure 1). The earthquake caused significant damage in the immediate epicentral area, widespread minor damage across Virginia and the National Capitol Area, and was felt from Georgia to Maine along the Atlantic seaboard of the U.S., as well as inland to Detroit and Chicago and in southeastern Canada from Montreal to Windsor. Notably, minor damage occurred to the National Cathedral and Washington Monument in Washington D.C. WJE and Tipping Mar (2011) conducted an immediate post-earthquake survey of damage to WAMO; they report that cracking and spalling occurred in the some exterior marble panels and interior supporting ribs and tiebeams of the pyramidion, that cracking and spalling of the exterior stone and mortar occurred extensively at the 450 to 500 foot level, and that lesser damage occurred over the entire length of the shaft.

1.3 REPORT ORGANIZATION

A description of the geologic setting of the project site is presented in Section 2.0. Information on historical ground shaking and seismicity is presented in Section 3.0. The site conditions are described in Section 4.0. Earthquake ground motion estimation methodology and inputs are explained in Section 5.0. Section 6.0 summarizes the results of the probabilistic and deterministic ground motion hazard assessment. The development of acceleration time histories is described in Section 7.0. A description of the methodology used for site response is presented in Section 8.0. Section 9.0 provides a summary of our geotechnical recommendations. A discussion of our recommendations for future analysis is presented in Section 10.0, and the basis for our recommendations is presented in Section 11.0. References are compiled in Section 12.0. Appendix A presents the Mueser Rutledge Consulting Engineer report on Subsurface Investigation for Washington Monument Security Improvements. A summary of the Modified Mercalli Intensity scaled is provided in Appendix B. Plots of response spectra and time histories are included in Appendix C for both the original and unscaled records.

1.4 PROJECT TEAM AND ACKNOWLEDGEMENTS

AMEC personnel that participated in this project and their primary responsibilities include:

- John A. Egan, Principal Engineer, Principal-in-Charge
- Donald Wells, Senior Geologist, Ground Motion Analysis, Peer Review
- Debra Gilkerson, Project Engineer, Project Manager, Ground Motion Analysis, Time History Development, Subsurface characterization, and Site Response Analysis.
- Courtney Johnson, Project Geologist, GIS data integration

AMEC would also like to acknowledge the data, insight, and guidance provided by Mr. Terry Paret of Wiss, Janney, Elstner Associates, Inc., throughout the project.

2.0 GEOLOGIC AND TECTONIC SETTING

Washington, D.C., lies along the Atlantic Continental Margin of the Eastern U.S. The city is located at the boundary of two major physiographic provinces, the Coastal Plain on the east and the Piedmont Plateau on the west (Figure 1). The Piedmont Plateau is characterized by rolling hilly topography, and is underlain by a complex terrane composed of metasedimentary and meta-igneous rock of Proterozoic to early Paleozoic age (more than about 417 million years old [Ma]) exposed at the surface (Figure 2). The Coastal Plain province is lower and flatter than the Piedmont Province, and is covered by a relatively thin, seaward-thickening wedge of undeformed Cretaceous to Tertiary (about 144 Ma to 1.6 Ma) fluvial and marine sedimentary deposits. These sedimentary rocks unconformably overlie the crystalline bedrock exposed in the Piedmont Province. The boundary of these provinces forms the Fall Line, so named because of the many waterfalls present where rivers crossed the boundary from

exposed crystalline rocks in the Piedmont Province to undeformed sedimentary rocks of the Coastal Plain Province (U.S. Geological Survey, 2012a). The Cretaceous sedimentary rocks in the Washington D.C. area are up to 450 m thick, and include interbedded clay, sand, silt, and gravel of the Potomac Group.

The Eastern U.S. has been tectonically stable since the early Cretaceous (99 Ma), as indicated by the presence of undeformed sedimentary rocks exposed across the Coastal Plain. Areas west of the Coastal Plain also have been tectonically stable, as geologic studies of the bedrock exposed in the Piedmont Province, and the Blue Ridge, Valley and Ridge, Appalachian Plateaus, and other provinces of the central and eastern U.S. show that the most recent major orogenic (mountain-building) event, the Alleghenian Orogeny, occurred during the Pennsylvanian and Permian Periods from about 325 to 260 Ma, and that rifting and magmatic intrusions associated with opening of the Atlantic Ocean occurred during the late Triassic Period, from about 220 Ma to 200 Ma (Withjack et al., 1998). An extended period with no significant tectonic, magmatic, and metamorphic activity is the basis for identification of a stable continental region (SCR). Specifically, a SCR is defined as a region of continental crust where significant tectonic, magmatic, and metamorphic activity have not occurred since the Early Cretaceous (99 Ma), and no significant rifting (extension or transtension) has occurred since the Paleogene Epoch (24 Ma) as described by Johnston et al. (1994).

While tectonically stable, erosion and deposition process have modified the land surface of the Eastern U.S., driven by the advances and retreats of continental glaciers and changes in sea level resulting from growth and melting of the continental glaciers. In mid-Atlantic coastal area that includes Washington D.C., fluvial erosion and deposition has occurred since the Miocene (post ~24 Ma) due to downcutting, lateral erosion, and backfilling of the Potomac River Valley, the Susquehanna River and Chesapeake Bay, and Delaware River and Bay, and other rivers, driven by rise and fall of sea level. Fluvial deposits of Miocene age and younger are present on a series of terraces, with the youngest terraces and fluvial deposits formed during the Pleistocene and Holocene (post 2.6 Ma and post 11,000 years before present). Broad floodplains underlain by alluvial deposits border most of the major rivers across the Coastal Plain, however, the major river valleys, including the Potomac River Valley, are backfilled with estuarine deposits accumulated as sea level rose following the end-Pleistocene deglaciation of North America. The estuarine deposits extend along the flats bordering the Potomac from Chesapeake Bay to the Fall Line, at the inland tidewater reach along the river (Reed and Obermeier, 1989).

The site for the new national capitol was selected by George Washington as the area on the Coastal Plain along the Potomac River and abutting the Fall Line. Four Pleistocene terraces are cut into the Cretaceous deposits that underlie Washington D.C. (T_1, T_2, T_3, and T_4, from youngest to oldest). Much of the city is built on the T_2 terrace, while the WAMO site lies near

the margin of the youngest terrace (T_1), at the edge of the Tidal Basin (Figure 3). The T_2 terrace deposits are considered to be of Sangamon Stage or interglacial (extending from about 128 thousand years ago (ka) to about 80 ka), while the T_1 terrace deposits are associated with the Wisconsin Stage (extending from about 80 to 12 ka; Reed and Obermeier, 1989;Fullerton et al., 2003).

Holocene fluvial and marsh(estuarine) sediments have been deposited along the margins of and over the T_1 Terrace or other older units deposits as sea level rose to its present level over the past 6 ka. Extensive tidal marshes formed along the major rivers east of the Fall Line as sea level rose, including along the Potomac River bordering Washington D.C. Broad areas of these tidal marshes along the Potomac were filled, including the area around the National Mall, Reflecting Pool, and Tidal west of the WAMO (Reed and Obermeier, 1989; Southworth and Denenny, 2006; Figure 3).

Bedrock underlying Washington, D.C. is commonly gneiss, which is identified as part of the Early Paleozoic Sykesville Formation, a dense meta-sedimentary rock that also includes phyllite, pelitic schist, and metagraywacke (Reed and Obermeier, 1989; Southworth and Denenny, 2006). Mueser Rutledge Consulting Engineers (2011; Appendix A) identify pelitic schist bedrock underlying the WAMO as Wissahickon Schist, following the terminology of Froelich and Hack, (1975) and Johnston (1964). The upper part of the bedrock typically is weathered and decomposed to a depth of several 10's of feet. Subsurface exploration at WAMO shows that the top of decomposed bedrock lies at a depth of about 30 m (100 feet) below the present ground surface (about 20 m below sea level; Figure 4). The top of bedrock dips eastward east to a depth of about 65 m below sea level in the area of the Capitol, about 2 km east of WAMO (Nikolaou et al., 2011). Cretaceous and Tertiary sedimentary rocks overlie bedrock in the area of the Capitol, but apparently have been eroded to the west as borings show that Pleistocene deposits, including a blue estuarine clay and alluvial sand and gravel deposits directly overlie bedrock at WAMO.

The Pleistocene deposits typically are less than about 10 m thick, but are as thick as 50 m where they fill old channels cut though older sediments and bedrock, such as at the WAMO site where the Pleistocene deposits are about 30 m thick (Figure 4) . The Pleistocene deposits underlying the WAMO site may include materials associated with both the T_1 and T_2 terrace deposition. The subsurface conditions and engineering properties of the Pleistocene deposits at the WAMO site are described in detail in Section 4.

3.0 SEISMOTECTONIC SETTING AND HISTORICAL GROUND SHAKING

An understanding of the regional tectonics, Quaternary geologic history, and seismicity of an area (i.e., the seismotectonic setting) facilitates the identification of geologic structures that may be modeled as seismic sources. It also provides context for developing tectonic models of crustal deformation that can be used in evaluating the tectonic role and seismic potential of

individual geologic structures. The seismic setting and effects of historical earthquakes in Washington, D.C., are described below. This information is used as a basis for selection of components of the seismic hazard model (described in Section 5) and in charactering the nature of historical ground motions in the context of potential future ground shaking at the site (Section 6).

3.1 SEISMIC SETTING

Washington, D.C., is located in the eastern part of the SCR of the Eastern and Central United States. Although SCR's characteristically have low rates of seismic activity, there are localized areas within the CEUS that are characterized by elevated rates of seismic activity. Several areas of notable seismic activity include the Eastern Tennessee, Charlevoix region of Quebec, Canada, Wabash Valley of Illinois and Indiana, Charleston, South Carolina, and the New Madrid, Missouri (including adjoining areas of Arkansas, Kentucky, and Tennessee; Figure 5). The first three areas are characterized by on-going small to moderate magnitude earthquakes (magnitude of less than about 6.5), while the latter two are areas are characterized as sources of repeated large magnitude earthquakes (RLME; magnitude greater than or equal to 6.5; Electric Power Research Institute [EPRI], 2012).

The Washington D.C. region is characterized by a low level of seismic activity (Figure 6). However, significant strong ground shaking has occurred in this area several times over the past ~300 years as a result of moderate magnitude earthquakes occurring in Virginia and large magnitude earthquakes occurring in the New Madrid, Missouri and Charleston, South Carolina regions. Despite extensive research over the past thirty years, including geologic, geophysical, and paleoseismic investigations, there remain significant uncertainties regarding causative sources and mechanisms that generate the larger earthquakes in these seismic zones (EPRI, 2012).

3.2 HISTORICAL GROUND SHAKING IN WASHINGTON DC

Significant earthquakes that have caused moderate-to-strong ground shaking and damage in Washington, D.C., include the 1811-1812 New Madrid, Missouri, earthquakes, the 1886 Charleston, South Carolina, earthquake, the 1897 Giles County, Virginia, earthquake, and the 2011 Mineral, Virginia, earthquake. A summary of the earthquake parameters and intensity of ground shaking and damage in Washington, D.C., for each of these earthquake sequences is provided below. Ground shaking intensity for recent earthquakes such as the 2011 Mineral, Virginia earthquake are commonly described in terms of peak ground acceleration and ground velocity (an earthquake time history) as recorded by strong motion accelerometers. As there are relatively few instruments to record ground shaking levels, particularly in the eastern U.S., ground shaking levels are often interpreted using reported shaking effects and observed damage. The most widely used scale in the U.S. to describe ground shaking levels is the Modified Mercalli Intensity (MMI) scale; a description of this scale is provided as Appendix B,

for reference to the MMI shaking levels reported for the historical earthquakes described below. Slight damage to structures typically is associated with MMI shaking levels or VI or higher, depending on the nature and quality of construction.

1811-1812 New Madrid, Missouri, Earthquakes

The largest earthquakes to occur in the central and eastern U.S. were the three large earthquakes occurring in the area of New Madrid, Missouri, from December 1811 to February 1812. The magnitude of these earthquakes is estimated to be between 7.5 and 7.7 (Hough, 2009). All three earthquakes were felt in Washington D.C., with Modified Mercalli Intensity (MMI) shaking effects of IV to V reported by Bakun et al. (2002); Stover and Coffman (1993) show the District as within the isoseismal area of MMI V effects, based on detailed studies of the earthquake sequence and anecdotal accounts in contemporary newspapers compiled by Nuttli (1973).

1886 Charleston, South Carolina, Earthquake

The September 1, 1886, Charleston earthquake is the largest historical event in the eastern U.S., with an estimated magnitude of 7.3. The earthquake resulted in widespread damage and ground failure (liquefaction) in the Charleston region, with ground shaking of MMI X in the meizoseismal area (area of maximum damage). This earthquake was felt by inhabitants of the District of Colombia as gentle swaying in upper levels of the Opera House, where some patrons rushed down and out of the building, and by shaking of furniture in a three-story building (Dutton, 1889). In nearby Alexandria, Virginia, it was reported that there was considerable alarm amongst the populace and many rushed into the streets. The effects in Washington, D.C., were reported as MMI IV by Bollinger (1977), although Stover and Coffman (1993) show the District as within the isoseismal area of MMI V effects.

1897 Giles County, Virginia, Earthquake

The May 31, 1897 estimated magnitude 5.9 earthquake in Giles County is the largest earthquake to occur in Virginia and the Washington, D.C., area. The earthquake resulted in moderate damage and MMI shaking of about VIII in Giles County. The earthquake was felt as gentle shaking in Washington, D.C., with MMI assigned as IV to V, with no reports of damage (Virginia Tech, 2012); Stover and Coffman (1993) show the District as just outside the isoseismal area of MMI V effects, which is consistent with the MMI assigned by Virginia Tech (2012).

2011 Mineral, Virginia, Earthquake

The August 23, 2011, magnitude (M_W) 5.8 earthquake near Mineral, Virginia, was the largest earthquake to occur in the eastern U.S. since the 1897 Giles County Virginia earthquake. The 2011 Mineral earthquake was centered in the CVSZ, approximately 130 km [81 miles] south-southwest of WAMO, and is the largest known earthquake associated with the CVSZ. The

U.S. Geological Survey (2011) reports that the earthquake occurred by reverse slip at shallow depth on a north or northeast-trending fault. Field investigations show that the fault rupture did not extend to the ground surface (Geotechnical Extreme Events Reconnaissance, 2012).

As mentioned previously, ground shaking from the earthquake was felt widely throughout the eastern U.S. and in southeastern Canada, and resulted in moderate damage in the epicentral region and slight damage over a wider area in Virginia and adjoining states. The damage and ground shaking effects of the earthquake are described in detail in a report published by the Geotechnical Extreme Events Reconnaissance (2011). The U.S. Geological compiles reports of felt ground shaking through the on-line "Did You Feel It" questionnaire (http://earthquake.usgs.gov/earthquakes/dyfi/). These reports indicate the MMI shaking in Washington ranged from IV to VI, with most reports in the vicinity of the WAMO indicating shaking of MMI V (U.S. Geological Survey, 2012b).

The reported MMI IV to V ground shaking in Washington D.C. for these historic earthquakes is consistent with the general absence of reported damage to structures. These shaking levels are associated with peak ground acceleration of approximately 0.07g, based on relationships presented by Ebel and Wald, (2003).

3.3 RECORDED GROUND MOTIONS FOR THE 2011 MINERAL, VIRGINIA EARTHQUAKE

The Mineral earthquake was recorded at U.S. Geological Survey National Strong Motion Program station sites along the east coast of the U.S. from South Carolina to Vermont. However, because there are few operating strong motion stations in the eastern U.S., only four recordings were obtained at an epicentral distance of less than 300 km (Table 1). The station most comparable to the azimuth and epicentral distance for WAMO of 130 km is at Reston, Virginia, at an epicentral distance of 122 km, and located about 26.5 km west-northwest of WAMO. The peak ground acceleration recorded at the Reston Station was 0.11g (Table 1), which is higher than the PGA inferred from the ground shaking effects reported near WAMO (less than 0.10 g). The site conditions at the Reston station are characterized as a deeply weathered soil profile over bedrock, with an average shear wave velocity for the upper 30 m reported as 364 m/s by the U.S. Geological Survey (Dr. Robert Kayen, U.S. Geological Survey, personal communication, 2012). This corresponds approximately to the boundary for Soil Profile Types D and C (360 m/s) as specified in the 2009 International Building Code (IBC; International Code Council, 2009). This shear wave velocity is generally in the same range of the shear wave velocity estimated for the WAMO site, which is described in the following section.

Additional information on the recorded strong ground shaking for the 2011 Mineral earthquake was obtained from instruments in a building in Washington D.C., located near the WAMO site. The nature of and interpretation of this data is described in Section 8.2.3.

4.0 CHARACTERIZATION OF SUBSURFACE CONDITIONS

Our understanding of the subsurface conditions at the WAMO site was developed based on a review of the previous geotechnical investigations as summarized by Mueser Rutledge Consulting Engineers (MCRE, 2011).

The subsurface stratigraphic conditions used in these analyses were characterized based on available logs of borings drilled previously by others in the immediate vicinity of the Monument, as well as results field and laboratory testing of soil properties associated with those borings. A total of 23 boring logs were available for review and characterization of the subsurface conditions; those logs are included in Appendix A of this report. The subsurface underneath the WAMO consists of approximately 12 feet of fill consisting mostly of silty sand that is loose to compact. Beneath the fill is a 25 foot layer of sand and gravel that is compact to very compact and known locally as T3. Underlying the sand and gravel later is a 40 foot think layer of soft to stiff plastic clay, the T1(D) layer. The T1(D) layer is underlain by 23 feet of decomposed rock that consists of very compact gray micaceous sand and silt with rock fragments. The soil parameters for unit weight, strength, and equivalent penetration resistance were estimated based on the data presented by MRCE in their 2011 report and is summarized for the site in Table 2. Table 2 includes average raw sampler penetration resistance (blow counts, N), for each subsurface layer, as well as the undrained shear strength for the plastic clay layer.

The shear wave velocity profile used in the analyses was developed based on the average blow counts observed in each cohesionless soil layer or the undrained shear strength for the clay layer, implementing empirical relationships using the penetrations resistance data (e.g., Sykora, 1987; Brandenberg, 2010) or shear strength data (e.g., Egan and Ebeling, 1985). The estimates of shear wave velocity are shown on Table 2. Based on the shear wave velocity profile, $V_{s,30}$ is estimated to be approximately 1,020 fps [310 m/s] for a profile extending from the ground surface, which corresponds to a stiff soil profile or Site Class D. For a profile extending from the base of the monument (i.e., at foundation level), however, $V_{s,30}$ is estimated to be approximately 1,350 fps [410 m/s], which corresponds to a very dense soil profile or Site Class C; we are of the opinion that this stiffer representation of the soil profile is appropriate for characterizing ground shaking conditions that have been and/or will be experienced by the monument during earthquakes in the region.

5.0 SEISMIC HAZARD METHODOLOGY AND MODELS

The methodology for conducting probabilistic and deterministic seismic hazard analysis, and the seismic source model and ground motion hazard models used in the analysis are described in this section. The methodology for conducting probabilistic and deterministic seismic hazard analyses is presented in Section 5.1. The seismic source model for the study region includes characterization of all sources of future earthquakes that may result in strong

ground shaking at the WAMO, as described in Section 5.2. The ground motion attenuation models selected to characterize potential strong ground shaking at WAMO from earthquakes on seismic sources are described in Section 5.3. The results of the site-specific ground motion analyses are described in Section 6.

5.1 METHODOLOGY FOR PROBABILISTIC AND DETERMINISTIC SEISMIC HAZARD ANALYSIS

The methodology for conducting probabilistic seismic hazard analysis (PSHA) and deterministic seismic hazard analysis (DSHA) are described in this section.

5.1.1 Probabilistic Seismic Hazard Analysis

The probabilistic seismic hazard analysis, commonly termed a PSHA, is based on an assessment of the recurrence of earthquakes on potential seismic sources in the region and on ground motion attenuation relationships appropriate for the types of seismic sources in the region and the subsurface conditions interpreted for the project site. Results of the hazard analysis are expressed as relationships between amplitudes of peak ground acceleration and response spectral acceleration, and the annual frequencies or return periods (return period being the reciprocal of annual frequency) for exceeding those ground motion amplitudes.

The PSHA analysis procedure requires the specification of probability functions to describe the uncertainty in both the time and location of future earthquakes and the uncertainty in the ground motion level that will be produced at the project site. The basic elements of the analysis are:

1. identification of potential (active) seismic sources that could significantly contribute to seismic hazard at the project site;
2. specification of an earthquake recurrence relationship for each seismic source, defining the frequency of occurrence of various magnitude earthquakes up to the maximum magnitude possible on the source;
3. specification of attenuation relationships defining ground motion levels as a function of earthquake magnitude and distance from an earthquake rupture; and
4. calculation of the probability of exceedance of peak ground acceleration and response spectral accelerations (i.e., seismic hazard) using inputs from the elements above, and development of equal-hazard (i.e., equal-probability-of-exceedance) response spectra from the results.

The PSHA is based on an assessment of the recurrence of earthquakes on and within potential seismic sources in the greater Washington, D.C., region (as described in Section 5.2) and on ground motion relationships appropriate for the types of seismic sources in the region. An important component of the seismic hazard model is the characterization of the uncertainties in identifying seismic sources and defining their parameters. A logic tree formulation is used to represent these uncertainties in the PSHA.

AMEC maintains a series of in-house computer programs that are used to perform PSHA and DSHA calculations. These programs are quite complex and are capable of incorporating all types of seismic source models with all types of ground motion attenuation models, but require significant effort to implement and validate. AMEC is currently updating our programs to implement a new seismic source model developed by AMEC and others for the Electric Power Research Institute (EPRI, 2012), however, the model implementation and validation is not yet complete. Therefore, because of budget, schedule, and logistical constraints, the PSHA was conducted using the commercial program EZ-FRISK^{TM} 7.62 (Risk Engineering, 2011). Additional information on this use of EZ-FRISK^{TM} for this project is provided in the following sections.

The site-specific seismic hazard analysis was performed to develop response spectra that represent two return periods: 475 and 2,475 years, corresponding to probabilities of exceedance of 10 percent and 2 percent in 50 years, respectively. The seismic hazard and response spectra are initially developed for an assumed outcrop reference rock condition having a V_{S30} equal to 760 m/s, which is consistent with the site class (i.e., firm-rock site condition, boundary of NEHRP site classes B and C) utilized by the U.S. Geological Survey (USGS) as its basis for development of the U.S. National Seismic Hazard Maps. Response spectra are then modified based on the site response analysis discussed in Section 8.

5.1.2 Deterministic Seismic Hazard Analysis

A deterministic analysis or DSHA is conducted to assess the strongest expected ground shaking that may result from a given earthquake scenario occurring on any fault source in the region. Commonly, such analyses use the maximum earthquake capability of a fault source that is based on the largest historical earthquake or, more typically, on the largest extent of the fault that is expected to rupture in an earthquake. For a DSHA, the uncertainty in source parameters typically is considered by evaluation of hazard fractiles such as plus/minus one sigma.

5.2 SEISMIC SOURCE CHARACTERIZATION

For Central and Eastern North America (CENA), two basic types of crustal seismic sources, faults and distributed seismicity sources, are included in seismic source models. Fault sources include known active faults, either mapped at the ground surface or modeled based on the occurrence of historical earthquakes. A limited number of fault sources have been identified in the CENA, with the most notable being the sources associated with the 1886 Charleston, South Carolina Earthquake, and the 1811-1812 New Madrid, Missouri earthquakes. These sources also are termed as Repeated Large Magnitude Sources (RLMS; EPRI, 2012), because there is paleoseismic evidence for the occurrence of multiple large magnitude earthquakes on these sources during the Holocene Epoch (the past 11,000 years).

Distributed seismicity sources represent potential for occurrence of earthquakes on other unknown faults across the region of interest. Several approaches can be used to model distributed seismicity, including areal source zones, which represent regions where the tectonic setting and mapped structures are inferred to indicate a uniform potential for occurrence of large magnitude earthquakes, and spatial smoothing, for which the rate of earthquake occurrence is assessed on a cell by cell or gridded basis and where the cell size, maximum magnitude, and smoothing characteristics are selected based on characteristics of the local and regional seismic and tectonic environment and judgment.

The parameters needed for each seismic source include the occurrence frequency of earthquakes for a range of magnitudes (earthquake recurrence relationships) and the maximum magnitude. The maximum magnitude, M_{max}, for a seismic source represents the largest possible earthquake for that source, regardless of its frequency of occurrence. Thus M_{max} defines the upper limit of the earthquake recurrence relationship for the source. The approaches used to assess earthquake recurrence relationships and M_{max} are dependent on whether a fault or distributed seismicity source is being evaluated, and for distributed seismicity sources, are region dependent. The approaches used for each type of source are described below.

5.2.1 Seismic Source Models for Central and Eastern North America

Comprehensive seismic source models for CENA have been prepared for specific purposes by several organizations, such as the USGS for the National Seismic Hazard Mapping Project (NSHMP; Petersen et al., 2008) and EPRI (2012) for use in evaluation of seismic criteria for nuclear facilities. These models are considered to provide a current and more comprehensive characterization of potential seismic sources in the CENA compared to previous seismic source models such as those prepared by EPRI (1988) and Bernreuter et al., 1989), which also were developed for use in evaluation of nuclear facilities.

The 2008 NSHMP and 2012 EPRI models both include fault sources and distributed seismicity sources, but the 2012 EPRI model incorporates a much broader assessment of geologic and tectonic data in characterizing potential seismic sources than does the 2008 USGS NSHMP model. Never-the-less, the 2008 NSHMP model forms the basis for the current National Seismic Hazard maps used with the 2009 IBC, and with ASCE/SEI Standards 7-05, 7-10, and 41-06 (ASCE/SEI, 2006, 2010, and 2006, respectively), and is judged to provide a reasonable representation for seismic sources in CENA.

As note previously, AMEC has not yet completed implementation and validation of the new EPRI seismic source model in our seismic hazard codes. Therefore to meet the needs of the current project, we used the 2008 USGS NSMHP model as a basis for assessing seismic hazard for the WAMO. The components of this source model, including the seismic sources and attenuation relationships are available as options for use in calculating seismic hazard in

the commercial program EZ-FRISK™. The program developer, Risk Engineering, validated the seismic source and attenuation model construction in EZ-FRISK, and notes that the program generally produces results that are generally consistent with (i.e., typically within less than 10 percent) of the ground motion values calculated by the USGS for the National Seismic Hazard Maps.

5.2.2 Components of the USGS National Seismic Hazard Mapping Project Seismic Source Model for Central and Eastern North America

The USGS NSHMP source model includes a number of fault sources, specifically representing the sources of the 1886 Charleston, South Carolina, earthquake, and the 1811-1812 New Madrid, Missouri, earthquakes, as well as two mapped active faults, the Cheraw fault and Meers fault in Colorado and Oklahoma, respectively. These sources are combined with background seismicity from distributed seismicity sources as follows.

The USGS NSHMP source model incorporates two models to assess the recurrence of earthquakes for distributed seismicity sources, included a spatially smoothed gridded seismicity approach, and a uniform background approach. The spatially smoothed approach accounts for the potential occurrence of large damaging earthquakes in areas where small to moderate magnitude earthquakes have occurred, while the uniform background zone provides a minimum level of hazard to account for the potential occurrence of damaging earthquakes in regions where little or no seismicity has occurred (Petersen et al., 2008). The distributed seismicity source also incorporates several special seismic zones for Eastern Tennessee, the Wabash Valley of Indiana, and the Charlevoix region of Quebec along the U.S. – Canadian Border, where the rate of background earthquakes is significantly higher than elsewhere in CENA.

The recurrence rates for damaging earthquakes for both approaches and the special zones is based on the observed rate of historical earthquakes from an independent earthquake catalog, in consideration of catalog completeness, assessed maximum magnitudes for the given region, and using a Gutenberg-Richter earthquake recurrence relationship.

The earthquake catalog used in the USGS and EZ-FRISK™ analysis is an independent catalog compiled by the USGS that covers the period from 1534 through 2006. The development of the catalog, magnitude conversions, and assessed completeness intervals are described in Petersen et al. (2008). The CENA catalog is based on body wave magnitude, m_{bLg}, because this is the primary magnitude listed for CENA earthquakes and because CENA attenuation relationships are based on this magnitude scale. Dependent earthquakes, including foreshocks and aftershocks, are removed as described by Petersen et al. (2008) such that the final catalog is considered to be de-clustered (an independent earthquake catalog). The final independent catalog is used to assess the activity (recurrence) rates in both the spatially smoothed and uniform hazard approaches, including the special seismic zones.

The rates are modeled using a truncated exponential or Gutenberg-Richter earthquake recurrence relationship, with a minimum magnitude of 5.0, M_{max} values assessed on a regional basis, and fault geometry as described by Petersen et al. (2008).

The implementation of these sources is documented in further detail in Petersen et al. (2008), and it is our understanding that these source models and associated maximum magnitudes and activity rates are implemented in EZ-FRISK™ such that the hazard results are generally very similar to results from the National Seismic Hazard Maps. For CENA, the USGS model is represented in EZ-FRISK™ by four fault sources and one combined gridded background source. The source characterization, including source geometry, assessment of maximum magnitudes and earthquake recurrence rates for fault and distributed seismicity sources are described in the following sections.

5.2.3 Fault Source Model for WAMO Assessment

Evaluation of M_{max} for crustal fault sources typically is developed using empirical relationships that relate fault rupture length and rupture area to maximum magnitude (Wells and Coppersmith, 1994). For each crustal fault, ranges of values for the rupture lengths, fault dips, and thicknesses of the seismogenic crust, including corresponding weights (relative probabilities) for different parameter values, are used to calculate maximum earthquake magnitudes. These calculations result in maximum magnitude distributions for each fault (i.e., all possible maximum magnitudes given the source parameters, their uncertainties, and the empirical relations) that are used in the subsequent hazard calculations. Alternatively, the maximum magnitude may be based on the largest earthquake known to have occurred on the fault source.

The slip rate reflects the rate at which strain energy (seismic moment) accumulates along a fault. The geologically derived seismic moment rate is used to translate slip rate into earthquake recurrence rate by partitioning the moment rate into earthquakes of various magnitudes according to a recurrence model. The characteristic earthquake magnitude recurrence model (Youngs and Coppersmith, 1985) is judged to be more representative of the seismicity of an individual fault than are exponential models that represent seismicity of regions. Therefore, the recurrence of maximum earthquakes on fault sources generally is modeled using the characteristic magnitude earthquake recurrence model.

Alternatively, the recurrence of maximum earthquakes may be based on the timing of historical earthquakes, such as identified from historical earthquakes and paleoseismic investigations.

One fault source is explicitly incorporated in the seismic source model, representing the source for the 1886 Charleston Earthquake. We use the fault source constructed for the NSHMP (Petersen et al., 2008), with a modification of their fault source areas to a line sources (e.g., Charleston source as shown on Figures 5 and 6). This modification was necessary for

implementation of the selected attenuation relationships in EZ-FRISK™, and has no effect on the ground motion hazard at WAMO. We also reviewed the characterization for the Charleston Source presented in the new EPRI (2012) source model. We note there are slight differences in the location of the sources and in the mean recurrence interval for the Charleston RLME; we performed a sensitivity check using a modified mean recurrence interval for RLME's on the Charleston source calculated from detailed results in EPRI (2012). By implanting this modified mean recurrence interval in the computations in EZ-FRISK™, we found that there was only a small change (less than a one percent increase) in the hazard results for WAMO. Because we cannot implement the full EPRI model in EZ-FRISK™ to assess the difference in results, we judge it is appropriate to use the original parameters from the 2008 NSHMP for the analyses presented in this report.

The fault source for the 1811-1812 New Madrid earthquakes also was considered in the preliminary hazard calculations; however, this source lies at a distance of about 1,100 km from the WAMO (Figure 5). Because both the developers for the U.S. Geological Survey National Seismic Hazard Mapping Project (Petersen et al., 2008) and for various attenuation relationships (described in Section 5.3) recommend that contributions from seismic sources at distances of more than 1000 km not be considered in PSHA), the New Madrid source and other potential seismic sources at distances of more than 1000 km from WAMO are not considered in the hazard analysis.

5.2.4 Distributed Seismicity Sources for WAMO

The distributed seismicity sources of the USGS NSHMP model are represented in EZ-FRISK™ as a single source for gridded background seismicity. As a result, the parameters for the component pieces of the USGS distributed seismicity source described above cannot be modified in EZ-FRISK™. Therefore, the hazard for distributed seismicity sources is expected to be similar for the EZ-FRISK™ analysis compared to the USGS NSHMP results. Because the USGS model is designed to provide a minimum level of hazard in all areas, it is our experience that a full site-specific implementation of a seismic source model, such as the models previously implemented by AMEC and our legacy firm of Geomatrix Consultants, Inc. (e.g., Wells et al., 2000), often provides slightly lower results from the distributed seismicity models for many areas of the U.S.

5.3 ATTENUATION RELATIONSHIPS

A ground motion attenuation model relates the amplitudes of peak acceleration and response spectral acceleration to earthquake magnitude, site conditions, and source-to-site distance. Past studies of strong-motion data indicate that the ground motions from various types of earthquake sources exhibit different characteristics in terms of the scaling of ground motion amplitudes with magnitude, source-to-site distance, and period of vibration. In addition, different attenuation models are required for different types of seismic sources such as crustal

faults and subduction-related sources, and for different tectonic settings such as active continental margins and stable continental regions.

A suite of alternative ground motion attenuation relationships were utilized for each type of seismic source. (i.e., fault sources and distributed sources). The uncertainty in the predicted value of a ground motion parameter for each attenuation relationship was modeled by assigning a statistical distribution around the median value relationships in accordance with values given by the authors of the respective attenuation relationships used in this study. For this study we used empirically developed ground motion attenuation relationships as described below. Numerous attenuation relationships for earthquakes occurring in stable continental regions have been developed for application in Central and Eastern North America (CENA). Because of the limited strong motion data set for CENA, the models have been based primarily on numerical simulations of strong ground motions. For the most part, these models have been developed for hard rock sites with shear wave velocities in excess of 2.5 km/sec. As a part of the National Seismic Hazard Mapping Project (NSHMP; Petersen et al, 2008) the attenuation relationships developed for hard rock sites were modified to be applicable at a shear wave velocity of 760 m/sec.

The conversion from hard rock to firm rock for several models was done using frequency dependent modification factors (Petersen et al., 2008). The NSHMP uses six or seven attenuation relationships to evaluate ground shaking, depending on the seismic source type (fault sources or distributed sources). The following models were used in the NSHMP and are used in the analysis for the WAMO site: Atkinson and Boore (2006), Campbell (2003), Frankel et al. (1996), Silva et al. (2002), Somerville et al. (2001), Tavakoli and Pezeshk (2005), and Toro et al. (1997). Table 3 lists the seismic source type with the applicable attenuation relationships and their assigned weights.

The NSHMP suite of attenuation relationships was select for use in the analysis for WAMO specifically because it is available for use in EZ-Frisk. Additionally, the use of the NSHMP suite of attenuation relationships allows for a direct comparison of our results to values obtained from the NSHMP. Many of these attenuation models have been further modified for use in CENA by the Electric Power Research Institute (i.e., EPRI 2004 and EPRI 2006 suites of attenuation relationships). These models have not been implemented in EZ-Frisk, and implementation of these models was not possible within the schedule and budget for the present analysis.

6.0 GROUND MOTION HAZARD ANALYSIS

The following section describes the ground motion hazard analysis performed for this study. The analysis methodology, results, and comparisons with strong motion data in the area are described in this section. As described in Section 5, both a probabilistic seismic hazard analysis (PSHA) and a deterministic seismic hazard analysis (DSHA) were performed to

characterize the potential earthquake ground shaking. Specifically, the objective of the seismic analysis was to develop site-specific horizontal and vertical, probabilistic and deterministic response spectra suitable for input in the site response analyses described in Section 8.

The calculations to develop seismic hazard curves and to assess ground motion characteristics for probabilities of exceedance (P_E) at 2 percent and 10 percent in 50 years (i.e., for peak ground acceleration and spectral accelerations), are described in Sections 6.1 and 6.2. The contributions to seismic hazard from specific seismic sources and deaggregation of seismic hazard for magnitude and distance contributions also is described in Section 6.2. The resulting equal hazard and deterministic response spectra from the PSHA and DSHA are presented in Section 6.3.

6.1 CALCULATIONS FOR FREQUENCY OF EXCEEDANCE

The mathematical formulation used in most PSHAs assumes that the occurrence of damaging earthquakes can be represented as a Poisson process. Under this assumption, the probability that a ground motion parameter, Z, will exceed a specified value, z, in time period t is given by:

$$P(Z > z \mid t) = 1 - e^{-\nu(z)\cdot t} \le \nu(z)\cdot t \qquad (6\text{-}1)$$

where $\nu(z)$ is the average frequency during time period *t* at which the level of ground motion parameter *Z* exceeds value *z* at the site from all earthquakes on all sources in the region. Equation (6-1) is valid provided that $\nu(z)$ is the appropriate average value for time period *t*. In this study, the hazard results are reported in terms of the frequency of exceedance $\nu(z)$.

The frequency of exceedance, $\nu(z)$, is a function of the frequency of earthquake occurrence, the randomness of size and location of future earthquakes, and the randomness in the level of ground motion they may produce at the site. It is computed by the expression:

$$\nu(z) = \sum_n \alpha_n(m^0) \int_{m^0}^{m^u} f(m) \left[\int_0^{\infty} f(r \mid m) \cdot P(Z > z \mid m,r) \cdot dr \right] \cdot dm \qquad (6\text{-}2)$$

where $\alpha_n(m^0)$ is the frequency of earthquakes on any given source *n* above a minimum magnitude of engineering significance, m^0; $f(m)$ is the probability density of earthquake size between m^0 and a maximum earthquake the source can produce, m^u; $f(r \mid m)$ is the probability density function for distance to an earthquake of magnitude *m* occurring on source *n*; and $P(Z>z \mid m,r)$ is the probability that, given an earthquake of magnitude *m* at distance *r* from the site, the peak ground motion will exceed level *z*. The frequency of earthquake occurrence, $\alpha_n(m^0)$, and the size distribution of earthquakes, $f(m)$, were determined by the earthquake recurrence relationships described in Section 5.2. The distribution for the distance between the

earthquake rupture and the site was determined by the geometry of the seismic sources also described in Section 5.2. The conditional probability of exceedance, $P(Z>z \mid m,r)$, was determined using the ground-motion attenuation relationships described in Section 5.3. The attenuation relationships defined the level of ground motion in terms of a lognormal distribution.

In the hazard computations performed by the USGS and presumably in EZ-FRISK™, the fault-specific sources and special seismicity zones were modeled by segmented planar surfaces with a fixed geometry, and the distributed seismicity sources are represented by uniformly distributed fault strike. Earthquakes were represented by rectangular rupture planes for the given magnitude earthquake using the rupture area relationship developed by Wells and Coppersmith (1994).

The hazard was computed considering the contributions of earthquakes of magnitude M_W 5 and larger ($m^0 = 5$). At each ground motion level, the complete set of results forms a discrete distribution for frequency of exceedance, $v(z)$. The computed distributions were used to obtain the mean frequency of exceeding various levels of peak ground motion (mean hazard curve).

6.2 PROBABILITIES OF EXCEEDANCE

Detailed seismic hazard results are presented for the site showing contributions from individual sources to the total hazard. Figures 7, 8, 9, and 10 show the total mean hazard at the site, and contributions from each individual source at peak ground acceleration (PGA), 0.3-, 1.0- and 2.0-second periods.

At all periods the hazard is dominated by the background seismicity. At longer periods, the hazard is still controlled by the background seismicity, but the Charleston Seismic Zone is a significant contributor (Figure 7 through 10). Figure 11a through Figure 11d present magnitude-distance contributions to the hazard for PGA and 0.3-, 1.0- and 2.0-second periods, respectively. Each figure shows the magnitude-distance contributions of the hazard for ground motions at a return period of 475-years. Figures 11e through Figure 11h show the results of the deaggregation for PGA and 0.3-, 1.0 and 2.0 seconds at a 2,475-year return period. Due to modeling constraints within EZ-Frisk, the attenuations relationships used for each source type were weighted equally when calculating deaggregation.

6.3 EQUAL HAZARD AND DETERMINISTIC RESPONSE SPECTRA

The resulting response spectra from the probabilistic and deterministic seismic hazard calculations are described below.

6.3.1 Probabilistic Response Spectra

PSHA results for the WAMO site were obtained for a range of hazard results (spectral accelerations) and twelve spectral periods (PGA, 0.02, 0.03, 0.05, 0.075, 0.1, 0.2, 0.3, 0.4,

0.5, 1.0, 2.0, and 3.0 seconds). The mean hazard curves for each spectral period were interpolated to obtain values of spectral acceleration associated with return periods of 475 and 2,475 years; these return periods correspond to probabilities of exceedance of approximately 10% and 2% in 50 years, respectively. These spectral ordinates were then connected to define uniform hazard response spectra (UHRS); the UHRS representing the 475- and 2,475-year return period hazard levels are plotted on Figure 12 and listed in Table 4.

6.3.2 Deterministic Response Spectra

We developed median (50th), and 84th-percentile (median plus one standard deviation) deterministic response spectra for scenario earthquakes representing the 2011 Mineral, Virginia, earthquake and the 1886 Charleston, South Carolina, earthquake. These earthquakes are the largest events that have occurred in the Eastern U.S. and resulted in the strongest ground shaking in Washington, D.C., since construction was completed at the WAMO.

The deterministic spectra were developed based on the estimated or measured moment magnitudes for these events, the closest distance to the site, and the weighted attenuation relationships as shown in Table 2 for the Mineral, Virginia, and Charleston, South Carolina, sources, respectively. The deterministic earthquakes considered in the analysis are:

- M_W 5.8 at reverse oblique earthquake in the Central Virginia seismic zone at a distance (R_{rup}) of approximately 130 km; and
- M_W 7.5 strike-slip earthquake in the Charleston seismic zone at a distance (R_{rup}) of approximately 560 km.

Results of the deterministic analysis are presented on Figure 13 and in Table 5.

7.0 DEVELOPMENT OF ACCELERATION TIME HISTORIES

This section describes the development of two suites of scaled time histories, first for the August 2011, Mineral, Virginia earthquake (the Mineral earthquake scenario suite) and secondly for a 2,475-year return period hazard level at the WAMO site.

7.1 SELECTION OF SEED TIME HISTORIES

Time histories were selected and linearly scaled such that the peak ground acceleration (PGA) corresponded with the target PGA. Two levels of ground motions, the Mineral earthquake scenario and the 2,475-year return period hazard level for the WAMO site. As discussed in the previous sections, PSHA results at PGA and spectral accelerations in the period range of PGA to 0.3 seconds are dominated by earthquakes occurring on distributed seismicity sources at distances of up to about 200 km. The dominant contributions shift towards larger magnitude earthquakes at larger distances with increasing spectral period. At periods of 1.0 second and longer, there is an increasing contribution from larger magnitude earthquakes occurring on the Charleston seismic source at a distance of more than 500 km.

Therefore, time histories representative of local seismic events, as well as the 1886 Charleston earthquake, were selected for use in site response analysis. The suite of time histories are comprised of actual strong motion recordings from the Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard- and Risk Consistent Ground Motion Spectra Guidelines (NUREG/CR-6728, McGuire, 2001) database that consists of ground motion recordings considered to be applicable to the Central and Eastern United States (CEUS). The ground motions consist of CEUS recordings, as well as Western United States (WUS) ground motion recordings that have been modified using the single-corner-frequency point source model and transfer functions to adjust the WUS recordings.

The seven seed time histories for each scenario were selected by screening a larger list of potential condidates of existing time histories, primarily based on the magnitude-distance, similar spectral shape to the target, and site conditions consistent with rock, a Geomatrix site class ending in 'A' or a NEHRP Site Class A or B (Geomatrix, 2000). The following range of parameters was used for the initial selection of candidate Mineral scenario time histories:

- Magnitude (M_W) between 5.5 and 6.5;
- Distance to fault rupture (R_{rup}) between 50 and 100 km;
- Strike-Slip, Normal, or Reverse Earthquakes; and
- Geomatrix 3rd letter 'A' or NEHRP Site Class A or B

The following range of parameters was used for the initial selection of candidate 2475-year return period time histories:

- Magnitude (M_W) between 7.0 and 8.0;
- Distance to fault rupture (R_{rup}) between 40 and 150 km;
- Strike-Slip, Normal, or Reverse Earthquakes; and
- Geomatrix 3rd letter 'A' or NEHRP Site Class A or B

The fourteen time histories used for scaling to each target spectra, and the associated metadata for each record from NUREG/CR-6728 database, are listed in Table 6.

7.2 DEVELOPMENT OF SPECTRALLY SCALED TIME HISTORIES

For the WAMO site, a suite of seven sets of three-component spectrum-scaled acceleration time histories were developed to represent the 2011 Mineral earthquake scenario ground motions. A second set of earthquake records was scaled to the 2,475-year return period design level for the site, for a total of 14 sets of spectrum-scaled time histories. Each set of time histories consists of three orthogonal components of motion; two horizontal and one vertical.

Linear scale factors were applied to each set of time histories such that the geometric mean of the PGA of the as-recorded spectra is equal to the PGA of the target spectrum. The PGA for the suite of acceleration time histories for the Mineral scenario were scaled to a target PGA of 0.08g to represent the intensity interpreted by U.S. Geologic Survey (USGS, 2012b) based on reports of felt effects in Washington, D.C.. The geometric mean of each suite of spectra and the target design response spectra are shown on Figure 14a for the horizontal components representing the Mineral earthquake scenario and Figures 14b for the horizontal components of records representing the 2,475-year return period hazard level. Plots of the response spectra and original and scaled time histories are provided in Appendix C.

8.0 SITE RESPONSE ANALYSIS

This section describes the equivalent linear free-field site response analyses performed for the WAMO seismic hazard analyses with Mineral scenario and the 2,475 year return period ground motions. These analyses provide site-specific estimates of the ground motions and strain-compatible dynamic soil properties for use in foundation evaluations considering the effects of the soil deposits underlying the WAMO site. It is our understanding that results of these site response analyses will be used as input into the structural evaluation of the monument.

The site subsurface materials at the monument site, the shear wave velocity profile are described in Section 4.0. The dynamic material properties, the site response analysis approach and results are described in this section.

8.1 DYNAMIC MATERIAL PROPERTIES

The modulus reduction and damping curves for the site response analyses published modulus reduction and damping curves for high plasticity clays with a plasticity index (PI) of 15 and 50 (Vucetic and Dobry, 1991) and the mean sand curve from Seed and Idriss, 1970. The modulus reduction and damping curves used for this project are shown on Figure 15.

8.2 EQUIVALENT LINEAR ANALYSIS

Total stress site response analyses were performed using the equivalent linear methodology. The equivalent linear analyses were used to estimate the ground motions at the bottom of the WAMO foundation 12 feet below the ground surface. These analyses were also used to estimate the effective shear strain and shear stress within the soil layers.

8.2.1 Methodology

Equivalent linear (EQL) analyses were performed using an in-house modified version of the site response computer program, SHAKE (Schnabel et al., 1972). SHAKE is an industry standard program for performing equivalent linear site response analyses of a layered site subjected to 1D (vertical) propagation of earthquake ground motions in the frequency domain. The input is a layered soil system with shear wave velocity, shear modulus reduction and

damping values defined by specified strain-dependent relationships, and an input acceleration time history. The output includes computed time histories of acceleration, stress, and strain at specified locations, and strain-compatible shear moduli and damping values for the soil layers. The seven sets of scaled horizontal time histories described in Section 7 for each return period were used as outcrop ground motion inputs in the site response analysis.

8.2.2 Equivalent Linear Analysis Results

Site response analyses described above were performed for the representative soil profile to assess free-field ground motions and strain-compatible soil properties for input ground motions corresponding to the 2011 Mineral earthquake ground shaking conditions and to a return period of 2,475 years hazard level. Results of site response analyses for site conditions representative of the WAMO site for both seismic hazard levels are presented in this section.

The results from the analyses include the following parameters, although not all of these parameters are presented in this report:

- Spectral acceleration (S_a) – The five percent damped spectral accelerations computed at the base of the monument (foundation level).
- Amplification function (amp) – The ratio at each frequency of the five-percent damped spectral acceleration (S_a) at base of the monument (foundation level) to the S_a of the input motion.
- Maximum strain – The maximum shear strain within each layer obtained during the earthquake shaking. The maximum shear strain value is reduced internally by SHAKE by 35 percent to obtain an equivalent shear strain which is used in the estimation of the final strain compatible material properties. The maximum strain may be reached at different times in different layers.
- Peak acceleration (PHA) – The maximum acceleration of the time history output at the top of each layer.
- Time Histories – The acceleration, velocity, or displacement of the top of each layer during the earthquake shaking.

The response spectra from the EQL site response analysis are shown on Figure 16a for the horizontal ground shaking components representing the 2011 Mineral earthquake scenario and Figure 16b for the horizontal ground shaking components representing the 2,475 year return period hazard level. The figures show the spectral accelerations for the elevation within the profile corresponding to the base of the monument (foundation level) below the ground surface.

8.2.3 Time History Recordings of Mineral, Virginia, Earthquake

WJE provided AMEC with time history recordings of the August 2011 Mineral, Virginia, earthquake obtained at a building site in Washington, D.C.. Although WJE is not able to disclose the building name and location to us, we understand it is reasonably nearby, so is

expected to have similar geologic and subsurface conditions as characterize the WAMO site. A total of eight sets ground motion recordings were provided. Each set of recordings consists of three components, transverse, longitudinal and vertical. Figure 17 shows the horizontal components of each recording and the geometric mean of all recordings; it may be noted that the geomean horizontal peak ground acceleration (PGA_H) of these recordings is approximately 0.075g. The vertical components of the ground motion recordings are shown on Figure 18; the geomean vertical peak ground acceleration (PGA_V) of these recordings is approximately ⅔ of the peak horizontal ground acceleration. Figure 19a and Figure 19b illustrate a comparison of the geomeans of the horizontal-component response spectra for the 2011 Mineral earthquake corresponding to the time histories mentioned previously as having been recorded at a building site in Washington, D.C., and the previously-presented equivalent-linear site response analysis results for the 2011 Mineral earthquake scenario and the 2,475-year return period, respectively. Although not identical, the comparison illustrates similar response characteristics between the analytical results and the recorded data; notably, the similar amplitudes and the apparent tuning effect of the site conditions at response periods between approximately 0.25 and 0.4 second. Also illustrated on Figure 19a for comparison are response spectra for assumed rock outcrop conditions (i.e., V_{S30} = 760 m/s) in Washington, D.C., estimated for the 2011 Mineral earthquake; using the scenario target as a basis, the comparison can be interpreted as demonstrating moderate deamplification of bedrock motions at shorter and longer response periods and significant amplification (factors in the range of 1.5 to 3) at the previously-mentioned intermediate periods of apparent site tuning effects. At periods greater 0.4 seconds the geomean of the recorded motions and the geomean of equivalent linear analysis at the 2,475-year return period level shown on Figure 19b differ from one another. The difference in longer period motions is derived from larger magnitude events and is shown on the deaggregations in Figure 11g and Figure 11h. The accelerations from the equivalent linear analysis are consistent with the nearby recordings at short periods as the short period accelerations are driven by smaller magnitude events, as shown in Figure 11e and Figure 11f.

A comparison of the ground motions recorded in Washington, D.C., reasonably near the WAMO, associated with the Mineral, Virginia, earthquake to the previously-discussed results of the probabilistic seismic hazard analysis (PSHA) conducted for the WAMO site was conducted. This comparison suggests that horizontal peak ground acceleration (PGA) and shorter-period ($T \leq 0.5s$) spectral acceleration (S_a) levels experienced at the WAMO site during ground shaking produced by the Mineral, Virginia, event likely correspond to hazard levels with return periods in the range of about 2,000 to 3,000 years (i.e., probabilities of exceedance in the range of approximately 1.6% to 2.4% in 50 years). We note that these hazard levels are similar to the 2,475-year return period (2% probability of exceedance in 50 years) utilized by ASCE/SEI 7-05 and ASCE/SEI 41-06 to characterize the Maximum Considered Earthquake (MCE) for the WAMO site. Because the Mineral, Virginia, earthquake

was a moderate-magnitude event, spectral acceleration (S_a) levels for longer-period ground motions (e.g., T ≥ 1s) experienced at the WAMO site likely do not approach hazard levels that characterize the Maximum Considered Earthquake (MCE) for the WAMO site. However, based on the Modified Mercalli Intensity (MMI) IV to V effects reportedly experienced in Washington, D.C., from the 1886 Charleston, South Carolina, earthquake (M_w 7.5 at 560 km), as discussed previously, we estimate that spectral acceleration (S_a) levels for longer-period ground motions (e.g., T ≥ 1s) experienced at the WAMO site likely did achieve hazard levels consistent with or exceeding those that characterize the Maximum Considered Earthquake (MCE) for the WAMO site.

As a separate note, if one considers a deterministic scenario representing the Mineral, Virginia, earthquake with respect to the Washington, D.C area (i.e., a M_w 5.8 event at approximately 130 km), we estimate that that horizontal peak ground acceleration (PGA) and shorter-period (T ≤ 0.5s) spectral acceleration (S_a) levels of ground shaking experienced at the WAMO site were between a 1 and 2 sigma level (84^{th} and 98^{th} percentile) level based on published ground motion attenuation relationships (e.g., Atkinson and Boore, 2006; amongst others), whereas the spectral acceleration (S_a) levels for longer-period ground motions (e.g., T ≥ 1s) was more on the order of the median (50^{th} percentile) level.

8.3 USE OF SPECTRUM-COMPATIBLE TIME HISTORY SUITE

Both suites of time histories (7 sets per suite) were developed for use in structural analyses. Each suite corresponds to a specific ground motion scenario; the 2011 Mineral earthquake scenario and the 2,475-year return period hazard level for the WAMO site. Because the time histories were developed as a suite of records, no single record should be used in analyses of the monument without consideration of the other six records.

9.0 GEOTECHNICAL RECOMMENDATIONS

The following sections present geotechnical/foundation parameters recommended for use in the nonlinear structural analysis.

9.1 RECOMMENDED BEARING CAPACITIES

Ultimate bearing capacity and allowable bearing stresses were estimated for the monument foundation based on the dimensions of the foundation system, the depth of the monument embedment below the surrounding ground surface, and the characteristics of the soil profile as summarized in Table 1. Given the dimensions of the foundation system and soil profile characteristics, it was determined that, although the monument is founded on a very dense stratum of sand and gravel, the proximity of the plastic clay layer, approximately 25 feet [7½ m] below the monument base (foundation level), and the shear strength properties of that plastic clay control the bearing capacity and load-deflection characteristics of the monument foundation-soil system for both long-term gravity (dead and live load) conditions and seismic

loading conditions. Based upon these various considerations, the ultimate global bearing capacity for the monument foundation is estimated to be approximately 27 ksf for static gravity loading conditions. This would suggest that an allowable bearing stress for dead plus live gravity loads at the base of the monument (foundation level) is approximately 9 ksf.

For seismic loading conditions, soils typically demonstrate increased strength and stiffness characteristics, commonly termed strain-rate effects (e.g., Whitman, 1970). These effects are generally small for cohesionless soils, such as the sands and gravels that immediately underlie the monument foundation, but can be quite substantial for plastic clay soils such as the layer that controls the bearing capacity and load-deflection characteristics of the monument foundation-soil system; Egan and Ryan (2006) have presented a simplified procedure for rationally incorporating strain-rate effects, including variations amongst soil types, into estimating the bearing capacity characteristics and load-deflection relationships appropriate for seismic loading conditions. Based on relationships presented by Egan and Ryan (2006), the plasticity of the clay soil suggests that the soil could exhibit undrained shear strength increases in the range of about 40 to 50 percent due to strain-rate effects associated with earthquake loading conditions. Because the overlying dense sand and gravel layer is expected to exhibit little, if any, strain-rate effect, the strain-rate effect increase exhibited in the clay's undrained shear strength characteristics does not translate as a direct increase of the ultimate bearing capacity. Nonetheless, incorporating that effect with the various other considerations described previously, an ultimate global bearing capacity for the monument foundation appropriate to earthquake (dynamic) loading conditions is estimated to be approximately 36 ksf.

9.2 RECOMMENDED VERTICAL LOAD-DEFLECTION RELATIONSHIPS

As mentioned previously, Egan and Ryan (2006) have presented a simplified procedure for rationally incorporating strain-rate effects, including variations amongst soil types, into estimating the bearing capacity characteristics and load-deflection relationships (often referred to as spring characteristics) appropriate for seismic loading conditions. That procedure is similarly valid whether a strain-rate effect for a soil is included (e.g., dynamic loading conditions) or is neglected (i.e., static gravity loading conditions). Based on the Egan and Ryan (2006) procedure, vertical load-deflection relationships for the monument foundation-soil system were evaluated to represent static gravity loading conditions, for which no strain-rate effect is considered, and seismic (dynamic) loading conditions, for which the previously-discussed strain-rate effects expected to be exhibited by the foundation soils are incorporated. These vertical load-deflection relationships for the monument foundation-soil system are illustrated on Figure 20.

In using these relationships to define a spring stiffness for a seismic increment of loading, the appropriate approach is to start on the static load-deflection curve at the P-δ corresponding to

the existing gravity foundation stress (i.e., we understand the gravity dead plus live load stress at the base of the monument [foundation level] is approximately 9 ksf), then jump to the dynamic load-deflection curve at the P-δ corresponding to your total seismic foundation stress (say 15 ksf [9 ksf static plus a 6 ksf seismic increment]); the differences in P and δ would thus define the spring stiffness for that seismic increment, about 13 ksf/in. If the seismic loading increment is other than 6 ksf, a similar approach should be followed to characterize the appropriate spring stiffness.

We note that these foundation-soil load-deflection relationships characteristics are appropriate to compressive or bearing pressure at the base of the foundation. No tensile or uplift stiffness should be assumed between the foundation and the supporting soil.

10.0 RECOMMENDATIONS FOR ADVANCED ANALYSES

We recommend that if the structural assessment indicates that further structural analyses are necessary for design of a seismic retrofit for WAMO, that additional seismic analyses be conducted to incorporate new information as follows:

1. The ground motion response spectra may be updated based on use of an advanced seismic hazard analysis. This analysis would be based on use of the new EPRI seismic source model for CENA and on the EPRI suites of modified attenuation relationships or other new attenuation relationships appropriate for CENA seismic sources (such as from the ongoing NGA East Project). AMEC is currently in the process of incorporating the updated source model and attenuation models in our seismic hazard codes, however the model validation process and quality assurance review are not complete such that the model could be used in the present analysis.
2. New data on site characteristics may be implemented in the attenuation models, specifically shear wave velocity data for the WAMO site to be collected and analyzed by the U.S. Geological Survey.

11.0 BASIS FOR RECOMMENDATIONS

This report was prepared for the exclusive use of the WJE, Tipping Mar and the National Park Service. The recommendations and other considerations presented in this report are intended for the use in evaluation of the Washington Monument. The recommendations were developed using information available for the site and our understanding of the current geologic conditions. No new or additional subsurface exploration was performed by AMEC during the present study.

In the performance of our professional services, AMEC, its employees, and its agents comply with the standards of care and skill ordinarily exercised by members of our profession practicing in the same or similar localities. No warranty, either express or implied, is made or intended in connection with the work performed by us, or by the proposal for consulting or other services, or by the furnishing of oral or written reports or findings. We are responsible for the conclusions and recommendations contained in this report, which are based on data

related only to the specific project and location discussed herein. In the event conclusions based on these data are made by others, such conclusions are not our responsibility unless we have been given an opportunity to review and concur with such conclusions in writing.

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TABLES

TABLE 1

RECORDED PEAK GROUND MOTION AND SPECTRAL ACCELERATIONS
FOR THE AUGUST 23, 2011 MINERAL, VIRGINIA EARTHQUAKE
Ground Motion Hazard and Geotechnical Evaluation
Washington Monument
Washington, District of Colombia

Mineral Virginia Earthquake of 23 Aug 2011, 17:51:04 UTC, 5.8Mw, 37.94N 77.93W, 6.0 km depth Event Id: usse082311a
CESMD Engineering Strong Motion Data Center, Table Last Updated: 2011-12-20 10:24:04

Id	Name	Number	Station	Name	N. Lat	W. Long	Epicenter Distance	PGAv1 (g)	PGAv2 (g)	PGV (cm/s)	PGD (cm)	Sa (g) 0.3 sec	Sa (g) 1.0 sec	Sa (g) 3.0 sec
NM	NMSN	CVVA	VA	Charlottesville	38.022	78.532	53.5	0.121	0.121	1.68	0.2	0.045	0.089	0.021
US	NEIC	CBN	VA	Corbin (Fredricksberg Obs)	38.205	77.373	58.2	0.135	0.135	7.13	1.6	0.021	0.01	0.001
NP	USGS	2555	VA	Reston Fire Station 25	38.951	77.336	121.6	0.109	0.092	3.05	-	0.225	0.023	0.002
NP	USGS	2549	VA	Pearisburg - Giles County CH	37.327	80.735	254.5	0.003	0.003	0.14	0.1	0.005	0.001	0
NP	USGS	2648	PA	Philadelphia - Drexel Univ	39.957	75.192	326.1	0.009	0.009	0.35	0.1	0.016	0.007	0.001
NP	USGS	2554	SC	Columbia - VA Hospital	33.975	80.961	519.3	0.003	0.003	0.18	0	0.015	0.001	0
NP	USGS	2654	NY	Buffalo - VA Medical Center	42.952	78.811	557.3	0.001	0.001	0.18	0	0.004	0.002	0
NP	USGS	2552	SC	Summerville - Fire Station	33.025	80.176	584.5	0.001	0.001	0.12	0.1	0	0	0
NP	USGS	2544	SC	Charleston - Cha Pla Hotel	32.781	79.932	603.1	0.002	0.001	0.13	0.1	0.004	0.002	0.001
NP	USGS	2653	NY	Albany - VA Med	42.652	73.773	629.9	0.007	- -	-	-	- -	- -	- -
NP	USGS	2606	MA	Northampton VA Medical Ctr	42.35	72.682	662.9	0.008	0.008	0.74	0.1	0.015	0.006	0.001
NP	USGS	2649	MA	Boston - Jamaica Plains	42.328	71.11	758	0.001	0.001	0.09	0	0.002	0.002	0
NP	USGS	2602	MA	Bedford - VA Hospital	42.504	71.273	759.6	0.001	0.001	0.07	0	0.002	0.001	0
NP	USGS	2652	Ma	nchester - VA Medical Center	43.013	71.442	787	0.001	0.001	0.13	0	0.002	0.001	0
NP	USGS	2655	VT	White River Junction VAMC	43.649	72.343	787.9	0.005	0.001	0.11	-	0.002	0.003	0.001

TABLE 2

SUBSURFACE PROFILE

Ground Motion Hazard and Geotechnical Evaluation
Washington Monument
Washington, District of Colombia

Layer	Material Type	Thickness (ft)	$N_{raw,avg}$ (bl/ft)	Shear Strength (ksf)	$V_{s,30}$est (m/sec)	Assumed Unit Weight (pcf)	G/Gmax and Damping Model
F	Fill (mostly Silty Sand)	37	12.6	N/A	220	120	Vucetic & Dobry, PI = 15
T3	Sand and Gravel	25	97.5	N/A	760	120	Seed & Idriss, Sand Mean
T1(D)	Plastic Clay	40	15.5	2.8	320	115	Vucetic & Dobry, PI = 50
D	Decomposed Rock	23	100	N/A	760	115	Seed & Idriss, Sand Mean

TABLE 3

ATTENUATION RELATIONSHIPS AND ASSIGNED WEIGHTS FOR SEISMIC HAZARD ANALYSIS
Ground Motion Hazard and Geotechnical Evaluation
Washington Monument
Washington, District of Colombia

Attenuation Relationship	Distributed Seismicity Sources	Fault Source - Charleston Seismic
Atkinson and Boore (2006) 140 Bar Stress Drop	0.125	0.10
Atkinson and Boore (2006) 200 Bar Stress Drop	0.125	0.10
Campbell (2003)	0.125	0.10
Frankel et al. (1996)	0.125	0.10
Silva et al. (2002)	0.125	0.10
Somerville et al. (2001)	0	0.20
Tavakoli and Pezeshk (2005)	0.125	0.10
Toro et al. (1997)	0.250	0.20

Note:
Attenuation relationships and weighted following NSHMP (Petersen et al., 2008)

TABLE 4

UNIFORM HAZARD SPECTRA SPECTRA FOR (V_{S30} = 760 M/S) SITE CONDITIONS FOR THE 475- AND 2,475-YEAR RETURN PERIODS

Ground Motion Hazard and Geotechnical Evaluation
Washington Monument
Washington, District of Colombia

Period (seconds)	Spectral Accelerations (g)	
	475-Year Return Period	2,475-Year Return Period
0.01 (PGA)	0.021	0.060
0.02	0.026	0.077
0.03	0.031	0.092
0.05	0.037	0.112
0.08	0.042	0.123
0.10	0.046	0.132
0.15	0.046	0.128
0.20	0.046	0.125
0.25	0.044	0.118
0.30	0.043	0.115
0.40	0.033	0.088
0.50	0.028	0.073
1.00	0.017	0.044
1.50	0.013	0.033
2.00	0.010	0.025
3.00	0.006	0.016

Note:

Response spectra are five-percent damped, except for PGA (0.01 seconds), which is not damped.

TABLE 5

MEDIAN AND 84TH PERCENTILE HORIZONTAL DETERMINISTIC RESPONSE SPECTRA

Ground Motion Hazard and Geotechnical Evaluation
Washington Monument
Washington, District of Colombia

Period (seconds)[1]	Spectral Acceleration (g)			
	2011 Mineral, Virginia Earthquake, M5.8 at 130 km, 50th Percentile[2]	2011 Mineral, Virginia Earthquake, M5.8 at 130 km, 84th Percentile	1886 Charleston Earthquake, M7.5 at 560 km, 50th Percentile[2]	1886 Charleston Earthquake, M7.5 at 560 km, 84th Percentile
0.01 (PGA)	0.022	0.043	0.011	0.021
0.02	0.028	0.055	0.013	0.025
0.03	0.033	0.066	0.015	0.028
0.05	0.042	0.083	0.017	0.032
0.08	0.045	0.090	0.018	0.035
0.10	0.050	0.100	0.019	0.038
0.15	0.048	0.096	0.021	0.041
0.20	0.046	0.093	0.023	0.044
0.25	0.043	0.087	0.024	0.046
0.30	0.041	0.083	0.025	0.048
0.40	0.030	0.061	0.023	0.044
0.50	0.023	0.048	0.021	0.041
1.00	0.010	0.022	0.016	0.033
1.50	0.006	0.013	0.014	0.028
2.00	0.004	0.008	0.011	0.023
3.00	0.002	0.004	0.008	0.016

Notes:

1. Response spectra are five-percent damped, except for PGA (0.01 seconds), which is not damped.
2. Distances represent closest distance of rupture to site (R_{Rup}).

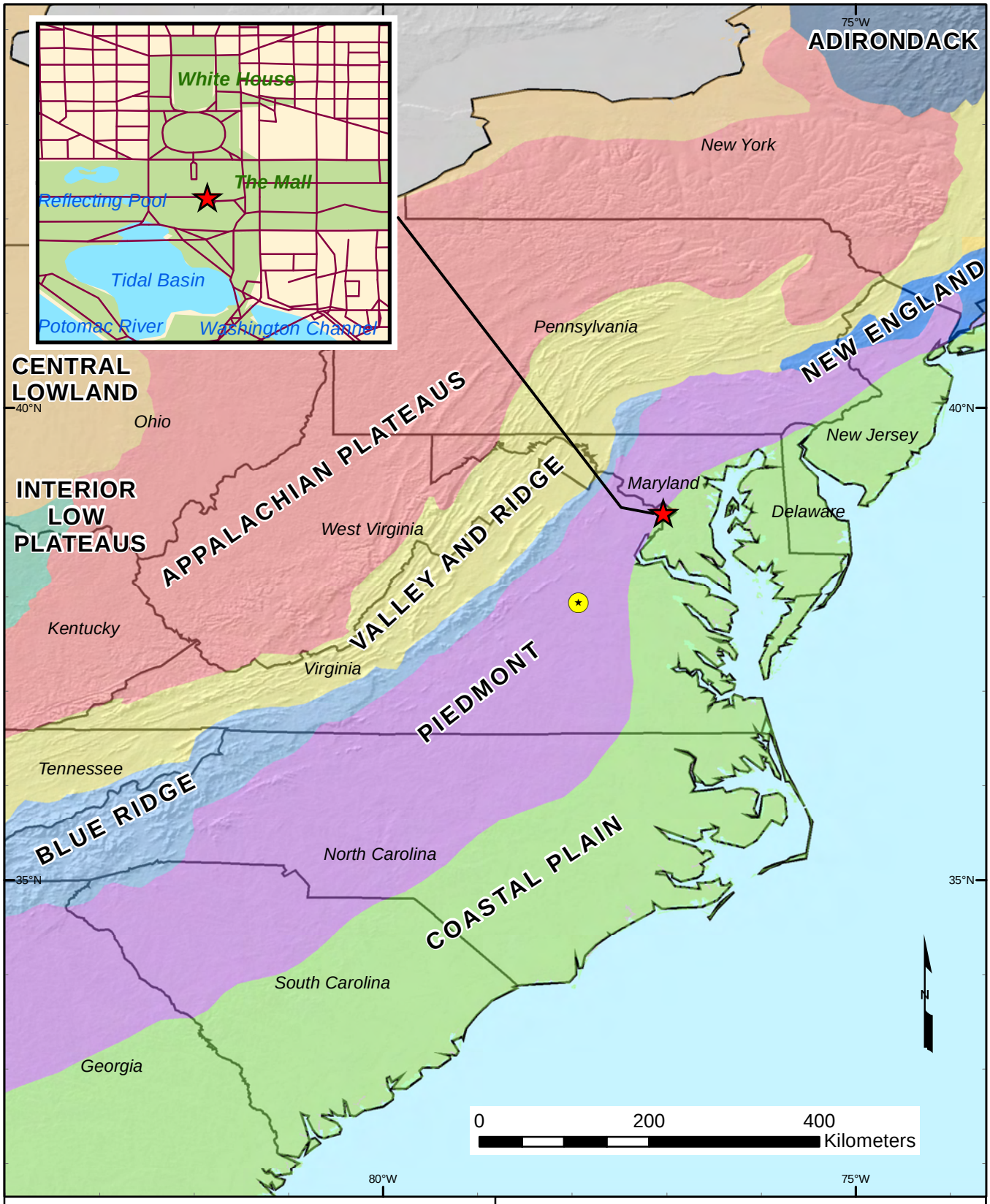
TABLE 6

TIME HISTORY RECORDINGS SELECTED FOR USE IN SITE RESPONSE ANALYSIS FOR THE MINERAL SCENARIO EARTHQUAKE SPECTRA AND THE 2,475-YEAR RETURN PERIOD UNIFORM HAZARD RESPONSE SPECTRA

Ground Motion Hazard and Geotechnical Evaluation
Washington Monument
Washington, District of Colombia

Ground Motion Scenario	Number	Earthquake Name	Year	Magnitude	Station Name	Distance (km)	Site Codes		PGA Range (g)
							GMX	USGS	
Mineral Scenario	103	N. Palm Springs	1986	6	Anza - Tule Canyon	55.4	AGA	B	0.120-0.210
Mineral Scenario	49	Saguenay	1988	5.9	ECTN:A64	99.1	-AA	-	0.013-0.014
Mineral Scenario	49	Saguenay	1988	5.9	GSC Site 8 - La Malbaie, Que	97.5	ABA	-	0.050-0.130
Mineral Scenario	49	Saguenay	1988	5.9	GSC Site 20 - Les Eboulements	95	IAA	-	0.104-0.237
Mineral Scenario	124	Georgia, USSR	1991	6.2	Ambralauri	73.7	A-A	-	0.018-0.035
Mineral Scenario	117	Whittier Narrows	1987	6	Malibu - Point Dume Sch	65.3	AMB	B	0.080-0.102
Mineral Scenario	117	Whittier Narrows	1987	6	Castaic - Old Ridge Route	78.3	A-B	B	0.067-0.127
2,475-Year RP	143	Duzce, Turkey	1999	7.1	Sakarya	42.7	--B	B	0.025-0.055
2,475-Year RP	129	Landers	1992	7.3	Villa Park - Serrano Ave #	131.4	--B	B	0.095-0.121
2,475-Year RP	141	Kocaeli, Turkey	1999	7.4	Mecidiyekoy	62.3	--B	B	0.084-0.132
2,475-Year RP	129	Chi-Chi, Taiwan	1999	7.6	HWA023	57.0	--2	A	0.072-0.073
2,475-Year RP	142	Chi-Chi, Taiwan	1999	7.6	HWA056	48.7	---	A	0.120-0.207
2,475-Year RP	142	Chi-Chi, Taiwan	1999	7.6	KAU078	102.8	--1	A	0.046-0.114
2,475-Year RP	142	Chi-Chi, Taiwan	1999	7.6	TAP060	128.4	--1	A	0.040-0.091

FIGURES



Explanation

- Site location
- 2011 Mineral Earthquake epicenter

Notes:
1.) Physiographic provinces are from Fenneman and Johnson (1946).

REGIONAL SITE LOCATION MAP SHOWING PHYSIOGRAPHIC PROVINCES
Ground Motion Hazard and Geotechnical Assessment
Washington Monument
Washington, District of Columbia

By: CJ	Date: 05/04/2012	Project No. OD12162670
amec		Figure 1

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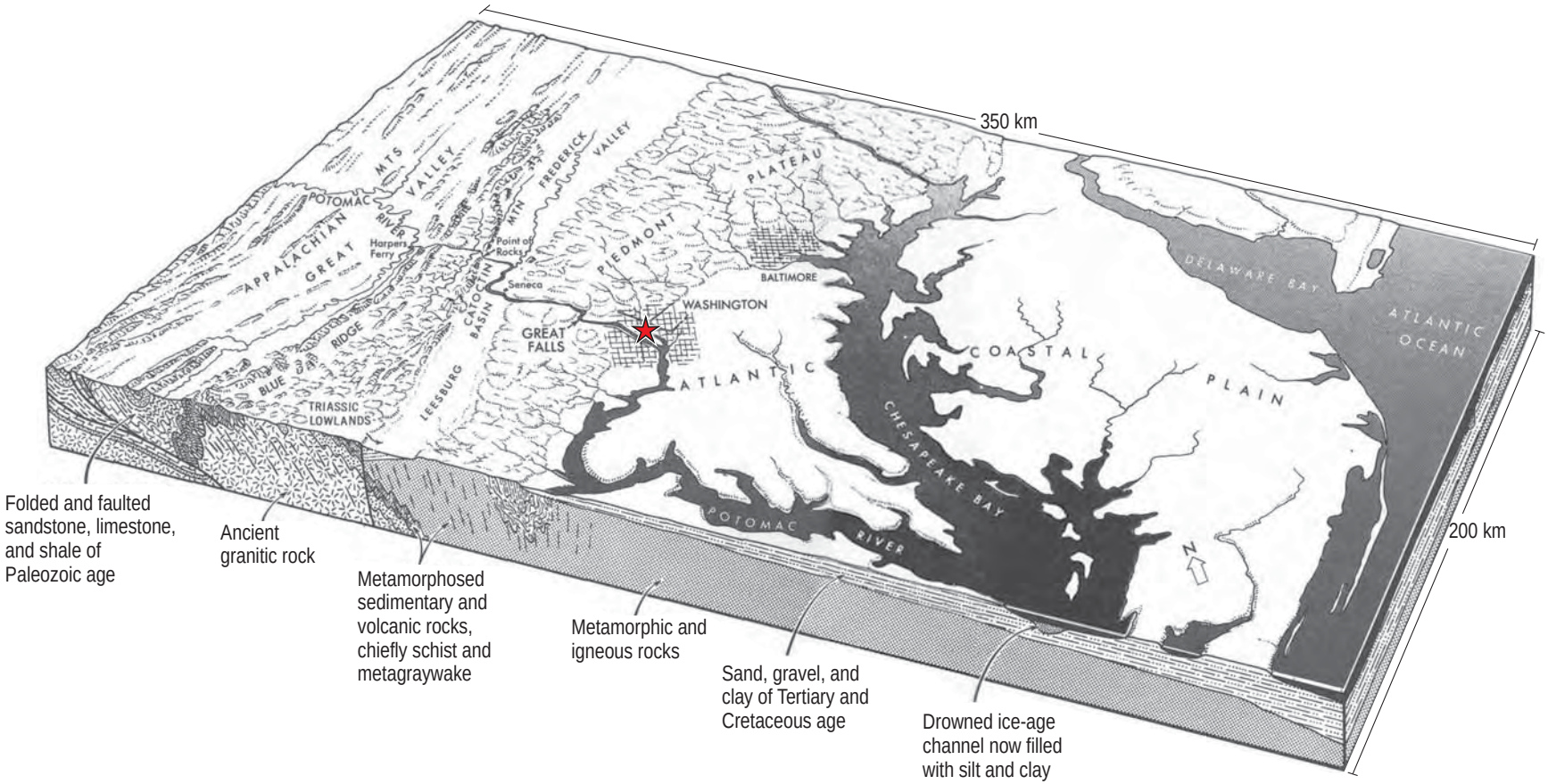

EXPLANATION

★ Washington Monument

From Reed et al. (1980)

BLOCK DIAGRAM SHOWING PHYSIOGRAPHIC PROVINCES AND GEOGRAPHIC AND GEOLOGIC FEATURES
Ground Motion Hazard and Geotechnical Assessment
Washington Monument
Washington, District of Columbia

By: DW	Date: 05/02/2012	Project No.	OD1262670
amec		Figure	2

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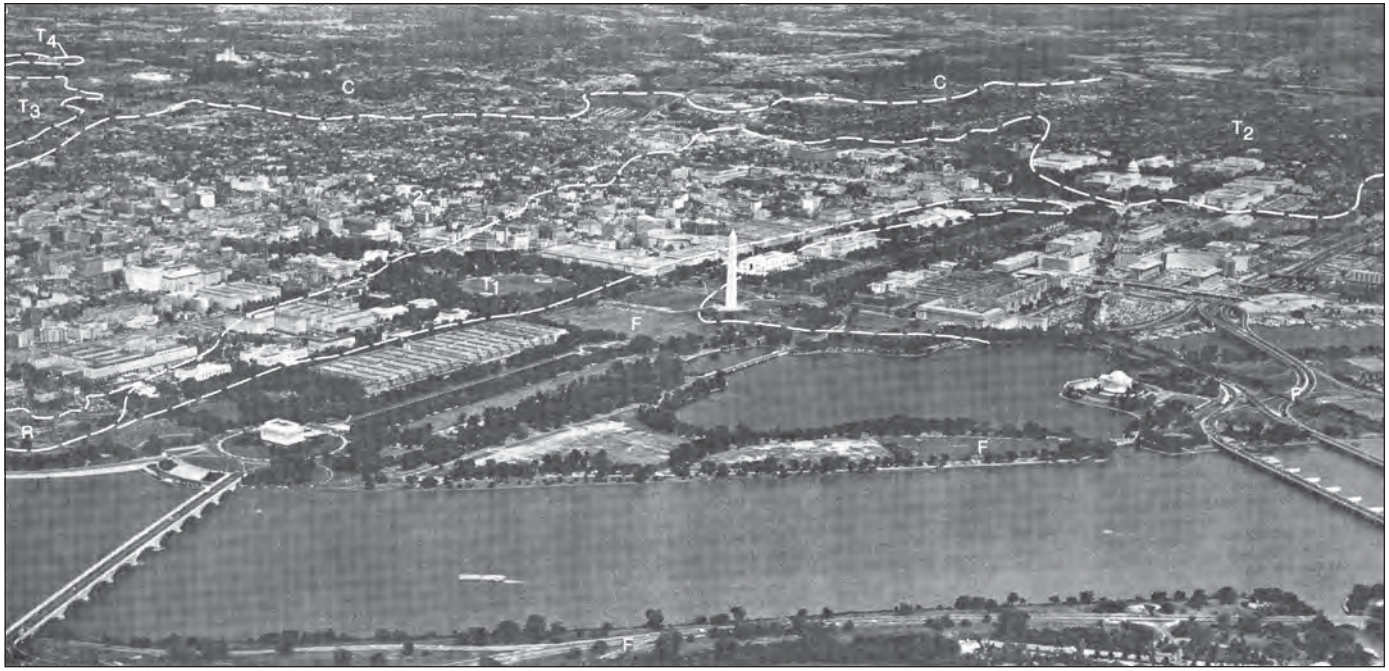

EXPLANATION

Geologic Units

F	Artificial fill
T_1, T_2, T_3, T_4	Pleistocene fluvial terraces
C	Cretaceous deposits
R	Crystalline rocks

From Reed and Obermier (1989)

OBLIQUE AERIAL VIEW OF DOWNTOWN WASHINGTON, D.C., SHOWING SURFICIAL GEOLOGIC UNITS AND GEOMORPHIC FEATURES
Ground Motion Hazard and Geotechnical Assessment
Washington Monument
Washington, District of Columbia

By: DW	Date: 05/02/2012	Project No.	OD1262670
amec		Figure	3

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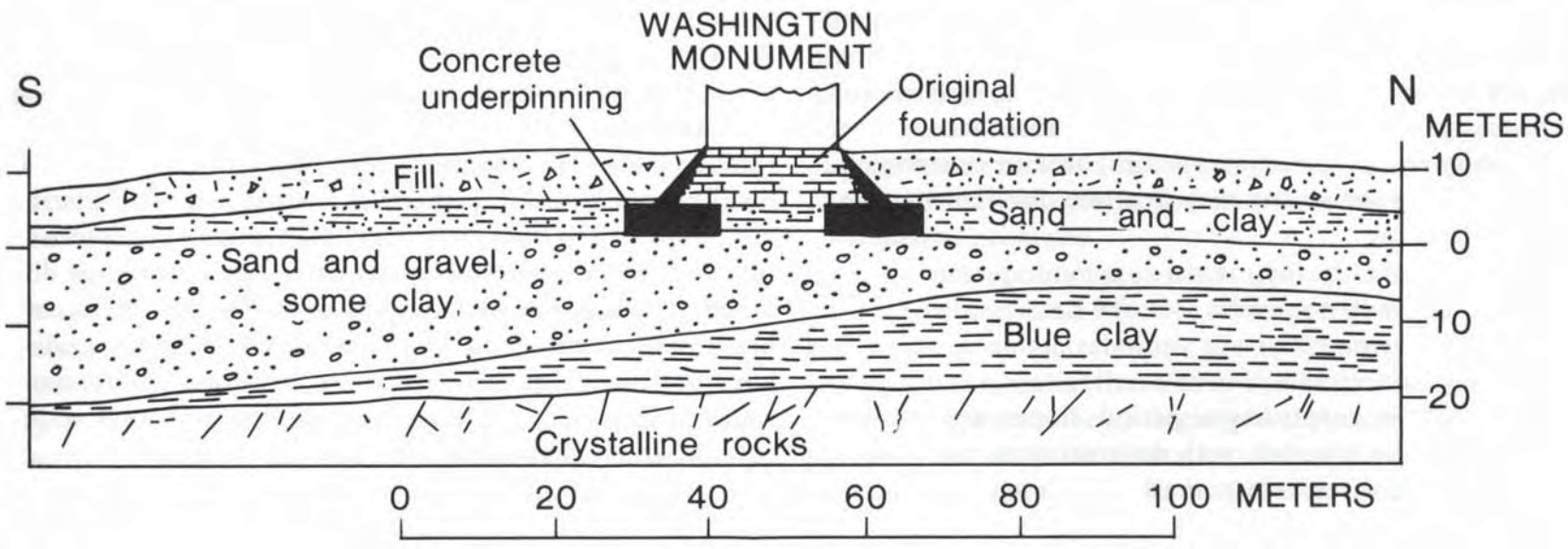

From Reed and Obermier (1989)

SCHEMATIC GEOLOGIC CROSS SECTION OF WASHINGTON MONUMENT SITE
Ground Motion Hazard and Geotechnical Assessment
Washington Monument
Washington, District of Columbia

By: DW	Date: 05/02/2012	Project No.	OD1262670
amec		Figure	4

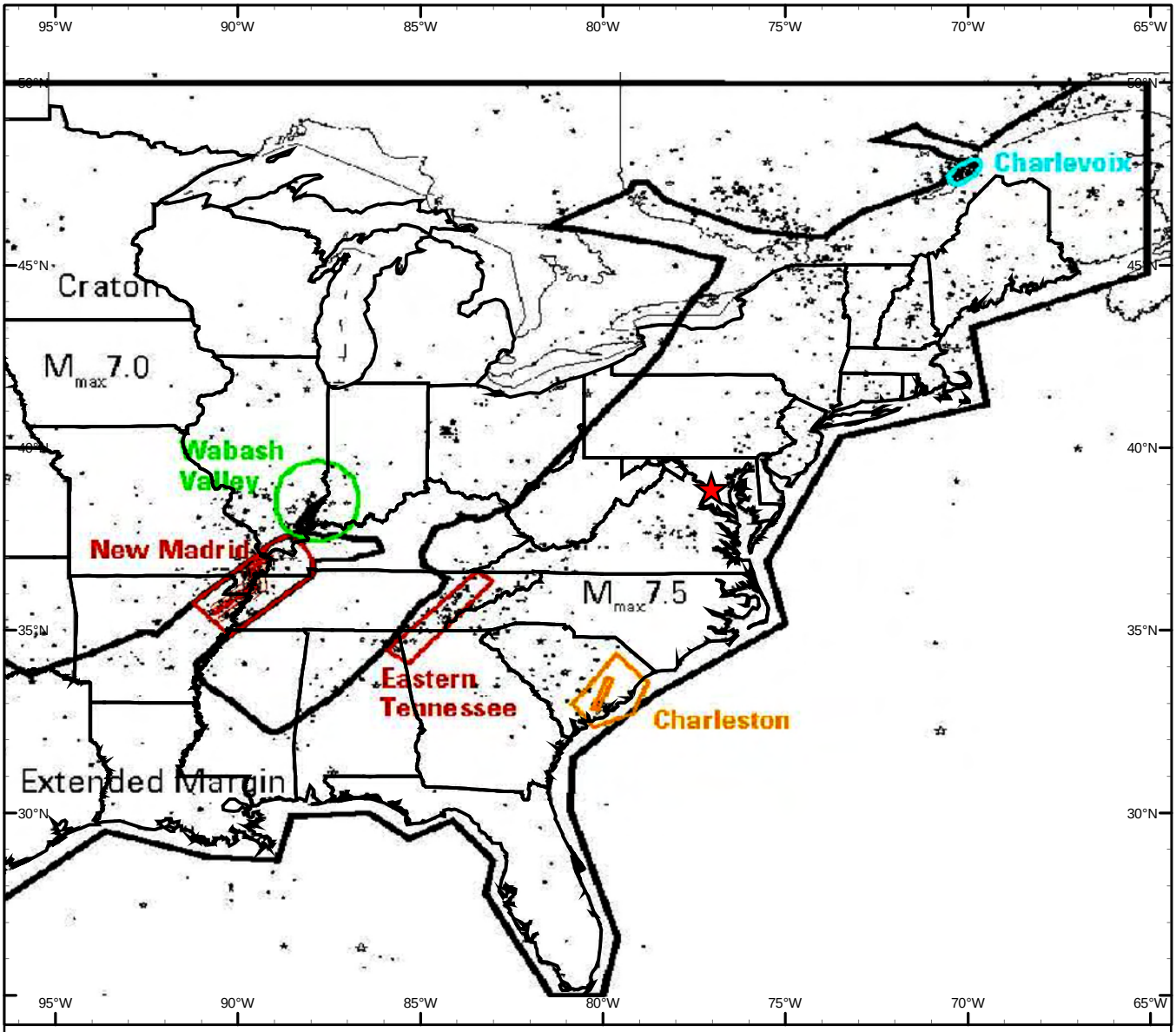

Figure from Petersen et al. (2008).

Explanation

- Site location
- Regional Mmax zone boundary
- Special zone or fault zone boundary

N

0 1,000 Kilometers

Notes:

1.) Sources used in this study are from the USGS 2008 National Seismic Hazard Mapping Project.

HISTORICAL SEISMICITY, FAULT SOURCE ZONES, AND REGIONAL MMAX ZONES FOR CENTRAL AND EASTERN U.S. USED IN THE NATIONAL SEISMIC HAZARD MAPPING PROJECT
Ground Motion Hazard and Geotechnical Assessment
Washington Monument
Washington, District of Columbia

By: CJ	Date: 05/29/2012	Project No. OD12162670
amec		Figure 5

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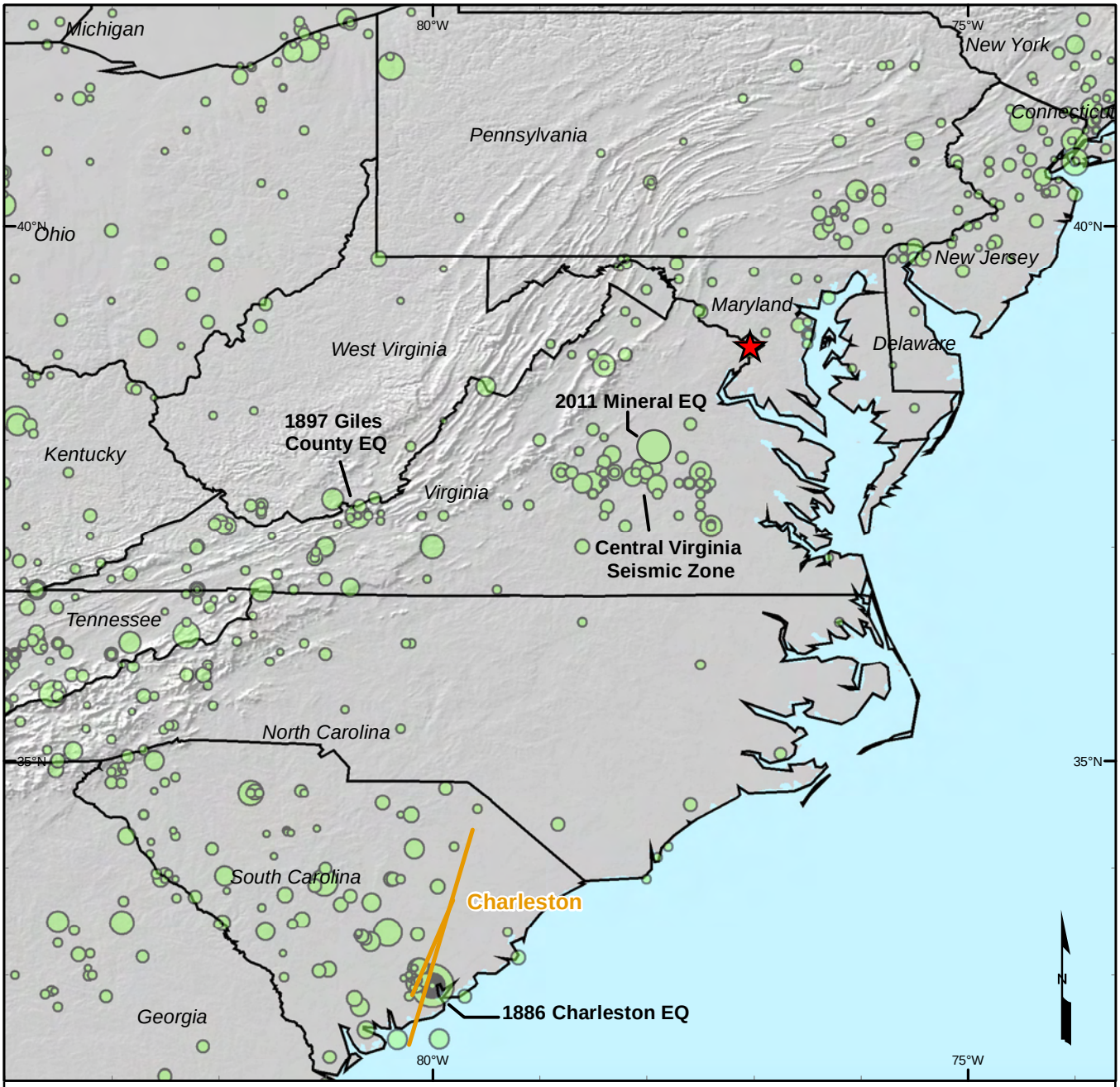

Explanation

Site location

Charleston fault sources used in this study

Independent Seismicity
(1534-2006)
Magnitude (M)

3.0
4.0
5.0
6.0
7.0

0 200 400 Kilometers

Notes:
1.) Charleston faults are modified from the USGS NSHMP (Petersen et al., 2008).
2). Seismicity from USGS NSHMP (Petersen et al., 2008).
3). 2011 Mineral Earthquake location from USGS (2011).

INDEPENDENT SEISMICITY AND FAULT SOURCE ZONE USED IN THE SEISMIC HAZARD ANALYSIS
Ground Motion Hazard and Geotechnical Assessment
Washington Monument
Washington, District of Columbia

By: CJ	Date: 05/04/2012	Project No. OD12162670
amec		Figure 6

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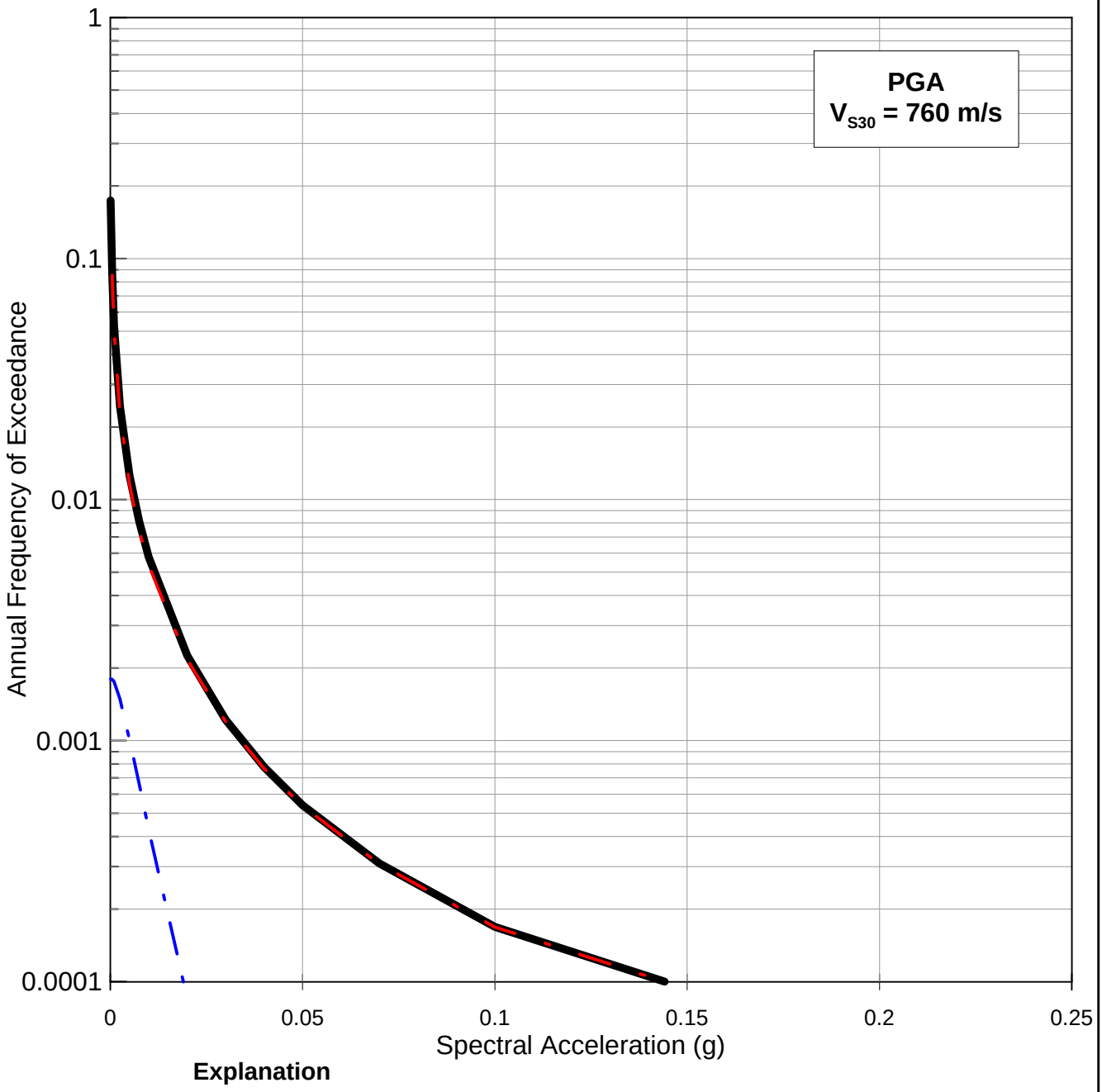

PROBABILISTIC SEISMIC HAZARD ANALYSIS (PSHA)
RESULTS AT PEAK GROUND ACCELERATION
Ground Motion Hazard and Geotechnical Assessment
Washington Monument
Washington, District of Colombia

By: DG	Date: 4/23/2012	Project No. OD12162670
amec		Figure **7**

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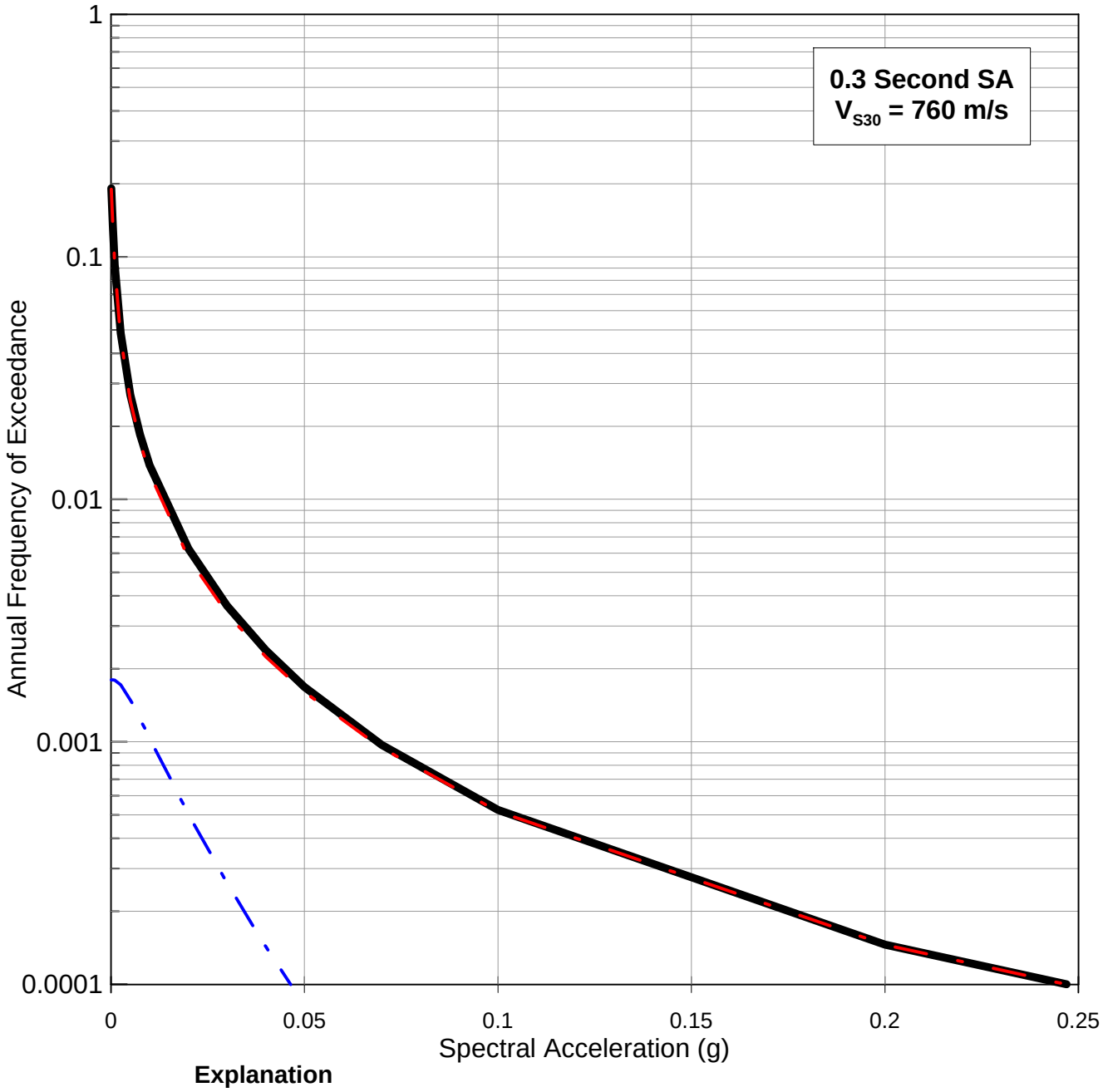

PROBABILISTIC SEISMIC HAZARD ANALYSIS (PSHA)
RESULTS AT A PERIOD OF 0.3 SECONDS
Ground Motion Hazard and Geotechnical Assessment
Washington Monument
Washington, District of Colombia

By: DG	Date: 4/23/2012	Project No. OD12162670
amec		Figure **8**

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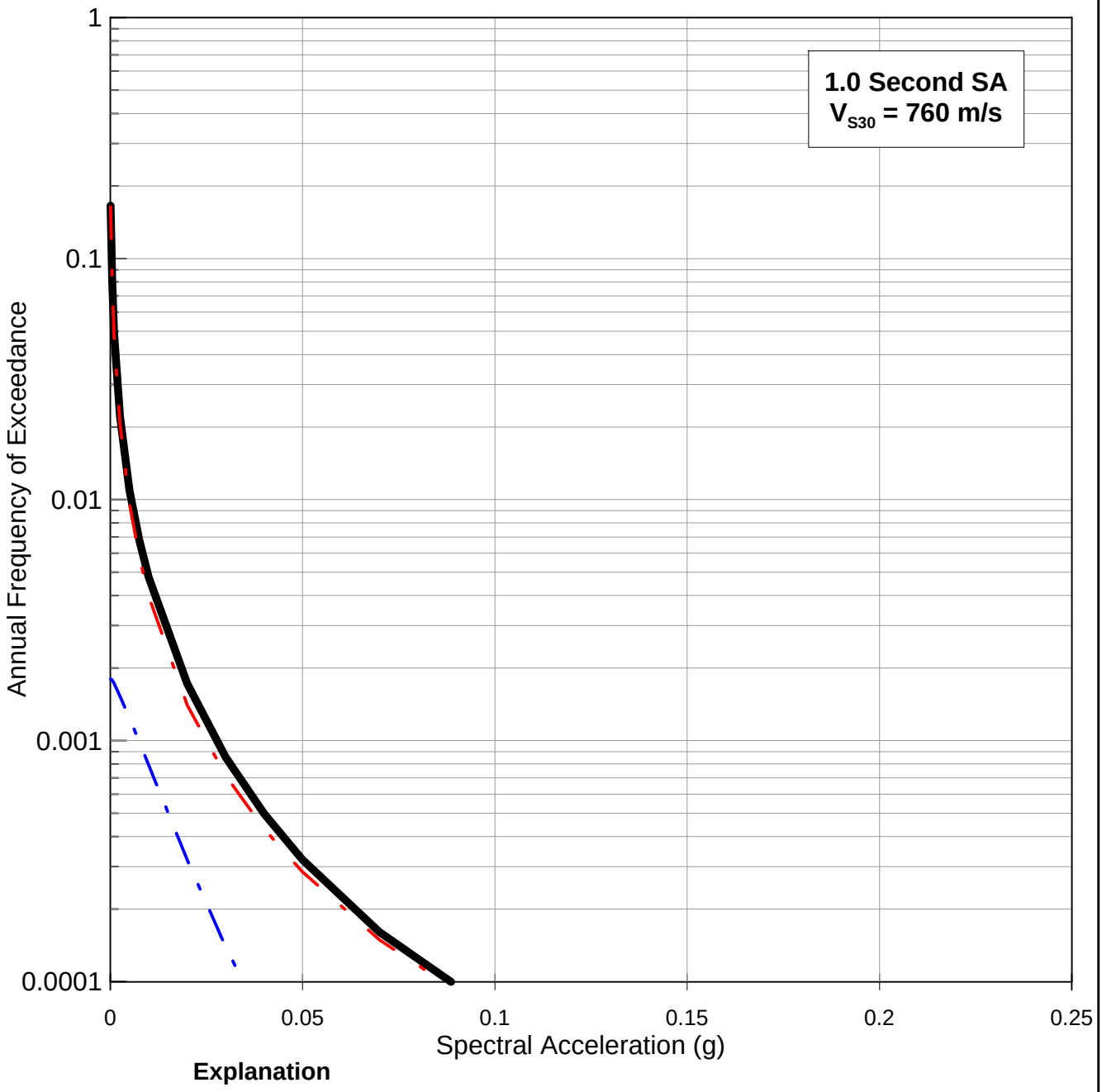

PROBABILISTIC SEISMIC HAZARD ANALYSIS (PSHA)
RESULTS AT A PERIOD OF 1.0 SECOND
Ground Motion Hazard and Geotechnical Assessment
Washington Monument
Washington, District of Colombia

By: DG	Date: 4/23/2012	Project No. OD12162670
amec		Figure **9**

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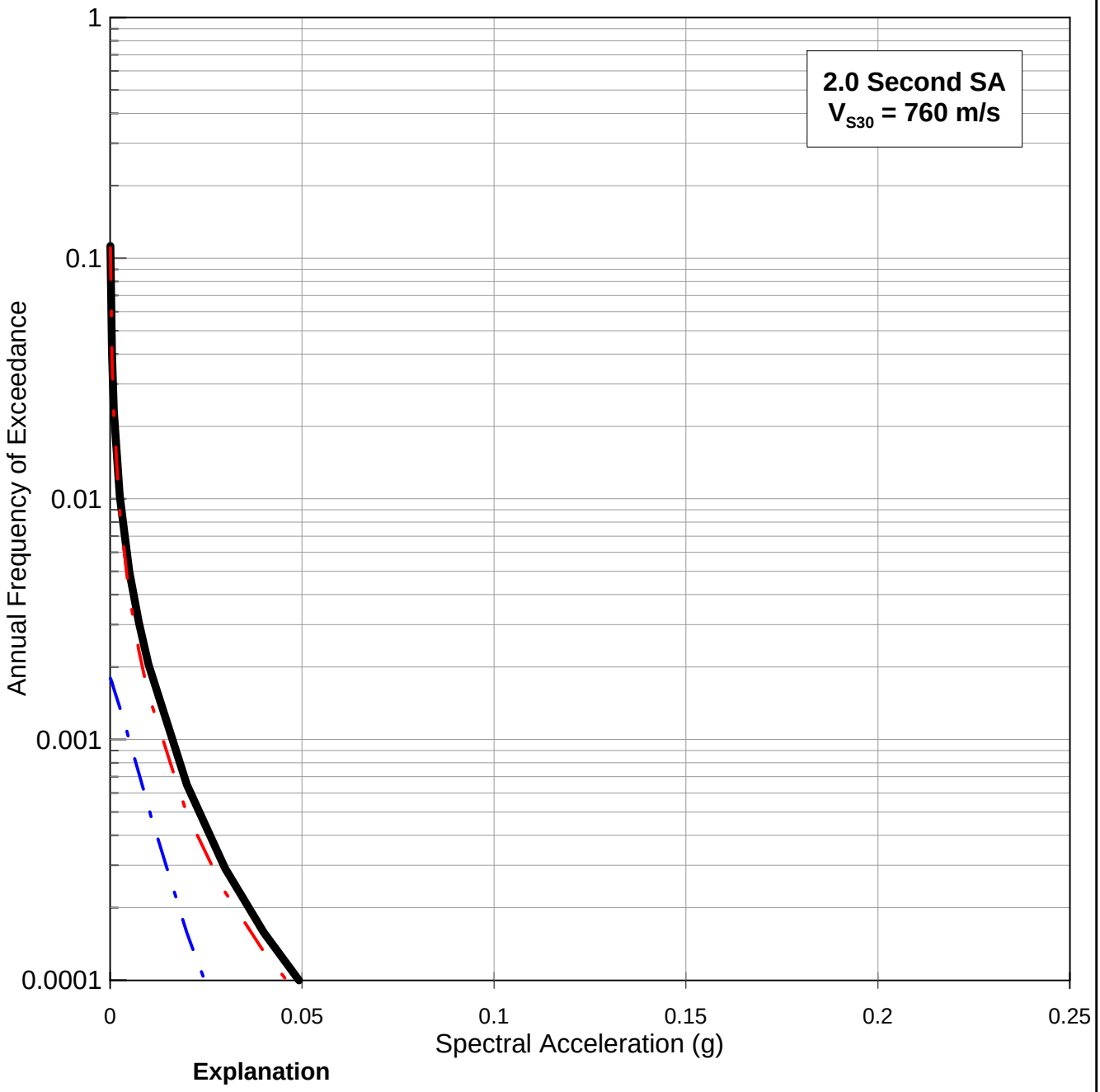

PROBABILISTIC SEISMIC HAZARD ANALYSIS (PSHA)
RESULTS AT A PERIOD OF 2.0 SECONDS
Ground Motion Hazard and Geotechnical Assessment
Washington Monument
Washington, District of Colombia

By: DG	Date: 4/23/2012	Project No. OD12162670
amec		Figure **10**

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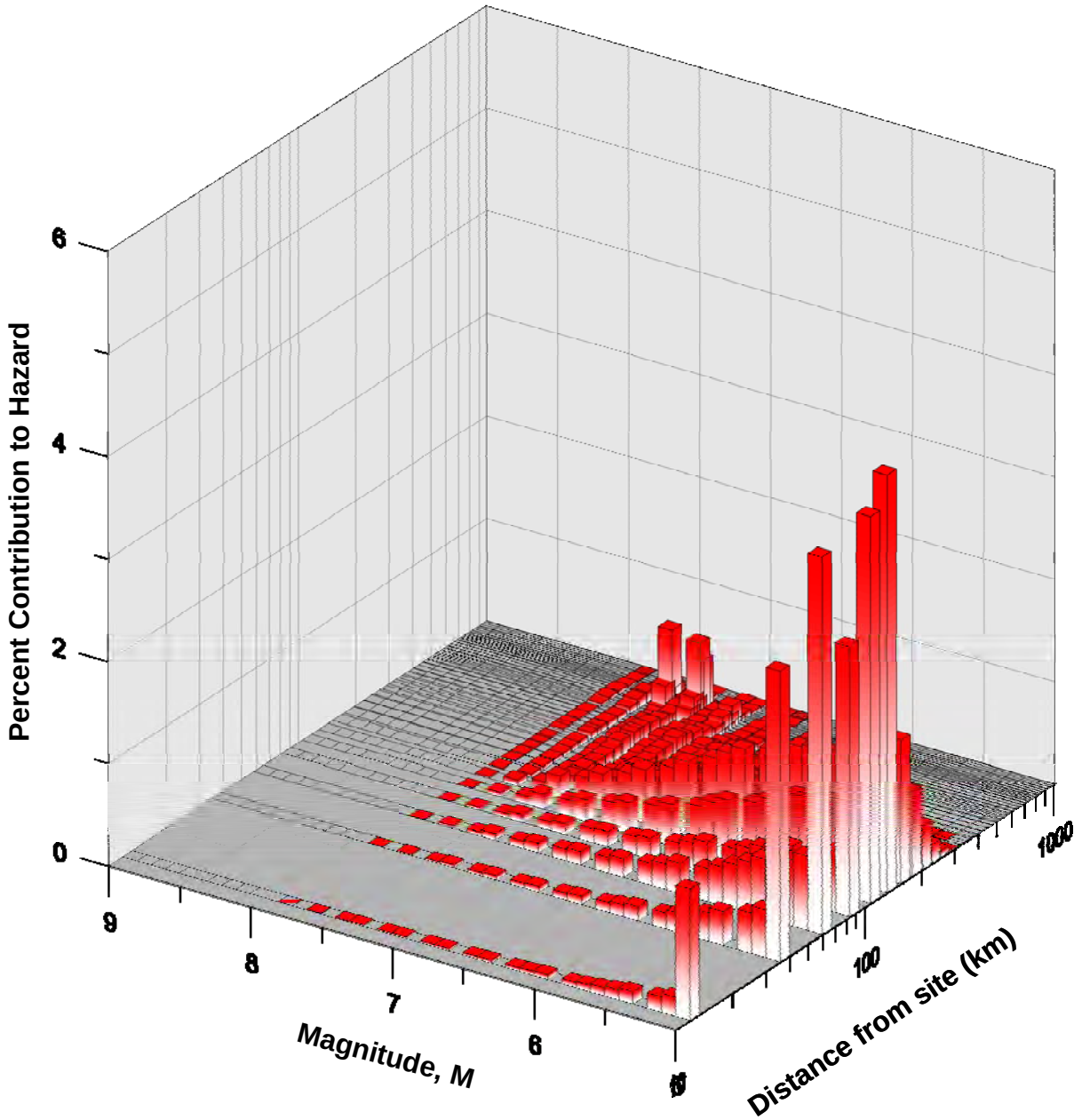
PGA, 475-YR RP
V_{S30} = 760 m/s



DEAGGREGATION OF PEAK GROUND ACCELERATION HAZARD FOR A 475-YEAR RETURN PERIOD
Ground Motion Hazard and Geotechnical Assessment
Washington Monument
Washington, District of Colombia

By: DG	Date: 4/23/2012	Project No. OD12162670
amec		Figure **11a**

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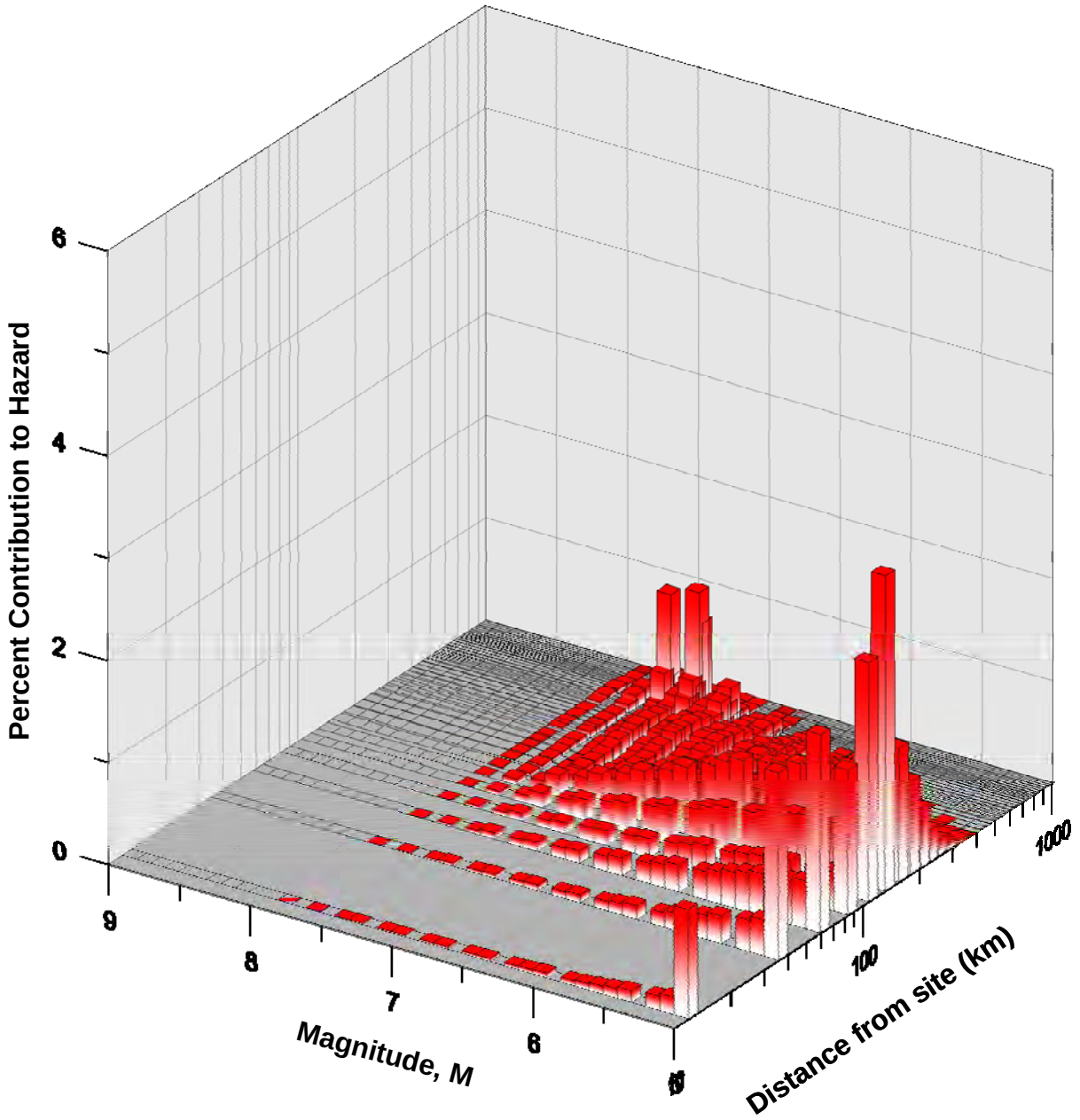
0.3 Second, 475-YR RP
V_{S30} = 760 m/s



DEAGGREGATION OF 0.3 SECOND SPECTRAL ACCELERATION FOR A 475-YEAR RETURN PERIOD
Ground Motion Hazard and Geotechnical Assessment
Washington Monument
Washington, District of Colombia

By: DG	Date: 4/23/2012	Project No. OD12162670
amec		Figure **11b**

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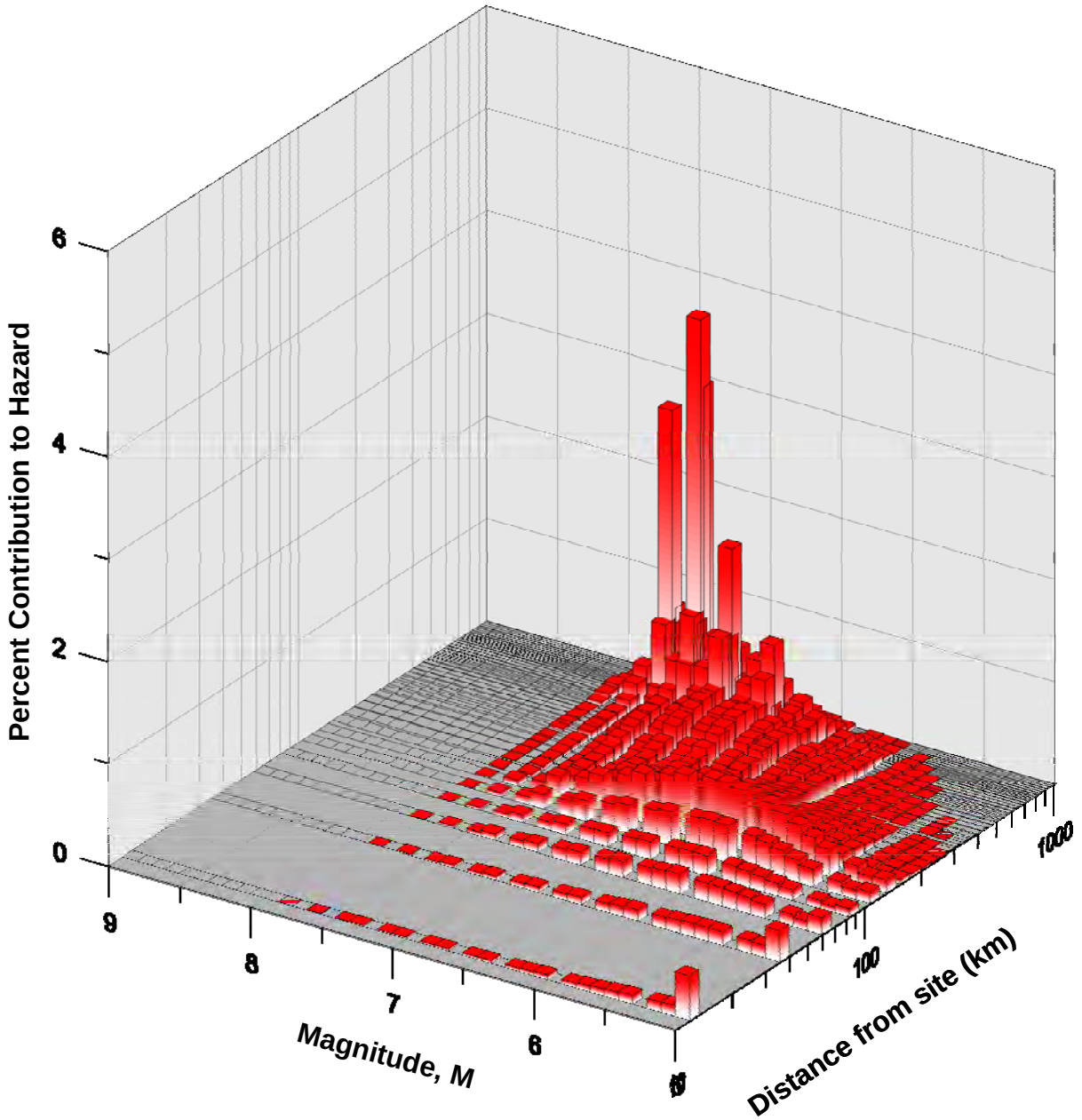
1.0 Second, 475-YR RP
V_{S30} = 760 m/s



DEAGGREGATION OF 1.0 SECOND
SPECTRAL ACCELERATION FOR A
475-YEAR RETURN PERIOD
Ground Motion Hazard and Geotechnical Assessment
Washington Monument
Washington, District of Colombia

By: DG	Date: 4/23/2012	Project No. OD12162670
amec		Figure **11c**

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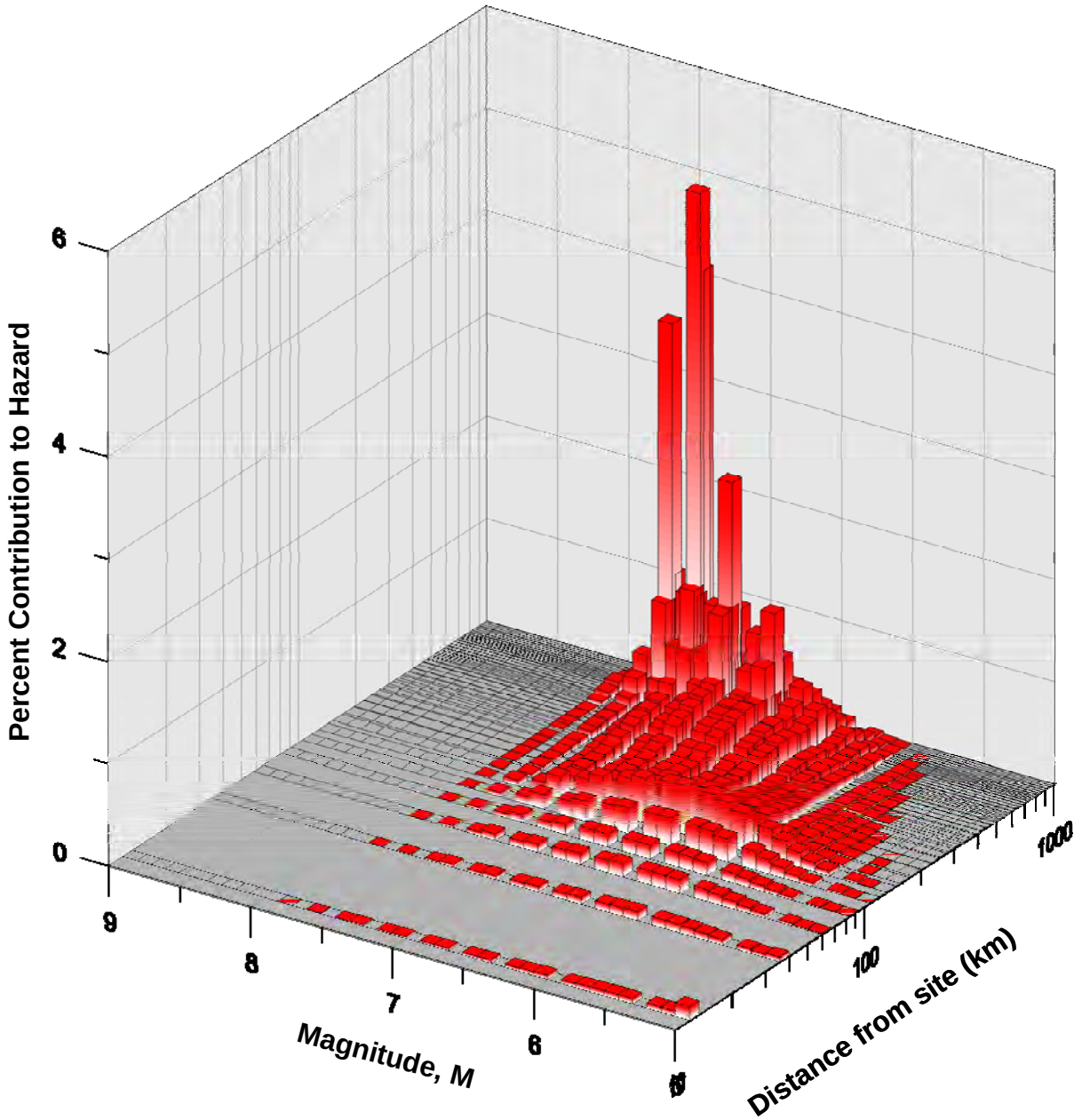
2.0 Second SA, 475-YR RP
V_{S30} = 760 m/s



DEAGGREGATION OF 2.0 SECOND
SPECTRAL ACCELERATION FOR A
475-YEAR RETURN PERIOD
Ground Motion Hazard and Geotechnical Assessment
Washington Monument
Washington, District of Colombia

By: DG	Date: 4/23/2012	Project No. OD12162670
amec		Figure **11d**

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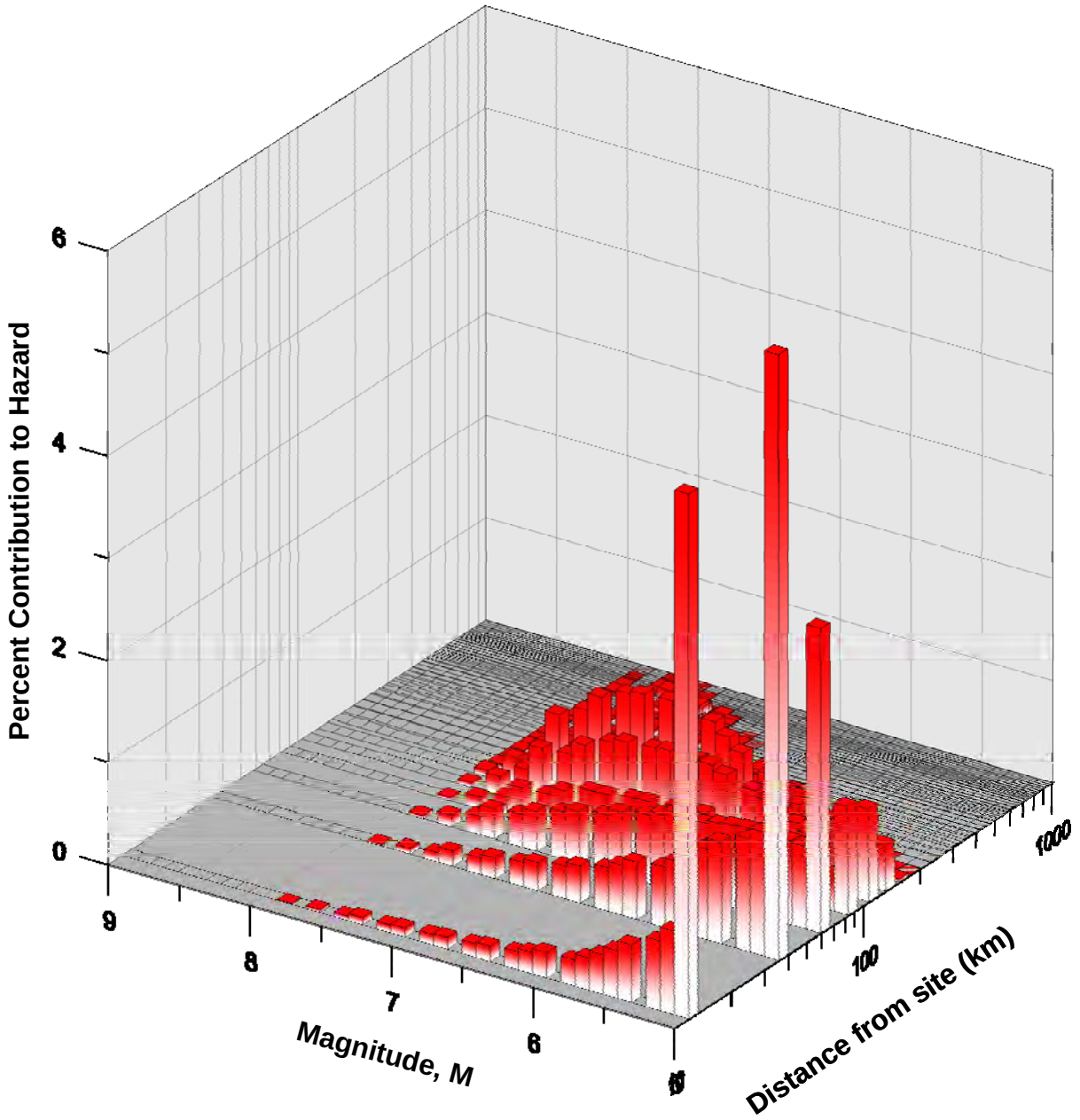
PGA, 2,475-YR RP
V_{S30} = 760 m/s



DEAGGREGATION OF PEAK GROUND ACCELERATION HAZARD FOR A 2,475-YEAR RETURN PERIOD
Ground Motion Hazard and Geotechnical Assessment
Washington Monument
Washington, District of Colombia

By: DG	Date: 4/23/2012	Project No. OD12162670
amec		Figure **11e**

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