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February 2008

Supplemental Earthquake Ground Motion Input for a Geologic Repository at Yucca Mountain, NV

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Supplemental Earthquake Ground Motion Input for a Geologic Repository at Yucca Mountain, NV

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Model Signature Page/Change History,

Complete only applicable items.

2. **Type** of **Mathematical** Model

☒ Process Model ☐ Abstraction Model ☐ **System** Model

Describe Intended Use of **Model**

The RVT site response model and the stochastic point-source ground motion model were used to develop supplemental ground motion input for seismic design of the repository block and surface facilities area at Yucca Mountain.

3. Title

Supplemental Earthquake Ground Motion input for a Geologic Repository at Yucca Mountain. NV

4. DI (Including Rev. No.):

MDL-MGR-GS-000007 REV 00

	Printed Name	Signature	Date
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11. Remarks

Limitations: There are no limitations on the use of the stochastic point-source ground motion model documented in this report. Model limitations, which do not affect the model's use, are addressed in Section 6.3.10. Model assumptions, idealizations, and simplifications are discussed in Section 6.3.5.

As described in Section 8, the annual frequencies of exceedance for uniform hazard spectra (UHS) at periods greater than 2 sec are greater than their nominal values. Design response spectra based on the UHS, and time histories spectrally matched to the design response spectra, are similarly affected. Users of these outputs should take this limitation into account when deciding if the outputs are adequate for a given intended use.

Change History

12. Revision No.	13. Description of Change
00	Initial issue.

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The following individuals, listed alphabetically, provided significant technical contribution to the development and review of this document: Ann Becker, Jacqueline Bott, Kevin Coppersmith, Mark Dober, Robert Green, Nicholas Gregor, Gerard Heaney, Meghan Koch, Ram Kulkarni, Maurice LaFountain, Chaiwat Law Pattanapong, Melinda Lee, Richard Lee, Segaran Logeswaran, Danielle Lowenthal-Savy, Susan Olig, Richard Quittmeyer, Laura Russon, Walter Silva, Niels Sorensen, Kenneth Stokoe, Fabia Terra, Patricia Thomas, Christian Torres, Shobhna Upadhyaya, Chi-Wah Wong, Ivan Wong, and Bob Youngs. The co-Principal Investigators, Ivan Wong and Walter Silva, participated in all aspects of the analyses. Mark Dober, Chaiwat Law Pattanapong, Nicholas Gregor, Jacqueline Bott, Fabia Terra, and Shobhna Upadhyaya performed the ground motion calculations. Richard Lee led a series of workshops to support conditioning of extreme ground motions. Ann Becker, Jacqueline Bott, and Richard Lee assisted in the model validation. Shobhna Upadhyaya and Kenneth Stokoe, with assistance from Ram Kulkarni and Chi-Wah Wong, evaluated the velocity data. Nicholas Gregor assisted in the development of software. Susan Olig managed the software quality assurance aspects for the study and Ann Becker, Laura Russon, Segaran Logeswaran, Danielle Lowenthal-Savy, and Shobhna Upadhyaya performed the software validation. Richard Quittmeyer assisted in the writing of the AMR. Melinda Lee assisted in the preparation of the report. Bob Youngs, Gerard Heaney, Meghan Koch, Maurice LaFountain, Niels Sorensen, Christian Torres, and Kevin Coppersmith performed the checking of the report. Our sincere appreciation to Debra Nevergold, James Whitcraft, and Richard Quittmeyer for their management of the Project and Edward Miller, Midge Simpson, and Marina Meier for software support.

EXECUTIVE SUMMARY

This report describes models and analyses used to develop ground motion inputs for the proposed geologic repository at Yucca Mountain, Nevada. These new ground motion inputs supplement those described in *Development of Earthquake Ground Motion Input for Preclosure Seismic Design and Postclosure Performance Assessment of a Geologic Repository at Yucca Mountain, Nevada* (BSC 2004 [DIRS 170027]). These ground motions are based on updated inputs to the ground motion site-response model and on an alternate approach to that used previously for incorporating the site response in developing ground motion inputs. The ground motion inputs also reflect new information on the characterization of extreme ground motions that can occur at Yucca Mountain. Specific objectives of this study are:

- For ground motion annual frequencies of exceedance (AFE) appropriate for preclosure design analyses, calculate hazard-consistent site-specific seismic design acceleration response spectra for a range of damping values; strain-compatible soil properties; and time histories (acceleration, velocity, and displacement). Provide seismic design inputs for the Repository Block waste emplacement level (RB) and for the Surface Facilities Area (SFA).

- For probabilistic analyses supporting the demonstration of compliance with preclosure performance objectives, provide mean seismic hazard curve for the SFA and RB. The results should reflect, as appropriate, available knowledge on the characterization of extreme ground motions that could occur at Yucca Mountain.

In these analyses, a random-vibration-theory-based equivalent-linear site-response model and a stochastic point-source ground motion model have been utilized. The purpose of the site-response model is to incorporate the effects of the local rock and soil conditions at the SFA and RB on earthquake ground motions. The model and its validation were described in BSC 2004 ([DIRS 170027]).

The stochastic point-source ground motion model is used to calculate ground motions based on properties of the earthquake source, propagation path, and site. This model is used in conjunction with the site-response model to evaluate the V/H (vertical to horizontal) ratios of ground motions. The model is also used to estimate extreme ground motions from earthquakes that can occur at Yucca Mountain. By assessing a distribution of extreme stress drops reasonably associated with such earthquakes, the model is used to characterize the probabilities that extreme ground motions can occur. This result is used to condition the probabilistic seismic hazard analysis (PSHA) ground motion hazard results for use in developing site-specific ground motions for the SFA and RB. The description and validation of the stochastic point-source ground motion model is contained in this report. In addition, this report also describes the use of these models, the model results, and the development of ground motion inputs based on these results.

Geological/geotechnical inputs to the site-response ground motion model include small-strain seismic velocities, densities, and nonlinear dynamic material properties. The velocity profiles and dynamic material property curves were developed based upon a geotechnical, geological, and geophysical program performed in 2000 to 2001 and additional data collected in a 2004 to

2005 field program. Velocity data were acquired using downhole and suspension logging techniques in boreholes and spectral-analysis-of-surface-waves (SASW) surveys. Dynamic laboratory testing using resonant column and torsional shear were performed on samples from the RB and SFA in 2000 and 2001.

For the RB, two base case shear-wave and compressional-wave velocity profiles are used to represent the variability in mean velocities observed in the data, which indicate both "soft" and "stiff" zones exist at Yucca Mountain. For the SFA, a single base case profile for both shear-wave and compressional-wave velocity is used for the area northeast of and three base case profiles for the area south of the Exile Hill fault splay. To accommodate the effect of the varying thickness of alluvium, site-response modeling was carried out for multiple values of alluvium thickness. For the area represented by the Northeast-of-the-Fault tuff velocity profile, alluvium thickness values of 30, 70, 100, and 200 ft were used. For the area represented by the South-of–the-Fault tuff velocity profiles, thickness values of 30, 70, and 100 ft were used. The base case profiles are used, along with information on the statistical correlation of layer thicknesses and layer velocities, to develop a suite of random velocity profiles that are used as model input.

Similarly for the nonlinear dynamic properties of site materials, multiple base case curves of normalized shear modulus and damping, as a function of cyclic shear strain, are developed to represent uncertainty in the mean values of these properties. Two sets of curves are developed for the tuff and two sets for alluvium at the site. In addition, adjustments to the curves are made as a function of depth to represent the effect of confining pressure on the materials. For input to the site response model, the mean curves for all materials are used as a basis to create randomized curves representing variability in properties across the site.

The starting point for the site response modeling is the output of the PSHA, which was calculated for a reference hard rock outcrop. As a result of the large epistemic uncertainty in PSHA estimates of median motions as well as untruncated aleatory variabilities about median estimates, PSHA results for extreme ground motions yield AFEs > 10^{-8}. Recent analyses and assessments indicate such results are inconsistent with the geologic setting at Yucca Mountain. One analysis made use of geological observations in underground excavations at Yucca Mountain, laboratory rock testing, numerical simulations of rock mass deformation, and site response modeling to estimate a level of peak horizontal ground velocity (PGV) that had not been exceeded in 12.8 million years. This nonexceedance observation over 10^{-7} yrs was used to condition the repository level PGV hazard curve to an AFE of 10^{-8}. In an effort to refine the earlier analysis, the present study used both the site nonexceedance observations, updated to reflect current site response model inputs, as well as an assessment (probability distribution) of extreme source processes. In the current hazard curve conditioning, revised reference hard rock outcrop horizontal hazard curves were developed for all structural frequencies considered in the original PSHA (CRWMS M&O 1998 [DIRS 103731]), as well as horizontal- and vertical-component PGV. The conditioned reference rock outcrop hazard curves were then used to develop horizontal and vertical ground motions for the RB and SFA.

Approach 3 as defined in NUREG/CR-6728 (McGuire et al. 2001 [DIRS 157510]) was used in developing hazard-consistent site-specific ground motions for the SFA and RB. Deaggregation of the PSHA results to identify controlling earthquakes for structural frequency ranges of 1 to 2 Hz and at 5 to 10 Hz (BSC 2004 [DIRS 170027]) was used to develop input for site response modeling. Response spectra for appropriate controlling earthquakes were scaled to PGA values ranging from 0.1 to 10 g. These response spectra form the basis for development of a database of site transfer functions that are used in determining the site-specific ground motions.

In implementing Approach 3 using the full integration method, the following steps were taken: 1) base case mean site properties were used to produce a randomized suite of velocity profiles as well as G/Gmax and hysteretic damping curves that are used to incorporate site variability in site response modeling; 2) transfer functions (amplification factors for horizontal motions and V/H ratios for vertical motions) were computed using the RVT-based equivalent-linear site response model; 3) the conditioned PSHA reference rock outcrop fractile and mean hazard curves were integrated with the transfer functions to arrive at a distribution of site-specific horizontal and vertical hazard curves; and 4) site-specific UHS were computed.

Based on Approach 3, hazard-consistent site-specific design ground motion inputs for preclosure analyses were determined for the RB waste emplacement drifts (about 335 m depth). Preclosure inputs also were determined for the SFA. Two design basis ground motion levels (DBGM-1 and DBGM-2) are used. DBGM-1 has a mean AFE of $1x10^{-3}$, while DBGM-2 has a mean AFE of $5x10^{-4}$. For beyond-design-basis ground motion (BDBGM) analyses and fragility analyses ground motions with a mean AFE of $1x10^{-4}$ are developed. For preclosure seismic safety analyses, the site-specific hazard curves and associated UHS from Steps 3 and 4 above are used. Thus, in this report, ground motions for design analyses (response spectra, time histories, and strain-compatible material properties) are presented for AFE of 10^{-3}, $5x10^{-4}$, and 10^{-4}. Hazard curves and associated UHS are presented for AFEs from 10^{-3} to 10^{-7} for the SFA and from 10^{-3} to 10^{-8} for the RB. Key results and products of this study are listed in Table E-1.

Note that in computing the UHS, spectral acceleration (SA) for a period of 3.3 sec was inadvertently used for a period of 3.0 sec. Thus, for periods greater than 2.0 sec the UHS has lower SA (higher AFE) than intended. Users of these data should take into account this limitation when deciding whether the data are adequate for an intended use. Design response spectra based on the UHS and time histories spectrally matched to design response spectra have the same limitation.

Table E-1. Preclosure Seismic Ground Motions for Design Analyses

Annual Frequency of Exceedance	Site	Design Response Spectra	Time Histories	PGA (g)		10 Hz SA (g)		1 Hz SA (g)		PGV (cm/sec)	
				H	V	H	V	H	V	H	V
10^{-3}	SFA	Horizontal and Vertical	5 three-component sets spectrally matched	0.33	0.22	0.82	0.55	0.29	0.15	23.19	—
5×10^{-4}	SFA	Horizontal and Vertical	5 three-component sets spectrally matched	0.45	0.32	1.17	0.86	0.43	0.23	34.13	—
10^{-4}	SFA	Horizontal and Vertical	5 three-component set spectrally matched	0.91	0.72	2.40	2.22	0.96	0.52	74.13	—
10^{-3}	RB EL	Horizontal and Vertical	1 three-component set spectrally matched	0.12	0.07	0.27	0.14	0.10	0.082	13.48	6.96
5×10^{-4}	RB EL	Horizontal and Vertical	1 three-component set spectrally matched	0.17	0.12	0.39	0.23	0.15	0.12	19.54	10.10
10^{-4}	RB EL	Horizontal and Vertical	1 three-component set spectrally matched	0.37	0.32	0.84	0.59	0.30	0.25	41.40	21.51
Seismic hazard curves for the SFA: Horizontal and vertical SA at 0.3, 0.5, 1, 5, 10, 20, and 100 Hz (PGA), Horizontal PGV											
Seismic hazard curves for the RB EL: Horizontal and vertical SA at 0.3, 0.5, 1, 5, 10, 20, and 100 Hz (PGA), PGV											

NOTES: PGA = peak ground acceleration
PGV = peak ground velocity
SA = spectral acceleration
RB EL = Repository block emplacement level
SFA = Surface facilities area
H, V = Horizontal, vertical

CONTENTS

Page

CONTENTS (Continued)

Page

CONTENTS (Continued)

Page

CONTENTS (Continued)

Page

FIGURES

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

FIGURES (Continued)

Page

TABLES

TABLES (Continued)

Page

TABLES (Continued)

Page

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

1D, 2D, 3D	one-, two-, three-dimensional
AFE	annual frequencies of exceedance
ACC	Accession Number
BDBGM	beyond design basis ground motion
BSC	Bechtel-SAIC Company, LLC
CEUS	central and eastern U.S.
CFR	Code of Federal Regulations
cm	centimeter(s)
COTS	commercial-off-the-shelf
COV	coefficient of variation
CRWMS M&O	Civilian Radioactive Waste Management System Management and Operating (Contractor)
D	
DBGM	Design Basis Ground Motion
DIR	Document Input Reference (sheet)
DOE	U.S. Department of Energy
DTN	Data Tracking Number
ECRB	enhanced characterization of the Repository Block
ε	number of standard deviations above the mean ground motion
EPRI	Electric Power Research Institute
ESF	Exploratory Studies Facility
FEMA	Federal Emergency Management Agency
FEPs	features, events, and processes
ft	feet
ft/sec	feet per second
g	gravitational acceleration (980 cm/sec^2) or gram(s)
g/cm^3	
G	shear modulus
GFM	Geologic Framework Model
G_{max}	low-strain (maximum) shear modulus
Hz	Hertz
IED	Interface Engineering Drawing
κ	kappa
km	kilometer
LBNL	Lawrence Berkeley National Laboratory
LMA	lower mean alluvium (curve)

ACRONYMS, ABBREVIATIONS, AND SYMBOLS (Continued)

LMT	lower mean tuff (curve)
m	meter(s)
mi	mile(s)
M	moment magnitude
NRC	U.S. Nuclear Regulatory Commission
NWTRB	Nuclear Waste Technical Review Board
σ	standard deviation
P	compression (wave)
PA	performance assessment
pcf	pounds per cubic foot
PE&A	Pacific Engineering and Analysis
PGA	peak ground acceleration
PGD	
PGV	peak ground velocity
PSHA	probabilistic seismic hazard analysis
PSRV	pseudo-velocity response spectrum
PSV	pseudo-velocity
QA	quality assurance
QARD	Quality Assurance Requirements and Description
QEMM	Quarterdeck Extended Memory Manager
Q(f)	frequency-independent damping
R	rupture distance
RB	Repository Block
RE	reference earthquake
REI	Risk Engineering Incorporated
RMS	root-mean-square
RVT	random-vibration theory
R*	modal distance
S	shear (wave)
SA	spectral acceleration
SH	horizontally-polarized shear (wave)
SV	vertically-polarized shear (wave)
SASW	spectral-analysis-of-surface-waves (surveys)
sec	second
SFA	Surface Facilities Area
SNL	Sandia National Laboratory
SPT	Standard Penetration Test
SRP	Standard Review Plan

ACRONYMS, ABBREVIATIONS, AND SYMBOLS (Continued)

TBV	to be verified
TDMS	Technical Data Management System
TIC	Technical Information Center
Tmbt1	pre-Rainier Mesa Tuff bedded tuff
Tmr	Rainer Mesa Tuff of the Timber Mountain Group
Tpbt4	pre-Tiva Canyon Tuff bedded tuff
Tpbt5	pre-Tuff unit “x” bedded tuffs (also known as post-Tiva Canyon Tuff bedded tuff)
Tpcpln	Tiva Canyon Tuff: crystal-poor member, lower nonlithophysal zone
Tpcpmn	Tiva Canyon Tuff: crystal-poor, middle nonlithophysal zone
Tpcpul	Tiva Canyon Tuff: crystal-poor member, upper lithophysal zone
Tpcpv	Tiva Canyon Tuff: vitric zone
Tpcrn	Tiva Canyon Tuff: crystal-rich, nonlithophysal zone
Tpcrv	Tiva Canyon Tuff: crystal-rich, vitric zone
Tpcrl	Tiva Canyon Tuff: crystal-rich, lithophysal zone
Tpki	Tuff unit “x”
TWP	Technical Work Plan
UDEC	Universal Discrete Element Code
UHS	uniform hazard spectrum
UMA	upper mean alluvium (curve)
UMT	upper mean tuff
URS	URS Corporation
USBR	U.S. Bureau of Reclamation
USGS	U.S. Geological Survey
UTA	University of Texas at Austin
ν	Poisson’s ratio
V/H	vertical-to-horizontal
V_P	compression-wave velocity
V_S	shear-wave velocity
VSP	Vertical Seismic Profiling
WHB	waste handling buildings
WUS	western U.S.
YMP	Yucca Mountain Site Characterization Project

1. PURPOSE

This report describes models and analyses used to develop ground motion inputs for preclosure design and safety analyses. These new ground motion inputs supplement those described in *Development of Earthquake Ground Motion Input for Preclosure Seismic Design and Postclosure Performance Assessment of a Geologic Repository at Yucca Mountain, Nevada* (BSC 2004 [DIRS 170027]). As described in the Technical Work Plan *Seismic Studies* (TWP-MGR-GS-000001 REV05) (BSC 2006 [DIRS 178322]), these ground motions are based on updated inputs to the site-response ground motion model and on an alternate approach to that used previously for incorporating the site response in developing ground motion inputs. The ground motion inputs also reflect new information on the characterization of extreme ground motions that can occur at Yucca Mountain. Earthquakes producing extreme ground motion are defined as those with source processes that generate anomalously large ground motions, far beyond those recorded to date. Specific objectives of this study are (BSC 2006 [DIRS 178322], Section 1.1):

- For ground motion annual frequencies of exceedance (AFE) appropriate for preclosure design analyses, provide site-specific seismic design acceleration response spectra for a range of damping values; strain-compatible soil properties; peak motions, strains, and curvatures as a function of depth; and time histories (acceleration, velocity, and displacement). Provide seismic design inputs for the Repository Block waste emplacement level (RB) and for the Surface Facilities Area (SFA) (Figure 1-1). Results should be consistent with the probabilistic seismic hazard analysis (PSHA) for Yucca Mountain (CRWMS M&O 1998 [DIRS 103731]; Stepp et al. 2001 [DIRS 158656]).

- For probabilistic analyses supporting the demonstration of compliance with preclosure performance objectives, provide a mean seismic hazard curve for the SFA. Results should be consistent with the PSHA for Yucca Mountain and reflect, as appropriate, available knowledge on the characterization to extreme ground motion at Yucca Mountain.

In this study, a site-response ground motion model (hereafter referred to as a "site-response model") and a stochastic point-source ground motion model (hereafter referred to as a "stochastic point-source model") have been utilized. The site-response model implements a random-vibration-theory (RVT) equivalent-linear formulation to calculate site response effects on ground motions. This model was described and validated in BSC (2004 [DIRS 170027], Sections 6.1 and 7). The purpose of the site-response model is to incorporate the effects of the site materials (rock and soil) at Yucca Mountain on earthquake ground motions. A PSHA (CRWMS M&O 1998 [DIRS 103731]; Stepp et al. 2001 [DIRS 158656]; BSC 2004 [DIRS 168030]) provides ground motion at a reference rock outcrop for the site (Point A; Figure 1-1), but those results do not include the response of the overlying local site material. Thus, an additional step using the site-response model is required to develop ground motion inputs appropriate for the SFA and the RB.

The purpose of the stochastic point-source model is to calculate ground motions based on properties of the earthquake source, propagation path, and site. This model is used in conjunction with the site-response model to evaluate the V/H (vertical to horizontal) ratios of ground motions at Yucca Mountain. The model is also used to characterize ground motions from extreme earthquakes that dominate the hazard in the Yucca Mountain vicinity at very low AFEs (< ~10^{-6}). These earthquakes are moderate (moment magnitude [**M**] 6 to 7), occur at small distances (< 15 km) from the site, and produce ground motions that are unlikely even for such events (Figure 6.4.1-10 and 6.4.1-16). Such ground motions have not been historically recorded worldwide. By assessing an upper range of stress parameter (stress drop) that could be reasonably associated with such earthquakes, the stochastic point-source model can be used to characterize the distribution of extreme ground motion that can occur at Yucca Mountain. This result is used in one approach to condition the PSHA ground motion hazard results for use in developing site-specific ground motions for the SFA and RB (Section 6.5.1, Appendix A). An alternate approach involves an evaluation of the level of ground motions that have not been experienced at Yucca Mountain. This approach is based on an analysis of the shear-strain threshold that would need to be exceeded to cause seismic-related fracturing of tuff lithophysal units and the observed lack of such deformation in underground excavations (Section 6.5.1, Appendix A, BSC 2005 [DIRS 170137]). The description and validation of the stochastic point-source model is contained in this report. In addition, this report also describes the use of these models, the model results, and the development of ground motion inputs based on these results.

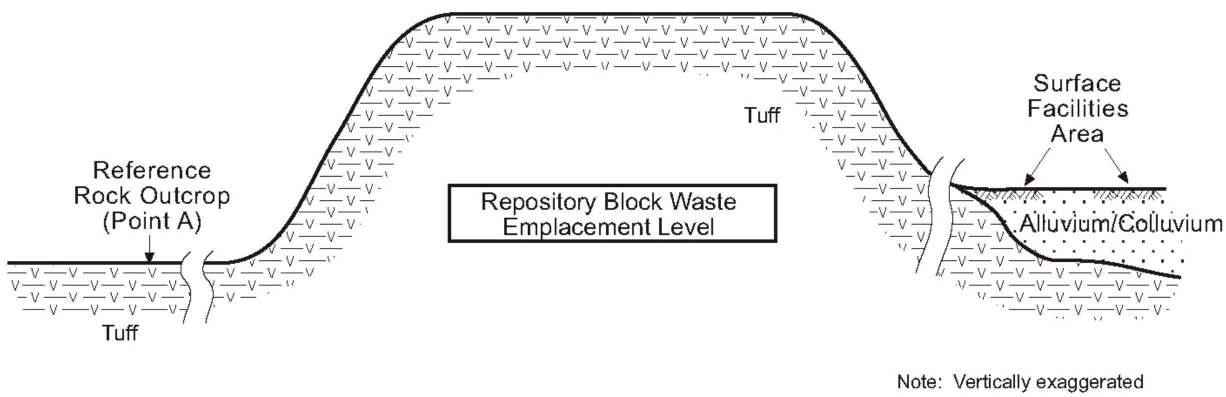
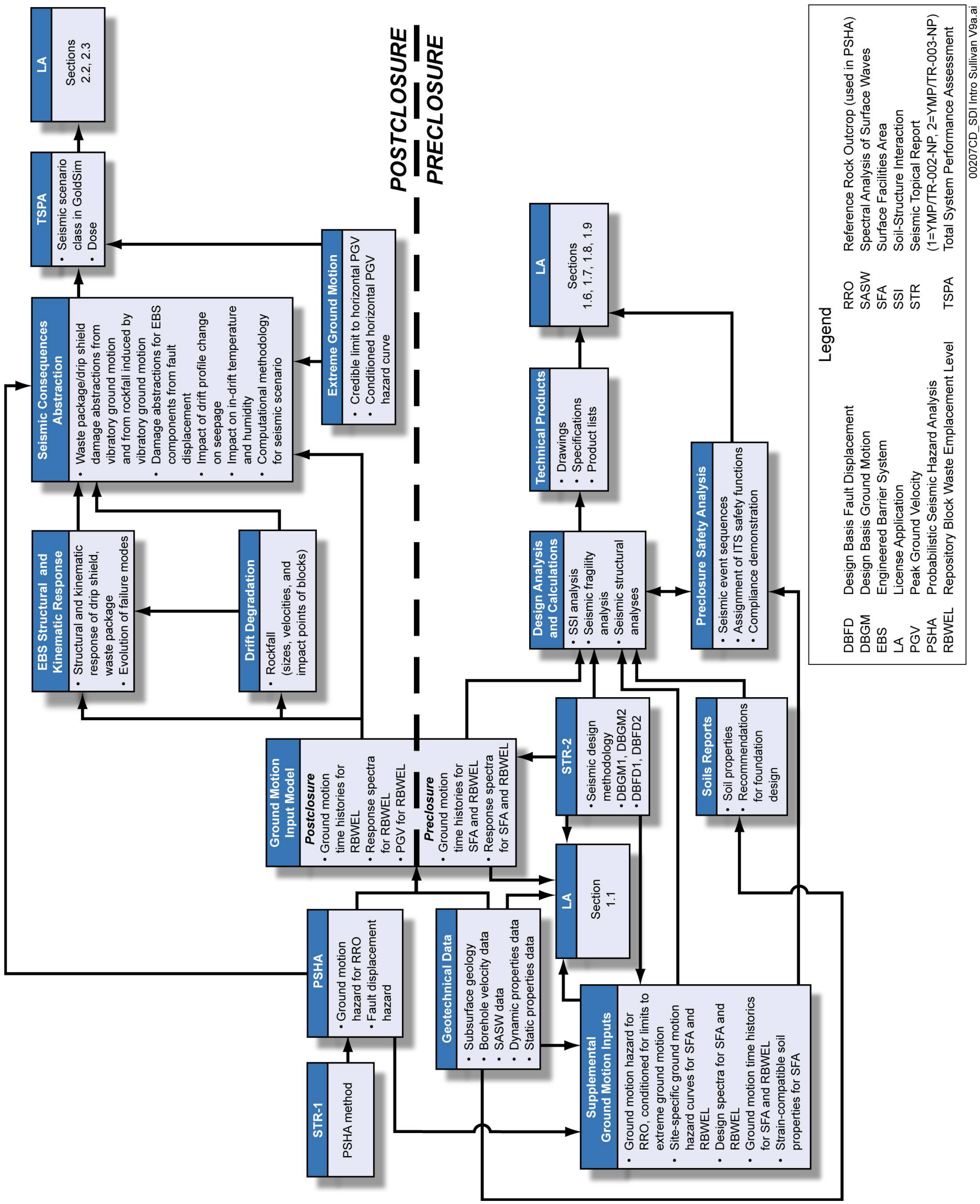


Figure 1-1. Schematic Representation of the Locat ions for Which Seismic Input Ground Motions are Developed

The relation of this study to other preclosure and postclosure seismic-related work is shown on Figure 1-2. For the supplemental ground motions documented in this report, the ground motion hazard results from the PSHA provide the basis for inputs to a site-response analysis. Prior to their use in developing site-specific ground motions, the PSHA hazard results are conditioned to reflect limits to ground motion at Yucca Mountain. Preclosure ground motions derived from the site response analysis and the conditioned PSHA hazard results are used for design of the surface facilities and in soil-structure interaction analyses for the important-to-safety surface facilities. They are also used for preclosure subsurface facility design and analyses and to support preclosure waste package design and analyses. Site-specific hazard curves are used in preclosure probabilistic safety analyses.



Note: The work documented in this report is represented by the box titled "Supplemental Ground Motion Inputs."

Figure 1-2. Documentation of Seismic Analyses

Preclosure seismic design methodology includes two levels of Design Basis Ground Motion (DBGM-1 and DBGM-2) (DOE 2007 [DIRS 181572], Section 3.1). DBGM-1 and DBGM-2 are associated with AFEs (hazard levels) of 1×10^{-3} and 5×10^{-4}, respectively. In addition, a "beyond design basis ground motion" (BDBGM) is defined to support the seismic fragility analysis for the preclosure safety analysis. The BDBGM is associated with a 1×10^{-4} AFE (DOE 2007 [DIRS 181572], Section 3.3).

In this report, results (5%-damped design response spectra, three-component sets of time histories matched to the seismic design response spectra, and strain-compatible soil properties) are provided for the 1×10^{-3}, 1×10^{-4}, and 5×10^{-4} AFEs. (Note that unless specified otherwise, all response spectra discussed and/or described in this report are 5%-damped.)

1.1 SCOPE OF WORK

The TWP *Seismic Studies,* TWP-MGR-GS-000001, Revision 05 (BSC 2006 [DIRS 178322]), planned the scope of work performed. Tasks listed in the TWP, which are documented, in whole or in part, in this report, consist of (BSC 2006 [DIRS 178322], Table 1):

- On the basis of rock mechanics, geologic and seismic information, assess the limits on extreme ground motions at Yucca Mountain and document the technical basis for them
- Update velocity profiles for the RB and SFA
- Update dynamic material properties for the tuff and alluvium/colluvium at Yucca Mountain
- Evaluate an alternative approach to determining the V/H ground motion ratio for the Yucca Mountain site, as a function of frequency, using a stochastic point-source model
- Evaluate the sensitivity of computed ground motions to the velocity profile depth at which the velocity conditions associated with the PSHA reference rock outcrop (Point A; 1,900 m/sec) are obtained.
- Update preclosure ground motion inputs and evaluate their conservatism.
- Develop seismic hazard curves for the SFA to support preclosure demonstration of performance with respect to 10 CFR 63 [DIRS 180319] objectives

This report also describes the validation of the stochastic point-source model.

When the TWP was prepared, it was envisioned that the work scope listed above would be documented in a revision of *Development of Earthquake Ground Motion Input for Preclosure Seismic Design and Postclosure Performance Assessment of a Geologic Repository at Yucca Mountain, Nevada* (MDL-MGR-GS-000003, REV01) (BSC 2004 [DIRS 170027]). However, further consideration after the TWP was approved resulted in a decision to document the work in a new report that supplements the earlier work. As the scope of work did not change, only the specifics of the report documenting the work, this was deemed a minor change with respect to

LP-2.29Q-BSC, Planning for Science Activities, Section 5.4.1. Thus, the changes are hereby documented in this report rather than in an interim change notice or revision to the TWP.

1.2 BACKGROUND

Preliminary ground motion inputs were first developed for the Yucca Mountain site in CRWMS M&O (1998 [DIRS 156499]). These inputs were for the emplacement drift level and for a rock outcrop at the surface. Inputs for the SFA were not developed because the site geology had not yet been sufficiently characterized. Subsequent efforts resulted in an initial characterization of the surface facilities site and led to updated preliminary inputs. These preliminary inputs provided the basis for analyses supporting the site recommendation (CRWMS M&O 2000 [DIRS 151288], BSC 2001 [DIRS 155187]).

A more extensive characterization of the geotechnical properties of the RB and SFA was carried out in 2000 and 2001 (BSC 2002 [DIRS 157829]). Results from these investigations formed the basis for the preclosure seismic design and postclosure performance assessment ground motions described in BSC (2004 [DIRS 170027]). In BSC (2004 [DIRS 170027]), ground motions for the SFA were based on subsurface velocity data obtained southwest of the Exile Hill splay fault. Subsequent to the development of those ground motions, the layout of surface facilities evolved and now extends to the north and northeast of the area originally characterized. For the analyses and modeling described in this report, additional seismic surveys northeast of the Exile Hill splay fault, in the Exploratory Studies Facility (ESF), and above the RB and data from USGS sonic velocity surveys, provide new information that are incorporated.

1.3 MODEL LIMITATIONS

A mathematical model is a mathematical representation of a conceptual model (system, process, or phenomenon) that is based on established scientific and engineering principles and from which the approximate behavior of a system, process, or phenomenon can be calculated within determinable limits of uncertainty. A limitation of models is that a mathematical representation is used that only approximates a physical process and cannot capture its every detail. The limitations of the RVT-equivalent-linear site-response model have been described in BSC (2004 [DIRS 170027], Sections 6.1.6, 6.1.14). Limitations of the stochastic point-source model are discussed in Section 6.3.10. There are also limitations to the inputs that are required by the models. These limitations, which are generally due to the availability and uncertainties of data, are discussed in Section 6.4.

1.4 ORGANIZATION OF THIS REPORT

The organization of this report conforms to the format specified in LP-SIII.10Q-BSC, *Models,* Attachment 2. Section 1 describes the purpose and background of the study, the scope of work, and a brief description of the models used in the analyses and their limitations. Section 2 describes the applicability of the Quality Assurance (QA) Program. Computer software and models used to support quality-affecting work are discussed in Section 3. Inputs and their sources, identified and documented in accordance with PA-PRO-0301, *Managing Technical Products Inputs*, are described in Section 4. Section 5 documents data assumptions made to perform the modeling and analyses. Section 6 summarizes the RVT-based equivalent-linear site response and stochastic point-source models and the model inputs. Modeling, analyses, and results are also described in detail in this section. Section 7 presents the model validation of the stochastic point-source model. Finally, Section 8 summarizes the conclusions of the study and Section 9 lists the inputs and references including cited documents, data, and software. Appendices are used to document details of modeling and analyses that are summarized in Section 6.

2. QUALITY ASSURANCE

Requirements of the *Quality Management Directive* (BSC 2007 [DIRS 180474]) apply to development of this model report and to supporting modeling activities and analyses. Applicability of the quality assurance program was evaluated in the TWP *Seismic Studies* (BSC 2006 [DIRS 178322], Section 8.1). Implementing procedures identified in the TWP (BSC 2006 [DIRS 178322], Section 4), or approved procedures that superseded them, controlled the conduct and documentation of the activities described in this report. This modeling activity does not investigate an item or natural barrier identified on the Q-List (BSC 2005 [DIRS 175539]).

As described in the TWP *Seismic Studies* (BSC 2006 [DIRS 178322], Section 8.3), the modeling and analysis activities described in this report require control of the electronic management of data. To ensure the integrity of transferred data, controls for transfer of electronic information consist of check sums, parity checks, and file-size comparisons performed by computer operating systems during data transfer and storage. In addition, compressing or "zipping" data files prior to transfer was performed in cases in which data are transferred from one physical location to another. Security and integrity of the electronic information developed during the work activities was maintained by storing the information on network drives and on hard drives of password-protected personal computers. Network drives and hard drives were periodically backed up, as appropriate, and the backups labeled and stored. This also ensured that data are protected prior to submittal to the records system and that they are retrievable. For submittal of electronic information to the records system or to the Technical Data Management System (TDMS), controls established in the relevant procedures were followed. There were no deviations from the planned methods of control.

3. USE OF SOFTWARE

Software was used in this study to develop inputs to a site-response model, to implement a stochastic point-source model and the site-response model, and to develop ground motion inputs based on model results. Brief descriptions of the programs used in this study follow. More detailed information on the programs, including a general description of inputs and outputs, program verification, and range of use, is found in the software qualification documentation associated with each program. Specific software inputs and outputs from this study can be found in appendices to this report. Table 3-1 lists qualified software used in this study.

Table 3-1. Software Used

Computer Program Name	Version Number	Software Tracking Number	Computer Type	Operating System	Reference
BASE4	4.0	10940-4.0-00	IBM PC-compatible	DOS 6.22	[DIRS 163293], BSC (2002 [DIRS 184876])
CORBB	1.0	10941-1.0-00	IBM PC-compatible	DOS 6.22	[DIRS 163295], BSC (2002 [DIRS 184877])
DUR	1.0	10942-1.0-00	IBM PC-compatible	DOS 6.22	[DIRS 163303], BSC (2002 [DIRS 184878])
EARTHVISION	5.1	10174-5.1-00	Silicon Graphics Indigo R4000	IRIX 6.5	[DIRS 167994], CRWMS M&O (2000 [DIRS 153526])
EXTHC	1.0	11242-1.0-00	IBM PC-compatible	DOS 6.22	[DIRS 182936], Russon (2007 [DIRS 184880])
HAZUHS	1.0	11194-1.0-00	IBM PC-compatible	DOS 6.22	[DIRS 182466], Upadhyaya (2007 [DIRS 184881])
INTEG1	1.0	10943-1.0-00	IBM PC-compatible	DOS 6.22	[DIRS 163304], BSC (2002 [DIRS 184882])
INTERPOL	1.0	10944-1.0-00	IBM PC-compatible	DOS 6.22	[DIRS 163305], BSC (2002 [DIRS 184883])
MAXMIN	1.0	10945-1.0-00	IBM PC-compatible	DOS 6.22	[DIRS 163309], BSC (2002 [DIRS 184884])
POST RASCAL	1.0	11231-1.0-00	IBM PC-compatible	DOS 6.22	[DIRS 182467], Logeswaran (2007 [DIRS 184885])
RASCAL SET	1.0	11232-1.0-00	IBM PC-compatible	DOS 6.22	[DIRS 182468], Becker (2007 [DIRS 184886])
RASCAL SET	1.1	11232-1.1-00, 11232-1.1-01	IBM PC-compatible	DOS 6.22, Windows 2003	[DIRS 184513], [DIRS 184053], Dober (2007 [DIRS 184887]), Dober (2007 [DIRS 184888])
REPLOT	1.0	10949-1.0-00	IBM PC-compatible	DOS 6.22	[DIRS 163318], BSC (2002 [DIRS 184889])
SOILHAZ SET	1.0	11234-1.0-00	IBM PC-compatible	DOS 6.22	[DIRS 182834], Logeswaran (2007 [DIRS 184890])
SCALE1	1.0	10946-1.0-00	IBM PC-compatible	DOS 6.22	[DIRS 163319], BSC (2002 [DIRS 184891])
SIGCOMB	1.1	11233-1.1-00	IBM PC-compatible	DOS 6.22	[DIRS 182835], Lowenthal-Savy (2007 [DIRS 184892])
SPCTLR	1.0	10947-1.0-00	IBM PC-compatible	DOS 6.22	[DIRS 163321], BSC (2002 [DIRS 184893])

Computer Program Name	Version Number	Software Tracking Number	Computer Type	Operating System	Reference
UDEC	3.14	10173-3.14-00	IBM PC-compatible	Windows 2000	[DIRS 172322], Carranza-Torres (2004 [DIRS 184894])
XYMULT	1.0	10919-1.0-00	IBM PC-compatible	DOS 6.22	[DIRS 163326], BSC (2002 [DIRS 184895])

Note: For the computer programs listed above that are qualified to run under the DOS 6.22 operating system, the Quarterdeck Extended Memory Manager (QEMM) Version 9.0 and the PharLap run-time DOS extender (386run.exe) must also be installed.

Software items were selected for use because they implement the models being employed in the development of ground motion inputs. RASCAL SET V1.0 and V1.1 (consisting of modules RASCALS, RASCALP, RANPAR, VELAVG, and SCP) implement the RVT-based equivalent-linear site-response model and the stochastic point-source model through its modules RASCALS and RASCALP. As part of its implementation of the RVT-based equivalent-linear site-response model, these modules also generate information used to determine strain-compatible soil properties. In addition, they provide the capability to develop ground motion time histories that are spectrally matched to a target design spectrum. Module RANPAR produces input and parameter files for RASCALS and RASCALP using a randomization approach selected by the user. RANPAR provides the capability for incorporating results of a Yucca Mountain site-specific velocity-layer thickness correlation analysis (Section 6.4.2.8; BSC 2004 [DIRS 170027], Section 6.2.3.5) in its stochastic generation of velocity profiles. Module VELAVG reads in a number of velocity profiles (either depth to top of layer and velocity or thickness and velocity), interpolates to a finer depth grid if necessary, computes log statistics using the POST-RASCAL module LOGNORM, and recombines layers of the average, 84th, and 16th percentile profiles if velocities are within an input range parameter. Module SCP reads the RASCALS and RASCALP output files of strain-compatible properties at the last iteration and computes their statistics (mean and standard deviation). RASCAL SET modules are designed to interact with each other and to facilitate batch mode processing.

RASCAL SET V1.0 and RASCAL SET V1.1 differ only in module SCP. For the final calculations using SCP, RASCAL SET V1.1 is used. Final calculations using the other modules in RASCAL SET were carried out using V1.0 prior to qualification of V1.1.

POST RASCAL V1.0 (consisting of modules LOGNORM, NORM, PARINP, SMRATIO, and SPMEAN) was used because it provides post-processing of outputs from RASCAL SET V1.0 and V1.1 and is designed to interface with the file input and output formats of RASCAL SET V1.0, V1.1 and SOILHAZ SET V1.0. It is also used because it facilitates batch mode processing. Module LOGNORM calculates mean and standard deviation of tabular data contained in a set of files. The distribution of the data is assumed to be lognormal. Weights are applied to each curve. Module NORM also calculates mean and standard deviation for tabular data, but assuming a normal distribution. Weights also are applied to each curve. Module PARINP reads in a given set of parameter files and computes the number of layers and depth for input with either modules NORM or LOGNORM. Module SMRATIO divides columns of data and is used to determine the ratio between response spectra to obtain a transfer function. Module

SPMEAN determines the mean, minimum, and maximum of the data in a series of input files and is used to envelop seismic transfer functions or response spectra.

EXTHC V1.0 is used to incorporate constraints provided by new data on existing seismic hazard curves. Specifically, for the Yucca Mountain site, it updates ground motion hazard values to determine values consistent with distributions of maximum sustainable site-specific shear strains and/or distributions of maximum sustainable earthquake source processes, specifically Brune stress drops. This "conditioned" hazard curve then serves as the input to development of site-specific seismic hazard curves using SOILHAZ SET V1.0.

SOILHAZ SET V1.0 (consisting of modules SOILUHS, SOILUHSI, SUHSINP, FRACTILE, and HCSCP) is used for the analysis to incorporate site-response results into site-specific ground motion hazard curves using Approach 3 of NUREG/CR-6769 (McGuire et al. 2002 [DIRS 163799], Section 6). SOILHAZ SET V1.0 computes site-specific hazard curves from rock hazard curves and strain-compatible soil properties. Module SUHSIMP prepares the input files used in the program SOILUHSI. Module SOILUHSI calculates site-specific hazard curves using amplification factors and the full-integration method from Approach 3 (based on the full integration method of Bazzuro and Cornell 2004 [DIRS 177290]). Module SOILUHS calculates site-specific hazard curves using approximate integration of the amplification factor over a range of rock amplitudes as described in NUREG/CR-6769 (McGuire et al. 2002 [DIRS 163799]). SOILUHS was not used in the work described in this report. Module FRACTILE calculates the fractile curves using output from SOILUHSI using weights (while also calculating fractiles) as well as calculating the envelope of hazard curves. Module HCSCP calculates hazard-consistent strain-compatible soil properties.

SIGCOMB V1.0 takes the standard deviation output files on the strain-compatible properties from the HCSCP module of SOILHAZ SET and combines them, taking into account the uncertainty (epistemic) between the base case dynamic properties due to the difference in the means between base case properties.

HAZUHS V1.0 is used to determine uniform hazard spectra (UHS) using the results of SOILHAZ SET V1.0. It is designed to interface with output files from SOILHAZ SET V1.0 and to facilitate batch mode processing and optionally applies amplification factors, and computes UHS using interpolation for specified AFEs.

The programs BASE4 V4.0, CORBB V1.0, DUR V1.0, INTEG1 V1.0, INTERPOL V1.0, MAXMIN V1.0, REPLOT V1.0, SCALE1 V1.0, SPCTLR V1.0, and XYMULT V1.0 are post-processing routines that support the development of ground motion inputs. BASE4 performs time domain baseline correction of acceleration time histories and integrates the corrected records to produce velocity and displacement time histories. CORBB computes correlation coefficients between two time histories. DUR computes Arias intensity (Kramer 1996 [DIRS 103337], page 82) versus duration of an acceleration time history. INTEG1 performs time domain integration of an acceleration time history to produce velocity and displacement time histories. INTERPOL is used to interpolate an expanded set of points for a user-defined curve such as a response spectrum. MAXMIN determines the maximum and minimum values from a series of input data, such as a time history, and the points at which they occur. REPLOT generates graphical representations of data. SCALE1 scales data values such as acceleration time histories. SPCTLR computes the response spectra of multiple time histories at specified dampings. XYMULT multiplies two columns of data together such as multiplying a response spectrum by a transfer function. These programs are selected for use because they are designed to interface with RASCAL SET, POST RASCAL, EXTHC, SOILHAZ SET, and HAZUHS and to facilitate batch mode processing.

EARTHVISION V5.1 is used to determine the range of thickness of overburden above the waste emplacement area. It is also used to determine the geologic units underlying the sites of various seismic velocity measurements that have been obtained in the Yucca Mountain vicinity. This information is used in developing velocity profiles for use in site-response modeling.

UDEC V3.14 is used to numerically simulate cyclic shear tests of tuff samples from the Topopah Spring Tuff formation. This modeling supplements laboratory testing by considering larger samples and carrying out simulations to larger shear-strain amplitudes. UDEC is selected for use because it implements a validated model for tuff mechanical deformation that was used in investigating drift degradation (BSC 2004 [DIRS 166107], Section 7.6).

All programs were used consistent with their intended use and within their range of validation. There are no limitations on use of outputs due to the software selected.

RASCAL SET V1.0, POST RASCAL V1.0, EXTHC V1.0, SOILHAZ SET V1.0, HAZUHS V1.0 and SIGCOMB V1.0 were used prior to qualification to develop preliminary outputs. When qualification of the programs was completed, all computations using those programs were re-run to verify the preliminary results. The final results based on runs with qualified software are presented in this report.

Commercial-off-the-shelf (COTS) programs used to support the work are listed in Table 3-2.

Table 3-2. Commercial-Off-the-Shelf Software Used

Computer Program Name	Version Number	Software Tracking Number
Grapher	3	510887-4.0-00
Microsoft Excel ®	2000	608802-2002-00

Grapher3 is a graphics program that was used to plot the results of work described in Sections 6.5.4 through 6.5.7. Microsoft Excel 2000 was used in the development of velocity profiles forming input to the model, and used to obtain weights when combining the 1-2 Hz and 5-10 Hz reference earthquake results in SOILUHSI. Documentation of the use of these commercial-off-the-shelf software programs, including algorithms, inputs, outputs, and other information, is contained in Appendices C and D.

4. INPUTS

This section describes the input data used in developing site-specific ground motions for a geologic repository at Yucca Mountain, Nevada. The section also lists project requirements and criteria that pertain to the work. Finally the section discusses codes, standards and regulations that are relevant to the work.

4.1 DIRECT INPUT

This subsection identifies direct inputs to the analyses and modeling detailed in this report. First, qualified data found in the TDMS are discussed. Then, data from outside sources are presented. For data from outside sources, a justification is provided for why the data are considered qualified for use within this technical product.

4.1.1 Qualified Input Data

Qualified input data used in analyses and modeling described in this report are identified in Table 4-1.

Table 4-1. Qualified Input Data

Input Data	Data Source	Data Tracking Number, Design Data, or Value	Data Used
Spectral Acceleration and Velocity Hazard Curves Extended to 1E-9 Based on the Results of the PSHA for Yucca Mountain.	BSC (2004 [DIRS 170027], Section 6.2.2)	MO03061E9PSHA1.000 [DIRS 163721]	Files h_*_extended.frac_mean and v_*_extended.frac_mean in which "*" stands for 003,005,1,2,5,10,20,100, and vel
Reference Event and Deaggregation Event Spectra at 10^{-3} AFE Based on the Results of the PSHA for Yucca Mountain	BSC (2004 [DIRS 170027], Section 6.2.2)	MO0211REDES103.000 [DIRS 170424]	Horizontal reference earthquake response spectra as identified in Table 6.4-3
Uniform Hazard, Reference Event and Deaggregation Event Spectra at $5X10^{-4}$ AFE Based on the Results of the PSHA for Yucca Mountain	BSC (2004 [DIRS 170027], Section 6.2.2)	MO0208UNHZ5X10.000 [DIRS 163722]	Horizontal reference earthquake response spectra as identified in Table 6.4-3
Reference Event and Deaggregation Event Spectra at 10^{-4} AFE Based on the Results of the PSHA for Yucca Mountain	BSC (2004 [DIRS 170027], Section 6.2.2)	MO0211DERES104.000 [DIRS 170423]	Horizontal reference earthquake response spectra as identified in Table 6.4-3
Uniform Hazard, Reference Event and Deaggregation Event Spectra at 10^{-5} AFE Based on the Results of the PSHA for Yucca	BSC (2004 [DIRS 170027], Section 6.2.2)	MO0308UNHAZ105.000 [DIRS 170425]	Horizontal reference earthquake response spectra as identified in Table 6.4-3

Input Data	Data Source	Data Tracking Number, Design Data, or Value	Data Used
Mountain			
Uniform Hazard, Reference Event and Deaggregation Event Spectra at 10^{-6} AFE Based on the Results of the PSHA for Yucca Mountain	BSC (2004 [DIRS 170027], Section 6.2.2)	MO0206UNHAZ106.001 [DIRS 163723]	Horizontal reference earthquake response spectra as identified in Table 6.4-3
Uniform Hazard, Reference Event and Deaggregation Event Spectra at 10^{-7} AFE Based on the Results of the PSHA for Yucca Mountain	BSC (2004 [DIRS 170027], Section 6.2.2)	MO0209UNHAZ107.000 [DIRS 163724]	Horizontal reference earthquake response spectra as identified in Table 6.4-3
Downhole Velocity Measurements at the WHB Site (Shear and Compression Wave Velocity Profiles from boreholes RF#13, 14, 15, 16, 18, 19, 20, 21, 22, 23, 24, 25, 26, 28, & 29) (WHB = Waste Handling Building)	BSC (2002 [DIRS 157829], Section 6.2.5)	MO0111DVDWHBSC.001 [DIRS 157296]	Table 6.4-11, Section 6.4.2.2, Appendix C, Appendix C\DATA FROM TDMS\ 2000_2001 Downhole Data\ DOWNHOLE WHB 2000_2001_s.xls
Downhole Velocity Measurements at the WHB Site (Shear and Compression Wave Velocity Profiles from boreholes RF#13 & RF#17)	BSC (2002 [DIRS 157829], Section 6.2.5)	MO0110DVDBOREH.000 [DIRS 157295]	Table 6.4-11, Section 6.4.2.2, Appendix C, Appendix C\DATA FROM TDMS\ 2000_2001 Downhole Data\ DOWNHOLE WHB 2000_2001_s.xls
SASW Velocity Data from the WHB Site Characterization Area (SASW = Spectral Analysis of Surface Waves)	BSC (2002 [DIRS 157829], Section 6.2.7)	MO0110SASWWHBS.000 [DIRS 157969]	Table 6.4-11, Section 6.4.2.2, Appendix C, Appendix C\DATA FROM TDMS\ 2000_2001 SASW Data\ MO0110SASWWHBS.000 SASW WHB 2000_2001_s.xls
SASW Velocity Data from the Top of Yucca Mountain (2000)	BSC (2002 [DIRS 157829], Section 6.4.2)	MO0203SEPSASWD.000 [DIRS 158084]	Table 6.4-14, Section 6.4.2.2, Appendix C, Appendix C\DATA FROM TDMS\ 2000_2001 SASW Data\ MO0110SASWWHBS.000 SASW WHB 2000_2001_s.xls
SASW Velocity Data from the Top of Yucca Mountain (2001)	BSC (2002 [DIRS 157829], Section 6.4.2)	MO0110SASWVDYM.000 [DIRS 158076]	Table 6.4-14, Section 6.4.2.2, Appendix C, Appendix C\DATA FROM TDMS\ 2000_2001 SASW Data\ MO0110SASWWHBS.000 SASW WHB 2000_2001_s.xls

Input Data	Data Source	Data Tracking Number, Design Data, or Value	Data Used
SASW Theoretical Dispersion Curves And Vs Profiles For FY04 And FY05 For YMP	SNL (2008 [DIRS 183779], Section 6, Attachments IV, V, and VI)	MO0609SASWSTDC.003 [DIRS 182125]	Table 6.4-11, Table 6.4-14, Appendix C, Appendix C\DATA FROM TDMS\ 2004_2005 SASW Data\ MO0701ABSRFLL2.000 SASW Developed TDMS Data for NPF Sites, 2004&2005.xls, Appendix C\DATA FROM TDMS\ 2004_2005 SASW Data\ MO0701ABSRFLL2.000 SASW Developed TDMS Data for YM Sites, 2004&2005.xls, Appendix C\DATA FROM TDMS\ 2004_2005 SASW Data\ MO0701ABSRFLL2.000 SASW Developed TDMS Data for ESF Sites, 2004&2005.xls, Appendix C\DATA FROM TDMS\ 2004_2005 SASW Data\ MO0701ABSRFLL2.000 SASW Developed TDMS Data for ECRB Sites, 2004&2005.xls
SASW Investigations for Repository Facilities, As-Built SASW RF Line Locations-2	SNL (2008 [DIRS 183779], Section 6, Attachments IV, V, and VI)	MO0701ABSRFLL2.000 [DIRS 182483]	Table 6.4-11, Table 6.4-14, Appendix C, Appendix C\DATA FROM TDMS\ 2004_2005 SASW Data\ MO0701ABSRFLL2.000 SASW Developed TDMS Data for NPF Sites, 2004&2005.xls, Appendix C\DATA FROM TDMS\ 2004_2005 SASW Data\ MO0701ABSRFLL2.000 SASW Developed TDMS Data for YM Sites, 2004&2005.xls, Appendix C\DATA FROM TDMS\ 2004_2005 SASW Data\ MO0701ABSRFLL2.000 SASW Developed TDMS Data for ESF Sites, 2004&2005.xls, Appendix C\DATA FROM TDMS\ 2004_2005 SASW Data\ MO0701ABSRFLL2.000 SASW Developed TDMS Data for ECRB Sites, 2004&2005.xls
Borehole Suspension Data for the WHB Site Characterization Area	BSC (2002 [DIRS 157829], Section 6.2.6)	MO0204SEPBSWHB.001 [DIRS 158088]	Section 6.4.2.2, Appendix C, Appendix C\DATA FROM TDMS\ 2000_2001 Suspension Data
Borehole Suspension Data for RF#13 at WHB Site Characterization Area	CRWMS M&O (1999 [DIRS 109209], Section 4.4, Appendix O)	MO0204SEISDWHB.001 [DIRS 158086]	Section 6.4.2.2, Appendix C, Appendix C\DATA FROM TDMS\ 2000_2001 Suspension Data

Input Data	Data Source	Data Tracking Number, Design Data, or Value	Data Used
Alluvium Thickness Contour Map of Midway Valley, NV; 07/23/2007 - 08/10/2007	SNL (2008 [DIRS 183779], Section 6.2.2.2)	GS070983114233.006 [DIRS 183649]	Range of alluvium thickness beneath important-to-safety surface facilities
Geotechnical Borehole Logs at the WHB site from RF#13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 28 & 29	BSC (2002 [DIRS 157829], Sections 6.2.2, 6.2.3, and 6.6.2)	GS030783114233.001 [DIRS 164561]	Alluvium thickness in each borehole, geologic unit contacts in each borehole
Developed Geophysical Log Data from Forensic Evaluation of Geophysical Log Data	BSC (2002 [DIRS 185001])	MO0112GPLOGWHB.001 [DIRS 157298]	Bulk density and gamma intensity log data
Qualified Geophysical Logs From Borehole UE-25A#1	MOL.19960320.0014	MO960408314213.001 [DIRS 182126]	Section 6.4.2.4.3, Appendix C\ GS990908314213.001 (a#1).xls
Qualified Geophysical Logs From Borehole UE-25B#1	MOL.19960320.0014	MO960408314213.006 [DIRS 182127]	Section 6.4.2.4.3, Appendix C\ GS990908314213.001 (b#1).xls
Qualified Geophysical Logs From Borehole UE-25C#1	MOL.19960320.0014	MO960408314213.007 [DIRS 182128]	Section 6.4.2.4.3, Appendix C\ GS990908314213.001 (c#1).xls
Qualified Geophysical Logs From Borehole UE-25C#2	MOL.19960320.0014	MO960408314213.008 [DIRS 182129]	Section 6.4.2.4.3, Appendix C\ GS990908314213.001 (c#2).xls
Qualified Geophysical Logs From Borehole UE-25P#1	MOL.19960320.0014	MO960408314213.010 [DIRS 131173]	Section 6.4.2.4.3, Appendix C\ GS960708312132.002 (p#1).xls
Qualified Geophysical Logs From Borehole USW G-3	MOL.19960320.0014	MO960408314213.023 [DIRS 130536]	Section 6.4.2.4.3, Appendix C\ GS960708312132.002 (GU-3,G-3).xls
Qualified Geophysical Logs From Borehole USW G-4	MOL.19960320.0014	MO960408314213.024 [DIRS 130551]	Section 6.4.2.4.3, Appendix C\ GS960708312132.002 (G-4).xls
Lithostratigraphic Contacts	BSC (2004 [DIRS 170029])	MO0004QGFMPICK.000 [DIRS 152554]	Appendix C, GFM31-2000 Q Contacts.xls, Workbook “zz_sep_135926”
Velocity Correlation Parameters for the Yucca Mountain Repository Block and Waste Handling Building Site	BSC (2004 [DIRS 170027], Section 6.2.3.6)	MO0208VCPRBWHB.000 [DIRS 163801]	Table 6.4-18, Table 6.4-19
Laboratory Dynamic Rock/Soil Testing Results from UE-25 RF#13	CRWMS M&O (1999 [DIRS 109209], Section 5.2 and Appendix Q)	MO9905LABDYNRS.000 [DIRS 103792]	Table 6.4-21
Dynamic Laboratory Test Results from the WHB Site, Fran Ridge Borrow Area and the ESF Tunnel	BSC (2002 [DIRS 157829], Sections 6.2.10. 6.3.3, and 6.5.3)	MO0203DHRSSWHB.001 [DIRS 158082]	Table 6.4-21
USBR Soil	BSC (2002 [DIRS	GS020483114233.004	Figure 6.4.4-13

Input Data	Data Source	Data Tracking Number, Design Data, or Value	Data Used
Classification and Relative Density Laboratory Data	157829], Section 6.2.9)	[DIRS 158242]	
Density of Tuff and Alluvium for Site-response Modeling	BSC (2004 [DIRS 170027], Section 6.2.3.7)	Tuff: 2.2 g/cm3 (137 pcf) Alluvium: 1.8 g/cm3 (112 pcf)	Tuff: 2.2 g/cm3 (137 pcf) Alluvium: 1.8 g/cm3 (112 pcf)
Subsurface - Underground Layout Configuration for LA General Arrangement	BSC (2007 [DIRS 182932])	800-KM0-SS00-00305-000-00A	Repository waste emplacement level footprint used to select velocity data relevant to developing ground motion inputs for the repository waste emplacement level
Gradation Analysis Test Results for Test Pit Bag Samples from the Waste Handling Building Site Characterization Area	BSC (2002 [DIRS 157829], Section 6.2.9)	GS020783114233.005 [DIRS 159542]	Figure 6.4.4-13
Geologic Framework Model (GFM2000)	BSC (2004 [DIRS 170029])	MO0012MWDGFM02.002 [DIRS 153777]	Appendix C\Geology for Unit Velocity Correlation.xls (Sheet 1) - Geologic cross-sections along each SASW survey line were used to evaluate correlations between geologic unit and seismic velocity. Section 6.4.2.9 - Range of overburden thickness above the repository waste emplacement footprint
Value of site attenuation parameter kappa used in the PSHA for Yucca Mountain	BSC (2004 [DIRS 168030], Section 6.3.3.1.1)	0.02 sec	0.02 sec
Modal magnitude and epicentral distance determined from deaggregation of the PSHA ground motion hazard at mean annual frequencies of exceedance of 1E-3, 5E-4, 1E-4, 1E-5, 1E-6, and 1E-7	BSC (2004 [DIRS 170027], Table 6.2-4)	Not applicable	Data used are summarized in Table 6.4-1
Drift Degradation Model Inputs and Outputs	BSC (2004 [DIRS 166107])	MO0408MWDDDMIO.002 [DIRS 171483]	Appendix B, Section B2.0
Density Data for Various Thermal Mechanical Units and Associated Lithostratigraphic Units	BSC (2004 [DIRS 166107], Table E-1)	SN0303T0503102.008 [DIRS 162401], SN0404T0503102.011 [DIRS 169129]	Appendix B, Table B-1

Input Data	Data Source	Data Tracking Number, Design Data, or Value	Data Used
Suggested Range of Mechanical Properties Developed from 11.5-in. Core Testing, Selected for Base-Case Design and Performance Analyses	BSC (2004 [DIRS 166107], Table E-10)	Not applicable	Appendix B, Table B-1
Elastic Properties Data from the Nonlithophysal Units of the Repository Horizon	BSC (2004 [DIRS 166107], Table E-6)	Not applicable	Appendix B, Table B-1
Tensile Strength Data from the TSw2 Thermal Mechanical Unit	BSC (2004 [DIRS 166107], Table E-7)	Not applicable	Appendix B, Table B-1
Uniaxial and Triaxial Test Data from Borehole Samples Near the ESF for the Tptpmn Lithostratigraphic Unit	BSC (2004 [DIRS 166107], Figure E-2)	Not applicable	Appendix B, Table B-1
Summary Statistics of Direct Joint Shear Test Results	BSC (2004 [DIRS 166107], Table E-5)	Not applicable	Appendix B, Table B-1
Uniaxial and Triaxial Test Data for the Tptpmn Lithostratigraphic Unit	BSC (2004 [DIRS 166107]), Table E-8, Figure E-2)	Not applicable	Appendix B, Table B-1

As discussed in Sections 6.4 and 6.5, these data are used in developing inputs for modeling and analysis activities to develop ground motion inputs. Sections 6.4 and 6.5 also provide details on how data uncertainties are handled in modeling and analysis activities. Inputs to the site-response model consist of seismic velocity profiles, dynamic material property curves, material densities, and control motions. Seismic velocity data from the RB and the SFA are used to determine velocity versus depth profiles (Section 6.4.2, 5.1). Alluvium thickness data are used to select a range of values for site-response modeling at the SFA. The outline of the waste emplacement area is used to identify velocity data that are relevant to characterizing the RB (Section 6.4.2). Results characterizing the correlation of velocity and layer thickness are used in stochastically generating suites of velocity profiles to represent aleatory variability in velocity profiles for site-response modeling (Section 6.4.2.8). The topographic component of the Geologic Framework Model is used along with the elevation of the waste emplacement area to determine the range of overburden thickness for site-response modeling (Sections 6.4.2 and 6.5.5). Borehole geotechnical logs provide information on the depth of alluvium at the SFA (Sections 6.4.2 and 6.5.4). Results of laboratory testing of the dynamic properties of site materials are used to characterize the behavior of shear modulus and material damping as a function of shear strain (Section 6.4.4). Gradation analysis of soil samples and the value of site attenuation (kappa) for Yucca Mountain are also used to develop dynamic material property curves (Section 6.4.4). Other laboratory data are used to assess the density of materials at the site (Section 5.6). Reference earthquakes that are used to represent the UHS for a given mean AFE (Section 6.4.1) provide control motions for site-response modeling.

Results of the PSHA serve as input to an analysis to condition ground motion hazard curves for the PSHA reference rock outcrop based on characterization of extreme ground motion at Yucca Mountain (Section 6.5.1). These results then feed the development of location-specific hazard curves that incorporate results of site-response modeling (Section 6.5.3). The location-specific hazard curves form the basis for development of design spectra and time histories for mean AFEs of 10^{-3}, $5x10^{-4}$, and 10^{-4}. Strain-compatible material properties at the SFA are also developed for these hazard levels.

Fracture representations for lithologic units at Yucca Mountain are used along with material and fracture properties to simulate numerically the variation in normalized shear modulus and damping ratio as a function of shear strain (Appendix B). The numerical simulations, which can "test" larger samples than possible in the laboratory, supplement results from laboratory testing. Values used are consistent with those used in modeling drift degradation (BSC 2004 [DIRS 166107]).

In cases for which only some of the data associated with a given data tracking number (DTN) are used, the specific data used and a justification are provided in the appropriate subsection of Section 6. Data used to develop the models were not used to validate the models.

4.1.2 Input Data Considered Qualified for Use Within This Report

In addition to qualified input data available from the TDMS, the modeling and analyses described in this report also use other nonsite-specific data as input. These data are considered qualified for use within this report as justified below in accordance with LP-SIII.10Q-BSC, Section 5.2.1(k). Input data considered qualified for use in this report are summarized in Table 4-2.

Table 4-2. Input Data Considered Qualified for Use Within This Report

Input	Source
Crustal velocity profile underlying the reference rock outcrop used in the PSHA	Schneider et al. (1996 [DIRS 103270], Table 5.2)
Horizontal and vertical ground motion prediction relations for the western U.S.	Abrahamson and Silva (1997 [DIRS 104205]); Abrahamson and Becker (1997 [DIRS 166530]) and Campbell and Bozorgnia (2003 [DIRS 183814)
Depth distribution of earthquakes in the western U.S.	McGuire et al. (2001 [DIRS 157510], Table 6.2)
Catalog of time histories for analyses	McGuire et al. (2001 [DIRS 157510], Appendix B)
Generic curves for shear modulus reduction and damping as a function of cyclic shear strain and typical range of modulus reduction curves for gravels	EPRI (1993 [DIRS 103320], Appendix 7, Figure 7.A-3, Section 7.A.5)
Crustal attenuation (Q)	Schneider et al. (1996 [DIRS 103270], Table 5.1)

The regional crustal velocity profile in the Yucca Mountain region is attached to the shallow shear-wave velocity profiles and is one of the inputs to the stochastic point-source model (Section 6.4.5). The profile was developed by Schneider et al. (1996 [DIRS 103270]). This profile is based on vertical seismic profiling (VSP) data from selected boreholes in the vicinity of Yucca Mountain (Majer et al. 1996 [DIRS 106330]), refraction data from Mooney and Schapper (1995 [DIRS 106384]), and a crustal model used by the U.S. Geological Survey (USGS) for earthquake locations (Harmsen 1993 [DIRS 105106], Appendix F). The model was developed as part of a USGS activity in which it was used by a group of six nationally-known ground motion modeling experts to simulate ground motions for Yucca Mountain using scenario earthquakes (Schneider et al. 1996 [DIRS 103270]). Modelers and other project participants reviewed the velocity profile prior to its use. The report describing the Scenario Ground Motion Project (Schneider et al. 1996 [DIRS 103270]) underwent technical review under the USGS Yucca Mountain QA Program. The profile was subsequently used in the PSHA for Yucca Mountain for ground motion simulations that formed part of the information considered by seven ground motion experts (CRWMS M&O 1998 [DIRS 103731], Section 5.3.1). The seven PSHA ground motion experts, who are some of the top ground motion experts in the U.S., concurred with the simulation inputs. The PSHA Project was also documented in a peer-reviewed journal paper (Stepp et al. 2001 [DIRS 158656]). In summary, the regional crustal velocity model of Schneider et al. (1996 [DIRS 103270]) was developed by the USGS, a reliable source of data and was concurred with by ground motion experts as part of two projects. Thus, the data are taken as qualified for their intended use within this report.

Values of V/H spectral ratios are used to determine site-specific vertical hazard curves (Section 6.5.2). Empirical V/H ratios derived from the ground motion prediction relationships of Abrahamson and Silva (1997 [DIRS 104205]) as modified for normal faulting (Abrahamson and Becker 1997 [DIRS 166530]) and Campbell and Bozorgnia (2003 [DIRS 183814]) provide part of the basis for this analysis. These empirical models represent the state-of-the-practice and are routinely used by the earthquake hazards community. Both relationships have been published in peer-reviewed journals. Modification of the Abrahamson and Silva (1997 [DIRS 104205]) relation for normal faulting was used by the experts providing ground motion interpretations for the Yucca Mountain PSHA (Abrahamson and Becker 1997 [DIRS 166530]).

The depth distribution of earthquakes in the western U.S. is used to determine appropriate focal depths for input to the stochastic point-source model (Section 6.4.5, 6.5.1). The values have been adopted from Table 6-2 in NUREG/CR-6728 (McGuire et al. 2001 [DIRS 157510]). The data in this source are corroborated by information on the depth distribution of earthquakes in the western U.S. from peer-reviewed scientific journal papers. Example papers that specifically include Nevada are Rogers et al. (1991 [DIRS 106702], pages 166-168) and Smith and Bruhn 1984 [DIRS 170607]). This depth distribution or similar distributions were used by the 6 seismic source expert teams in the PSHA for Yucca Mountain (CRWMS M&O 1998 [DIRS 103731], Section 4.2.4.2, Appendix E). These values or similar values have also been used in several urban, regional, and state hazard maps developed by URS Corporation supported by the USGS and the Federal Emergency Management Agency (FEMA) (e.g., Wong et al. 2004 [DIRS 170544]). The recognition within the scientific and engineering community of the authors, support staff, and reviewers associated with McGuire et al. (2001 [DIRS 157510]), the corroboration of the data by data published in peer-reviewed journals, and its use in the seismologic community justify taking these data as qualified for their intended use within this technical product.

Response spectral calculations are combined with recorded strong ground motion data from a catalog of time histories to produce site-specific time histories for Yucca Mountain locations of interest (Section 6.3.2). These time histories are adopted from NUREG/CR 6728 (McGuire et al. 2001 [DIRS 157510], Appendix B), which has been sponsored and reviewed by the NRC staff and published as a NRC contractor report (see discussion above). A similar set of recorded strong motion data is available through the Pacific Earthquake Engineering Research Center (PEER) (http://peer.berkeley.edu/smcat). PEER is supported by the federal government, the state of California, and private industry to carry out research in the area of performance-based earthquake engineering. Through PEER, investigators from over 20 universities and several consulting companies conduct research in earthquake-related geohazard assessment, geotechnical and structural engineering, risk management, and public policy. The PEER strong motion database supports this research. The recognition within the scientific and engineering community of the authors, support staff, and reviewers associated with McGuire et al. (2001 [DIRS 157510]), and its corroboration by the PEER strong motion database, justify taking these data as qualified for their intended use within this technical product.

Generic curves for shear modulus reduction and damping as a function of cyclic shear strain are used in developing site-specific curves for Yucca Mountain (Section 6.2.4). These generic curves have been developed by a group of internationally-known experts in geotechnical engineering and reviewed by a panel of experts under the auspices of the Electric Power Research Institute (EPRI). The generic curves from EPRI (1993 [DIRS 103320]) have been used by the earthquake engineering community in hundreds of studies, many of which have been published in peer-reviewed journals (e.g., Schneider et al. 1993 [DIRS 110467]). The recognition within the scientific and engineering community of the authors and reviewers of EPRI (1993 [DIRS 103320]) and its use in the earthquake engineering community, justify taking these data as qualified for their intended use within this technical product.

Crustal attenuation is an input to the stochastic point-source model that is used to provide numerical simulations of V/H ratios and to characterize extreme ground motions at Yucca Mountain. The value of crustal attenuation used in modeling is taken from Schneider et al. (1996 [DIRS 103270], Section 5) based on the work of Singh and Herrmann (1983 [DIRS 183042]). The reliability of Schneider et al. 1996 [DIRS 103270]) is discussed above with respect to the regional crustal velocity profile. The qualifications of the authors of Schneider et al. (1996 [DIRS 103270]) and the use of the results in work under the auspices of the USGS justify taking these data as qualified for their intended use within this technical product.

4.1.3 Use of Models

The RVT-based equivalent-linear site-response model is used in this study to determine the effect of site materials on ground motion. The model addresses wave propagation through the rock/soil column and nonlinear behavior of the material under dynamic shear loading conditions. A one-dimensional model that employs a frequency domain approach is used (Silva and Lee 1987 [DIRS 103325]). Results of the PSHA, conditioned to reflect new information on extreme ground motions at Yucca Mountain, form the control motion; the power spectrum of the control motion is propagated through the rock/soil column using the P-SV or SH propagators of Silva (1976 [DIRS 103326]). Nonlinear properties of the rock/soil layers (i.e., strain-dependent shear modulus and damping) are treated using an equivalent linear approach (Seed and Idriss 1970

[DIRS 103324]). The approach approximates a second-order nonlinear equation over a limited range of its variables by a linear equation. RVT is used to determine peak time domain values of shear strain based on the shear-strain power spectrum. Strain-dependent shear modulus and hysteretic damping curves are then used to define new parameters for each layer based on the effective strain computations. This process is repeated until the changes in parameters are below a specified tolerance level.

Use of this model is justified because it provides the effect on ground motions caused by propagation of the motion through the site materials. The model will be used (implemented using the software code RASCAL SET) as intended and within its range of validity. Level III validation of the model is documented in *Development of Earthquake Ground Motion Input for Preclosure Design and Postclosure Performance Assessment of a Geologic Repository at Yucca Mountain* (MDL-MGR-GS-000003 REV 00 and REV 01) (BSC 2003 [DIRS 166274], Section 7; BSC 2004 [DIRS 170027], Section 7). Additional activities to expand and enhance the technical basis for model validation are described in Revision 01 of that model report (BSC 2004 [DIRS 170027], Section 7.3.5). This model provides an adequate representation of site-response effects for its intended use in the development of site-specific hazard curves for the SFA and the RB waste emplacement area. Product output associated with BSC (2004 [DIRS 170027]) has DTN MO0409MWDGMMIO.000 [DIRS 172216].

The discontinuum model implemented using the Universal Discrete Element Code (UDEC) software is used to evaluate tuff dynamic material properties and mechanical behavior. Use of this model is justified because it provides a calibrated and validated representation of the deformation of nonlithophysal tuff at Yucca Mountain (BSC 2004 [DIRS 166107], Section 6, Section 7.6). In the UDEC model, the rock mass is represented as an assembly of polygonal elastic blocks. Properties are selected such that the rock mass has proper deformability and strength characteristics, and responds elastically for stresses up to its peak strength. However, after the peak strength is reached, the model represents the failure process, including fracturing and dislodging of blocks under quasi-static and dynamic loading. This is accomplished by subdivision of the rock mass into many blocks of approximately the same size as those that may ultimately be formed during yielding. Fractures are bonded by the strength and stiffness values that allow correct representation of the rock mass strength and modulus. Prior to yielding, the fractures in the rock mass are essentially “invisible” or “incipient” and the rock mass behaves in an elastic, isotropic fashion during loading and unloading. However, once the shear or tension strength of the incipient fractures is reached, the rock mass can realistically fail through propagation of fractures as the forces dictate. The UDEC discontinuum model has been previously validated (BSC 2004 [DIRS 166107], Section 7.6). The model will be used within its range of validity.

The geologic framework model (BSC 2004 [DIRS 170029]) is used as the basis for geologic information to evaluate the correlation between seismic velocity data and lithostratigraphy. The model also serves as the source of information on the overburden thickness between the surface and the waste emplacement level. Use of this model is appropriate because it represents the integrated model of site geology. The model has been previously validated (BSC 2004 [DIRS 170029], Section 7) and will be used within its range of validity.

4.2 CRITERIA

Regulatory requirements addressed by seismic ground motion development are identified in Table 4-3. While the work described in this report is focused on providing ground motion inputs that support preclosure analyses, the results also bear on postclosure issues and analyses. Thus, in listing regulatory requirements, both relevant preclosure- and postclosure-related requirements are included.

Table 4-3. Requirements Pertaining to the Site-Specific Ground Motion Modeling and Analyses

Title	10 CFR 63 Section
Content of Application	10 CFR 63.21(c)(1),(9)
Purpose and Nature of Findings	10 CFR 63.101(a)(2)
Concepts	10 CFR 63.102(f),(j)
Performance Objectives for the Geologic Repository Operations Area Through Permanent Closure	10 CFR 63.111(b)
Requirements for Pre-Closure Safety Analysis of the Geologic Repository Operations Area	10 CFR 63.112(b)-(d),(f)
Requirements for Performance Assessment	10 CFR 63.114(a)-(g)

This report addresses 10 CFR 63.21 [DIRS 180319] by describing ground motions from earthquakes in the Yucca Mountain region that potentially affect the design of the geologic repository operations area and performance of the geologic repository. It thus provides information needed for a complete description of the site. The results also support characterization of features, events, and processes (FEPs) that might affect performance of a geologic repository.

This report addresses criterion 10 CFR 63.101 [DIRS 180319] by describing the technical basis for the range of parameters and variability distributions used in developing seismic inputs for analyses supporting the assessment of performance of a geologic repository.

This report addresses criterion 10 CFR 62.102 [DIRS 180319] by providing ground motion inputs that characterize one of the potential hazards and the initiating events that must be evaluated in the Preclosure Safety Analysis. It also addresses this criterion by describing ground motion inputs that are appropriate for analyses supporting assessment of the postclosure performance of a geologic repository at Yucca Mountain, including determination of those features, events, and processes expected to materially affect compliance with postclosure performance objectives. The inputs are based on the results of the PSHA for Yucca Mountain conditioned to reflect new information on extreme ground motion and, thus, reflect the range of credible earthquakes for the Yucca Mountain site.

This report addresses criterion 10 CFR 63.111 [DIRS 180319] by providing ground motion inputs that allow design to take into account seismic-initiated Category 1 and Category 2 event sequences in a manner such that preclosure performance objectives are met.

This report addresses criterion 10 CFR 63.112 [DIRS 180319] by providing the site-specific preclosure ground motions needed to analyze naturally occurring hazards at the geologic repository operations area.

This report addresses criterion 10 CFR 63.114 [DIRS 180319] by describing ground motion inputs that form part of the information on disruptive initiating events that is used to evaluate the performance of the geologic repository at Yucca Mountain. The report also describes the uncertainties and variability in parameter values that provide input to the development of ground motion inputs and the alternative models evaluated. In addition, the report describes ground motions that can initiate or contribute to events having at least one chance in 10,000 of occurring over 10,000 years. It thus provides information that is used to determine whether features, events, and processes should be included or excluded from the performance assessment and to evaluate seismic effects on the degradation, deterioration, or alteration processes of engineered barriers in the performance assessment. Finally, the report addresses this criterion by providing the technical basis for the stochastic point-source model and describes the validation of that model.

Criteria are also provided by the *Yucca Mountain Review Plan, Final Report* (NRC 2003 [DIRS 163274]). Relevant acceptance criteria from this document are:

Acceptance criteria listed in Section 1.5.3 of NRC (2003 [DIRS 163274]) are based on meeting requirements of 10 CFR 63.21(b)(5) [DIRS 180319], which relate to description of site characterization work:

1. *The "General Information" section of the license application contains an adequate description of site characterization activities.*

2. *The "General Information" section of the license applications contains an adequate description of site characterization results.*

This report addresses Part 1 of criterion 1 and Parts 1 and 2 of criterion 2 by providing ground motion inputs with various annual frequencies of being exceeded that form part of the understanding of features and processes present in the Yucca Mountain region.

Acceptance criteria listed in Section 2.1.1.5.1.3 are based on meeting requirements of 10 CFR 63.111(a)(1), (a)(2), (b)(1), (c)(1), and (c)(2) [DIRS 180319], which relate to consequence analysis methodology and meeting radiation protection requirements for normal operations and Category 1 event sequences:

1. *Consequence analyses adequately assess normal operations and Category 1 event sequences, as well as factors that allow an event sequence to propagate within the Geologic Repository Operations Area.*

2. *Consequence calculations adequately assess the consequences to workers and members of the public from normal operations and Category 1 event sequences.*

3. *The Dose to Workers and Members of the Public From Normal Operations and Category 1 Event Sequences is Within the Limits Specified in 10 CFR 63.111 (a)].*

This report provides information that contributes to addressing Part 1 of criterion 1, Parts 1 and 3 of criterion 2, and Part 1 of criterion 3 by providing ground motion inputs for annual frequencies of exceedance of 10^{-3}, 5×10^{-4}, and 10^{-4}.

Acceptance criteria listed in Section 2.1.1.5.2.3 of NRC (2003 [DIRS 163274]) are based on meeting requirements of 10 CFR 63.111(b)(2) and (c) [DIRS 180319], which relate to design meeting numerical radiation protection requirements for Category 2 event sequences:

1. *Consequence analyses include Category 2 event sequences as well as factors that allow an event sequence to propagate within the geologic repository operations area.*

2. *Consequence calculations adequately assess the consequences to members of the public from Category 2 event sequences.*

3. *The dose to hypothetical members of the public from category 2event sequences is within the limits specified in 10 CFR 63.111(b)(2).*

This report provides information that contributes to addressing Part 1 of criterion 1, Parts 1 and 3 of criterion 2, and Part 1 of criterion 3 by providing information on the annual frequency of seismic ground motion exceedance within the geologic repository operations area. Ground motion inputs are based on site-specific data and incorporate appropriate uncertainties.

Acceptance criteria listed in Section 2.1.1.1.3 of NRC (2003 [DIRS 163274]) are based on meeting requirements of 10 CFR 63.112(c) [DIRS 180319], which relate to the site description as it pertains to the Preclosure Safety Analysis:

5. *The license application contains descriptions of the site geology and seismology adequate to permit evaluation of the preclosure safety analysis and the Geologic Repository Operations Area design.*

This report addresses Part 6 of criterion 5 by providing ground motion inputs forming part of the description of the geology and seismology of the site in support of the preclosure safety analysis and design of the geologic repository operations area. The ground motion inputs are based on results of acceptable methodologies for evaluating seismic hazards at the site.

Acceptance criteria listed in Section 2.1.1.3.3 of NRC (2003 [DIRS 163274]) are based on meeting requirements of 10 CFR 63.112(b) and (d) [DIRS 180319], which relate to identification of hazards and initiating events for preclosure safety analysis:

1. *Technical basis and assumptions for methods for identification of hazards and initiating events are adequate.*

2. *Site data and system information are appropriately used in identification of hazards and initiating events.*

3. *Determination of frequency or probability of occurrence of hazards and initiating events is acceptable.*

4. *Adequate technical bases for the inclusion and exclusion of hazards and initiating events are provided.*

This report addresses Parts 1, 2, 3, and 4 of criterion 1, Part 1 of criterion 2, Parts 1 and 3 of criterion 3, and Parts 1 and 2 of criterion 4 by providing the technical basis and assumptions for ground motion inputs developed to support design of the geologic repository operations area and the preclosure safety analysis. It describes how site data and other information were appropriately used in developing the inputs, including consideration of uncertainties. It describes how the ground motion inputs are consistent with the ground motion hazard determined by the PSHA for Yucca Mountain and conditioned to reflect new information on extreme ground motion. The ground motion inputs provide part of the technical basis for including or excluding ground motion hazards and ground motion initiated events.

Acceptance criteria listed in Section 2.1.1.7.3.1 of NRC (2003 [DIRS 163274]) are based on meeting requirements of 10 CFR 63.112(f) [DIRS 180319], which relate to design bases and design criteria for design of structures, systems, and components important to safety and safety controls:

1. *The relationship between the design criteria and the requirements specified in 10 CFR 63.111(a) and (b), the relationship between the design bases and the design criteria, and the design criteria and design bases for structures, systems, and components important to safety are adequately defined.*

This report addresses Part 1 of criterion 1 by providing ground motion inputs that reflect the mean annual probability of exceedance associated with Design Basis Ground Motion (DBGM)-1 and DBGM-2 as identified in DOE (2007 [DIRS 181572]).

Acceptance criteria listed in Section 2.1.1.7.3.2 of NRC (2003 [DIRS 163274]) are also based on meeting requirements of 10 CFR 63.112(f) [DIRS 180319], which relate to design bases and design criteria for design of structures, systems, and components important to safety and safety controls:

1. *Geologic repository operations area design methodologies are adequate.*

This report addresses Part 4 of criterion 1 by developing seismic inputs that take into account DOE methodologies described in DOE (2007 [DIRS 181572]).

Acceptance criteria listed in Section 2.2.1.2.2.3 of NRC (2003 [DIRS 163274]) are based on meeting requirements of 10 CFR 63.114(d) [DIRS 180319], which relate to identification of events with probabilities greater than 10^{-8} per year:

1. *Events are adequately defined.*

2. *Probability estimates for future events are supported by appropriate technical bases.*

3. *Probability model support is adequate.*

4. *Probability model parameters have been adequately established.*

5. *Uncertainty in event probability is adequately evaluated.*

This report addresses Parts 1 and 2 of criterion 1, Part 1 of criterion 2, Part 1 of criterion 3, Part 1 of criterion 4, and Part 1 of criterion 5 by describing supplemental ground motion hazard curves for the repository waste emplacement level. The ground motion inputs are derived from the ground motion hazard determined by the PSHA for Yucca Mountain, conditioned to reflect new information on extreme ground motion. Use of annual mean hazard incorporates uncertainty in the annual frequency of ground motion being exceeded. The report also describes the stochastic point-source model and its validation. In addition, the report discusses how inputs to the model were determined and how uncertainties are incorporated and propagated through the analysis.

Acceptance criteria in Section 2.2.1.3.2.3 of NRC (2003 [DIRS 163274]) are based on meeting the requirements of 10 CFR 63.114(a)-(c) and (e)-(g) [DIRS 180319], which relate to mechanical disruption of engineered barriers:

2. *Data are sufficient for model justification.*

3. *Data uncertainty is characterized and propagated through the model abstraction.*

This report addresses Parts 1 and 3 of criterion 2 and Parts 1, 2, and 3 of criterion 3 by describing the use of data to develop inputs to the site-response analysis and to stochastic point-source modeling of extreme ground motion. It also describes how data uncertainty is incorporated into the modeling and analysis. The data uncertainties are incorporated into the site-response model and are propagated to seismic hazard curves for the repository waste emplacement level.

4.3 CODES, STANDARDS, AND REGULATIONS

There are no codes, standards, or regulations, other than those identified in Section 4.2, directly pertaining to the work described in this report. However, the following documents published by the NRC provide guidance for developing seismic inputs using the site-response model. The American Society of Civil Engineers/Structural Engineering Institute (ASCE/SEI) Standard 43-05 also provides guidance for some aspects of the work described in this report. In Section 6 of this report, use of these recommendations and guidance is noted.

- NUREG/CR-6728 (McGuire et al. 2001 [DIRS 157510], Sections 4, 5, and 6), *Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard- and Risk-Consistent Ground Motion Spectra Guidelines*, provides recommendations for developing seismic inputs. Recommendations followed in the work documented in this report include those for determining hazard-consistent response spectra at a soil site (Approach 3) and spectral matching of seismic time histories.

- NUREG-0800, Section 3.7.1 (NRC 2007 [DIRS 180931]) and Section 3.7.2 (NRC 2007 [DIRS 180932]), *Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants, Design of Structures, Components, Equipment, and Systems.* Section 3.7.1 provides guidance for spectral matching to determine time histories consistent with developed response spectra. Section 3.7.2 provides guidance on soil-structure interaction analyses and development of strain-compatible soil properties to support such analyses.

- ASCE/SEI 43-05 (2005 [DIRS 173805], Section 2), *Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities* provides recommendations for development of seismic time histories used in design analyses and for consideration of the variation in soil properties in soil-structure interaction analyses.

5. ASSUMPTIONS

This section describes assumptions made in the absence of direct confirming data or evidence that are used in the modeling and analyses described in this report. Model limitations are described in Sections 6.2.5 and 6.3.10. Treatment of data uncertainty is discussed in Section 6.4 as part of the description of model inputs.

5.1 SEISMIC VELOCITY OF THE CALICO HILLS FORMATION AND PROW PASS TUFF LITHOSTRATIGRAPHIC UNITS

Assumption. For the purposes of site-response modeling, the available sonic velocity data are used as the basis for an assumption that the V_S for the Calico Hills Formation is 5600 ft/sec and for the Prow Pass Tuff is about 6000 ft/sec.

Rationale for Assumption. Site-response modeling for Yucca Mountain is intended to take into account the effect on ground motion of geological materials located above the reference rock outcrop. The ground motion hazard for this hypothetical outcrop with shear-wave velocity (V_S) of 1900 m/sec was derived from the PSHA (CRWMS M&O 1998 [DIRS 103731], Section 5.7; BSC 2004 [DIRS 168030], Section 6.3.3.1.1). Therefore the column of tuff and soil that is represented in site-response modeling should extend to a depth at which a V_S of 1900 m/sec is consistently achieved.

In BSC (2004 [DIRS 170027], Section 6.2.3) available data were interpreted to develop V_S profiles that reached 6000 ft/sec (taken as equivalent to 1900 m/sec) at a depth of about 1100 ft in the RB and at a depth of about 500 ft beneath the SFA. Subsequent collection of additional data (SNL 2008 [DIRS 183779], Sections 6.2.5, 6.3, and 6.5.2; Section 6.4.2 of this report) indicates that the depth at which a V_S of 6000 ft/sec is consistently achieved is at a greater depth. Thus, V_S information is needed for lithostratigraphic units underlying the Paintbrush Group tuffs (Table 5-1).

Table 5-1. Major Tertiary Volcanic Stratigraphic Units in the Yucca Mountain Vicinity

Group	Formation
Timber Mountain Group	Ammonia Tanks Tuff (Tma) Rainier Mesa Tuff (Tmr)
Paintbrush Group	Tiva Canyon Tuff (Tpc) Yucca Mountain Tuff (Tpy) Pah Canyon Tuff (Tpp) Topopah Spring Tuff (Tpt)
	Calico Hills Formation (Tac)
Crater Flat Group	Prow Pass Tuff (Tcp) Bullfrog Tuff (Tcb) Tram Tuff (Tct)

Spectral-analysis-of-surface-wave (SASW) surveys provide information on the V_S generally to a depth of about 500 to 1000 ft (Section 6.4.2). Except for some surveys in the RB area, a V_S of

6000 ft/sec is not achieved at the depth limits of the interpreted SASW results. Downhole seismic logging data are generally limited to depths of about 500 ft in the SFA and 100 ft in the RB. Thus, velocity data collected during the period from 2000 to 2005 establish that the depth at which material with a V_S of 6000 ft/sec is greater than about 1000 ft, but do not define the depth at which such material is found.

Velocity data for lithostratigraphic units underlying the Topopah Spring Tuff is limited. Sonic velocity data are available, but they are not all qualified. For the purposes of site-response modeling, the available sonic velocity data are used as the basis for this assumption.

Sonic velocity data ([Birdwell] 3-D Velocity logs) are compiled as part of the data with Data Tracking Numbers (DTN) GS960708312132.002 [DIRS 113584] and GS990908314213.001 [DIRS 150287]. These data contain sonic velocity results for 16 boreholes, 15 of which are considered to be sufficiently near the repository (within 4 km) as to represent the velocity underlying the RB and SFA. Data from borehole UE-25 J-13, which is about 6 km from the waste emplacement area footprint, were not included. Note, however, that inclusion of data from UE-25 J-13 results in differences of less than 1% in the calculated velocities (Appendix C, , Workbook "Average Velocity Deeper Units (Calico Onwards)(Thickness) (with Inferred).xls"). The 15 relevant boreholes are summarized in Table 5-1.

Table 5-1. Sonic Velocity Data Used to Support Assumption 5.1

Borehole Identifier	Total Depth (ft)	V_S measurements (Yes/No)	V_P measurements (Yes/No)
USW G-1	6000	No	Yes
USW G-2	6006	Yes	Yes
USW G-3/GU-3	5031/2644	Yes	Yes
USW G-4	3003	Yes	Yes
UE-25a#1	2501	No	Yes
UE-25b#1	4002	Yes	Yes
UE-25p#1	5923	Yes	Yes
USW H-1	6000	Yes	Yes
USW H-3	4000	Yes	Yes
USW H-4	4000	Yes	Yes
USW H-5	4000	No	Yes
USW H-6	4002	No	Yes
UE-25c#1	3000	Yes	Yes
UE-25c#2	3000	Yes	Yes
UE-25c#3	3000	Yes	Yes

Source: DTNs GS960708312132.002 [DIRS 113584] and GS990908314213.001 [DIRS 150287]

While the geophysical data associated with DTNs GS960708312132.002 [DIRS 113584] and GS990908314213.001 [DIRS 150287] are not qualified, a number of the underlying sonic logs are qualified. Table 5-2 summarizes the qualification status of sonic velocity logs for the boreholes listed in Table 5-1. In most of the boreholes, multiple logging runs were made. The table lists the sonic velocity logging run number, the date of the logging run, and whether the resulting log is qualified.

Table 5.2. Qualification Status of Sonic Velocity Logs

Borehole Identifier	Qualified	Not Qualified
USW G-1	Runs 1-4 (04/02/80), 5-7 (04/21/80), 8 (08/11/80)	Runs 7 (08/11/80)[1], 9 (08/12/80)[1,2], 10-11 (08/12/80)
USW G-2	Runs 3-4 (10/13/81), 5-6 (10/14/81), 9-12 (10/18/81), 13-14 (10/20/81)	Runs 1-2 (05/23/81)[1], 7-8 (10/17/81)
USW G-3	Runs 1-2 (03/22/82)	None listed in MOL.19960320.0014
USW GU-3	Runs 1-2 (04/03/82), 5-10 (04/30/82), 11-12 (05/15/82), 13-14 (05/17/82)	Runs 3-4 (04/23/82)
USW G-4	Runs 1-2 (11/09/82), 3-4 (11/21/82)	None listed in MOL.19960320.0014
UE-25a#1	Runs 1-2 (08/26/78)	None listed in MOL.19960320.0014
UE-25b#1	Runs 1-2 (04/23/81), 3-4 (08/07/81)	None listed in MOL.19960320.0014
UE-25p#1	Run 1 (12/01/82), 3-4 (03/14/83)	None listed in MOL.19960320.0014
USW H-1	None listed in MOL.19960320.0014	Runs 1-2 (10/15/80)[1], 3-4 (10/27/80), 5 (11/24/80)[1], 6 (11/26/80)[1]
USW H-3	None listed in MOL.19960320.0014	1-2 (02/03/82)[1], 1-2 (03/03/82)
USW H-4	None listed in MOL.19960320.0014	None listed in MOL.19960320.0014
USW H-5	None listed in MOL.19960320.0014	None listed in MOL.19960320.0014
USW H-6	None listed in MOL.19960320.0014	None listed in MOL.19960320.0014
UE-25c#1	Runs 1-2 (09/10/83)	None listed in MOL.19960320.0014
UE-25c#2	Run 1 (02/10/84)	None listed in MOL.19960320.0014
UE-25c#3	None listed in MOL.19960320.0014	Runs 1-2 (04/17/84)

Notes: 1 – Log identified as "3-D Velocity" rather than "(Birdwell) 3-D Velocity" in MOL.19960320.0014
2 – There are two runs "9" listed in MOL.19960320.0014 with a date of 08/12/80.

Source: Foust (1995 [DIRS 182324])

Using geologic data associated with DTN MO0004QGFMPICK.000 [DIRS 152554], the sonic velocity data for the Calico Hills Formation and Prow Pass Tuff were separated out and analyzed. In addition, data for the Bullfrog Tuff and Tram Tuff, which underlie the Prow Pass Tuff, were also examined. For boreholes for which V_S data were obtained, those data were used directly. For boreholes or depth intervals for which only compression-wave velocity (V_P) data were available, associated V_S values were calculated using a Poisson's ratio of 0.3 BSC (2004 [DIRS 170027], Section 6.2.3.3.2). Data for the Calico Hills Formation includes measurements from the pre-Topopah Spring Tuff bedded tuffs because of their similar characteristics. Similarly, data for the pre-Calico Hills Formation bedded tuffs are grouped with the Prow Pass Tuff data. Sonic velocity data for the Calico Hills Formation and Prow Pass Tuff are shown in Figures 5-1 and 5-2, respectively.

To determine a representative V_S value for the Calico Hills Formation, the Prow Pass Tuff, and the Bullfrog Tuff, V_S data (or V_P data converted to a V_S using a Poisson's ratio of 0.3) were used to compute a lognormal mean for each unit for each borehole as follows:

$$Lognormal\ Mean = e^{\left(\mu + \frac{\sigma^2}{2}\right)}$$

in which μ is the mean of the natural logarithm of the V_S values and σ is their standard deviation. Then a lognormal mean of the means for each unit across all boreholes was computed. Results are summarized in Table 5-3. Computing the median (geometric mean) of the data gives similar results (Table 5-3). The calculations carried out using Microsoft Excel 2000 are given in Appendix C.

Table 5-3. Summary of V_S for the Three Deep Units

Lithostratigraphic Unit	Lognormal Mean (Geometric Mean) V_S (ft/sec)	V_S Standard Deviation (ln[V_S] Standard Deviation)
Calico Hills Formation	5590 (5481)	584 (0.10)
Prow Pass Tuff	6129 (6023)	739 (0.12)
Bullfrog Tuff	6427 (6353)	478 (0.07)

Source: Appendix C, Workbook "Average Velocity Deeper Units (Calico Onwards)(Thickness) (with Inferred).xls," Worksheet "Summary," "AVERAGE UNIT VELOCITY (feet/sec) FOR FOUR DEEP UNITS (Lognormal Mean of the lognormal means of 15 Boreholes) (Excluding J-13)"

Limited SASW surveys are also interpreted to provide velocity information for the Calico Hills Formation and the Prow Pass Tuff (SNL 2008 [DIRS 183779], Section 6.3.3). Based on data from 4 surveys, for the Calico Hills Formation a median V_S value of about 5500 ft/sec is obtained (SNL 2008 [DIRS 183779], Figure 6.3-9). Data from 2 surveys give a median V_S of about 5400 ft/sec for the Prow Pass Tuff. For all these surveys, the results for the Calico Hills Formation and the Prow Pass Tuff occur at the deepest part of the interpreted profile. In a number of instances, these interpretations are based on sparse data and thus are uncertain.

Laboratory measurements of velocity for the Calico Hills Formation and Prow Pass Tuff taken on unconfined core samples are generally lower than those seen in situ. For the Calico Hills Formation, SNL (2008 [DIRS 183779], Table 6.5-7) reports a median velocity of 4397 ft/sec based on 10 measurements. A median velocity of 5438 ft/sec is obtained for the Prow Pass Tuff based on 21 measurements.

Based primarily on the sonic velocity results, the V_S for the Calico Hills Formation is assumed to be 5600 ft/sec and the V_S for the Prow Pass Tuff is assumed to 6000 ft/sec. The top of the Prow Pass Tuff is determined to be equivalent to the PSHA reference rock outcrop conditions and thus, in site-response modeling, the control motion is propagated through the Calico Hills Formation and overlying units. Uncertainty and variability in velocity profiles that are incorporated into the site-response modeling or examined in sensitivity studies are discussed in Section 6.5.

5.2 SATURATION AND POROSITY OF TOPOPAH SPRING TUFF LITHOSTRATIGRAPHIC UNITS

Assumption. Saturation of the Topopah Spring Tuff lithostratigraphic units is 80% and porosity is 20%.

Rationale for Assumption. Numerical simulations of the dynamic properties of lithostratigraphic units of the Topopah Spring Tuff formation are carried out using UDEC V3.14, as described in Appendix B. Specifically, simulations are carried out for the upper lithophysal zone (Tptpul), the middle non-lithophysal zone (Tptpmn), the lower lithophysal zone (Tptpll), and the lower non-lithophysal zone (Tptpln). In carrying out these simulations, values of saturation and porosity are assumed to calculate density (i.e, density = dry density + (saturation × porosity × water density)).

Mean values of saturation determined from borehole core samples for lithophysal and non-lithophysal units of the Topopah Spring Tuff range from about 0.7 to 0.9 (Flint 1998 [DIRS 100033], Table 7). These data provide the rationale for assuming a value of 80% in the modeling presented in Appendix B.

Porosities for welded, non-lithophysal tuff range from 0.09 to 0.16 (BSC 2004 [DIRS 169734], Section 3.7.3.1.1). For lithophysal units, the lithophysal porosity must also be considered. Lithophysal porosities range from 0.0 to about 0.3 (BSC 2004 [DIRS 169734], Section 3.7.3.1.1). Based on these values, porosity of 20% is assumed for modeling presented in Appendix B.

Because the simulations presented in Appendix B are quasi-static with no gravity acting (only initial stress), the value used for density does not affect the simulation results.

5.3 JOINT PROPERTIES FOR TOPOPAH SPRING TUFF LITHOSTRATIGRAPHIC UNITS

Numerical simulations of the dynamic properties of the Topopah Spring Tuff lithostratigraphic units (Appendix B) include the effect of joints. Joint sets included in the simulations are classified as sub-vertical, sub-horizontal, or random. Joint properties are provided as a function of class and lithostratigraphic unit of the Topopah Spring Tuff (Appendix B-Table 1). Some properties are determined based on qualified inputs and analyses; others are assumed. In this section the assumed values are described and their bases provided.

<u>Cohesion and Friction Angle</u>.

Assumption. For sub-vertical joints, joint cohesion and joint friction angle values of 0 MPa and 33 degrees, respectively, are assumed; for sub-horizontal joints, values of 0.7 ± 0.1 MPa and 44 ± 2 degrees, respectively, are assumed; and for random joints, values of 0 MPa and 33 degrees, respectively, are assumed.

Rationale for Assumption. In Appendix B, for the middle non-lithophysal zone and the lower non-lithophysal zone, values for joint cohesion and joint friction angle are taken from BSC (2004 [DIRS 166107], Table E-5) for the different sets of joints. Values for the upper lithophysal zone and the lower lithophysal zone are not provided in that report. However, because the lithophysal units are similar in mineralogy, thickness, and tectonic history, it is reasonable to adopt the same values of joint cohesion and joint friction angle for the lithophysal units as for the non-lithophysal units.

Dilation Angle.

Assumption. For joint dilation angle, defined as the ratio of normal displacement to plastic shear displacement, a value of 0 degrees is assumed for all joints.

Rationale for Assumption. During joint shearing the dilation angle generally is not constant. It increases from zero to a maximum value with increasing shear displacement, and then tends to decrease again to zero with further shearing (as damage of the joint wall material accumulates). Its value also depends significantly on the amount of normal stress supported by the joint. During initial shearing, damage of the joint wall material occurs (e.g., asperities are sheared or crushed/ground), which reduces the dilation angle. Although some recovery of the dilation angle may occur upon shear reversal, subsequent cycles also cause damage accumulation that further reduces the dilation angle. Because the purpose of the analyses described in Appendix B is to determine steady-state damping effects in a rock mass from repeated shear cycles, it is reasonable to assume that sufficient joint damage has occurred such that the joint dilation angle is zero.

Joint dilation causes a very slight increase in the confinement (or mean stress) in the rock mass. Because a stress boundary condition is used along the top of the model, such confining effects will be limited as the model is allowed to displace vertically upward in response to any dilation.

Tensile Strength.

Assumption. Joint tensile strength is assumed to have a value of 0 MPa for vertical to sub-vertical joints in all units, as well as any random joints.

Rationale for Assumption. Vertical to sub-vertical joints are generally rough to smooth, unaltered, and unfilled joints. They represent discontinuities, which by definition have no tensile strength. This assumption is consistent with common rock-mechanics practice that most joints have very low to zero tensile strength. For sub-horizontal joints, the tensile strength is computed as the cohesion divided by the tangent of the friction angle.

Shear Stiffness.

Assumption. Joint shear stiffness for the lithophysal units is assumed to be proportional to the joint shear stiffness of the non-lithophysal units.

Rationale for Assumption. Values of rock mass and joint shear stiffness for all units are scaled to obtain the appropriate shear-wave velocity as measured in the field. Because the lithophysal units are similar in mineralogy, thickness, and tectonic history, it is reasonable to adopt the approach for the lithophysal units as for the non-lithophysal units. Scaling factors used are 0.48, 0.90, 0.85, and 0.51 for the upper lithophysal unit, middle non-lithophysal unit, lower lithophysal unit, and lower non-lithophysal unit, respectively (Appendix B-Table 1).

Normal Stiffness.

Assumption. Joint normal stiffness is assumed to be twice the joint shear stiffness.

Rationale for Assumption. Joint normal stiffness is typically nonlinear and increases with increasing normal stress. The pre-peak strength joint shear stiffness is typically linear but tends to become nonlinear (decrease) as peak strength is approached. The relative magnitude of the joint normal and shear stiffness are typically within one order of magnitude. For the purpose of these calculations, the normal stiffness is taken as constant and twice the shear stiffness value. Typically, results are not sensitive to this parameter value unless it is varied by several orders of magnitude.

5.4 EXTREME STRESS DROP DISTRIBUTION

Assumption. The assumed distribution for extreme stress drop is lognormal with a median of 400 bars and a log-normal standard deviation of 0.6. For implementation, the distribution is approximated by three values: 150 bars, 400 bars, and 1100 bars with weights of 0.2, 0.6, and 0.2, respectively (Appendix A, Sections A3.2.1.3 and A4.3).

Rationale for Assumption. An extreme stress drop is one that would produce extreme ground motion-- ground motion far in excess of levels recorded historically. Considered probabilistically, extreme ground motions are characterized by very low AFEs and their ability to be physically realized within the geologic setting of Yucca Mountain has been questioned (Corradini 2003 [DIRS 171191], Reiter 2004 [DIRS 170694], Bommer et al. 2004 [DIRS 184601]). A distribution for an extreme stress drop, in the context of the stress parameter for the stochastic point-source ground motion model, is assumed. The assumption is used to provide reasonable conditioning of the AFEs for reference rock outcrop ground motion at Yucca Mountain, consistent with the geologic setting.

In developing the technical basis for an assumed extreme stress drop distribution, a series of workshops were held involving experts in the study of stress drop and the use of the stochastic point-source ground motion model (Appendix A, Section A3.2.1). The experts consisted of Dr. Gail Atkinson, Dr. David Boore, Dr. Arthur McGarr, and Dr. Walter Silva. During the workshops the experts discussed various data sets and approaches for assessing a distribution for extreme stress drop. The technical basis for the assumed distribution is informed by those discussions and documented in Appendix A, Section A3.2.1.3.

5.5 LOWER-BOUND STRAIN-COMPATIBLE SHEAR-WAVE VELOCITY

Assumption. The lower-bound strain-compatible shear-wave velocity taken to be 500 ft/sec.

Rationale for Assumption. NRC (2007 DIRS [180932], Section 3.7.2) indicates that, in developing strain-compatible material properties for soil-structure interaction analyses, the lower bound shear modulus should not be less than that value consistent with standard foundation analysis that yields foundation settlement under static loads exceeding design allowables. Taking a mat settlement value (δ) of 2 in, a maximum building load (σ_v) of 5 ksf, and a depth of compressible material of 70 ft (BSC 2007 [DIRS 184595]), Young's modulus is computed as

$$E = \left(\frac{\sigma_V}{\delta}\right) depth = 2.1 \times 10^3 \; ksf$$

Shear modulus (G) is then computed as

$$G = \frac{E}{2(1+\upsilon)} = 840\ ksf$$

in which Poisson's ratio (ν) is taken as 0.25. Finally, shear-wave velocity is computed as

$$V_S = \left(G/\rho \right)^{1/2} = 465\,ft/\sec$$

in which unit mass (ρ) is taken as 3.885 slug/ft^3. This result is rounded to 500 ft/sec to give the assumed value.

The above estimate is only meant to demonstrate that it is very unlikely for the shear wave velocity to be lower than 500 fps. This reasoning is consistent with the fact that the onsite alluvial soils consist of sandy gravel and cobbles with some cementation. In addition, the conservative estimate of settlement used in the above estimate can only occur if the entire 70 feet of alluvium consists of material with such a low shear wave velocity, which again, is highly unlikely.

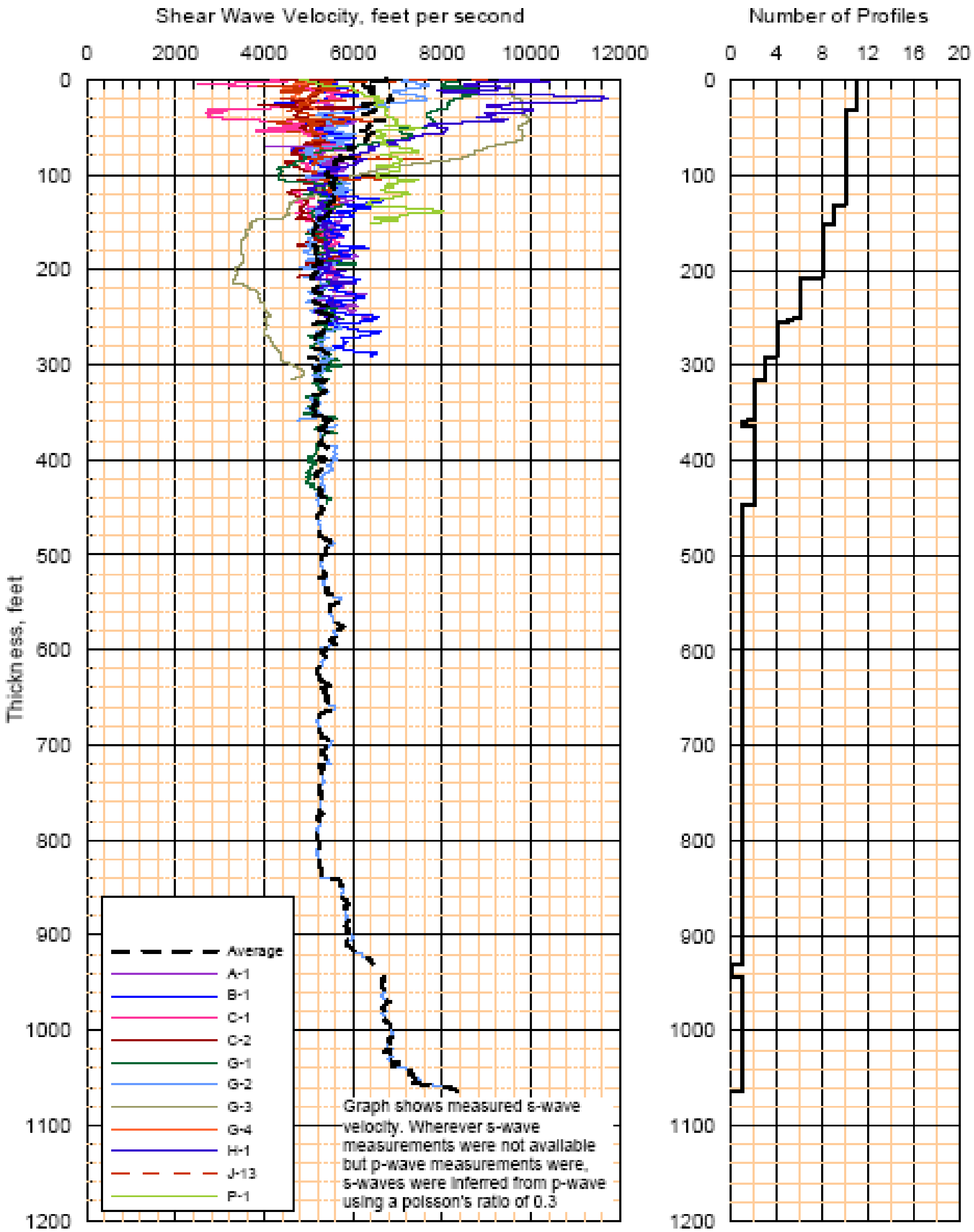
5.6 ALLUVIUM AND TUFF BULK DENSITY

Assumption. Alluvium has a uniform bulk density of 1.8 g/cm^3 (112 pcf). Tuff of the Timber Mountain and Paintbrush Groups has a uniform bulk density of 2.2 g/cm^3 (137 pcf). Tuff of the Calico Hills Formation and Prow Pass Tuff has a uniform bulk density of 2.4 g/cm^3 (150 pcf).

Rationale for Assumption. Densities are required input in the site response modeling but the resulting ground motions have a negligible sensitivity to the parameter since they vary little throughout the profiles. Also, material profiles represent a one-dimensional approximation to the conditions at the site and not a specific geologic column except in a gross sense (alluvium, tuff of the Timber Mountain and Paintbrush Groups, tuff of the Calico Hills Formation and Prow Pass Tuff). In addition, velocities and dynamic material properties of column layers are randomized for the site response modeling. Because of the lack of ground motion sensitivity to the range of material densities, a single uniform density is used each for alluvium, for tuff of the Timber Mountain and Paintbrush Groups, and for tuff of the Calico Hills Formation and Prow Pass Tuff. Densities are adopted that show an increase in density with depth.

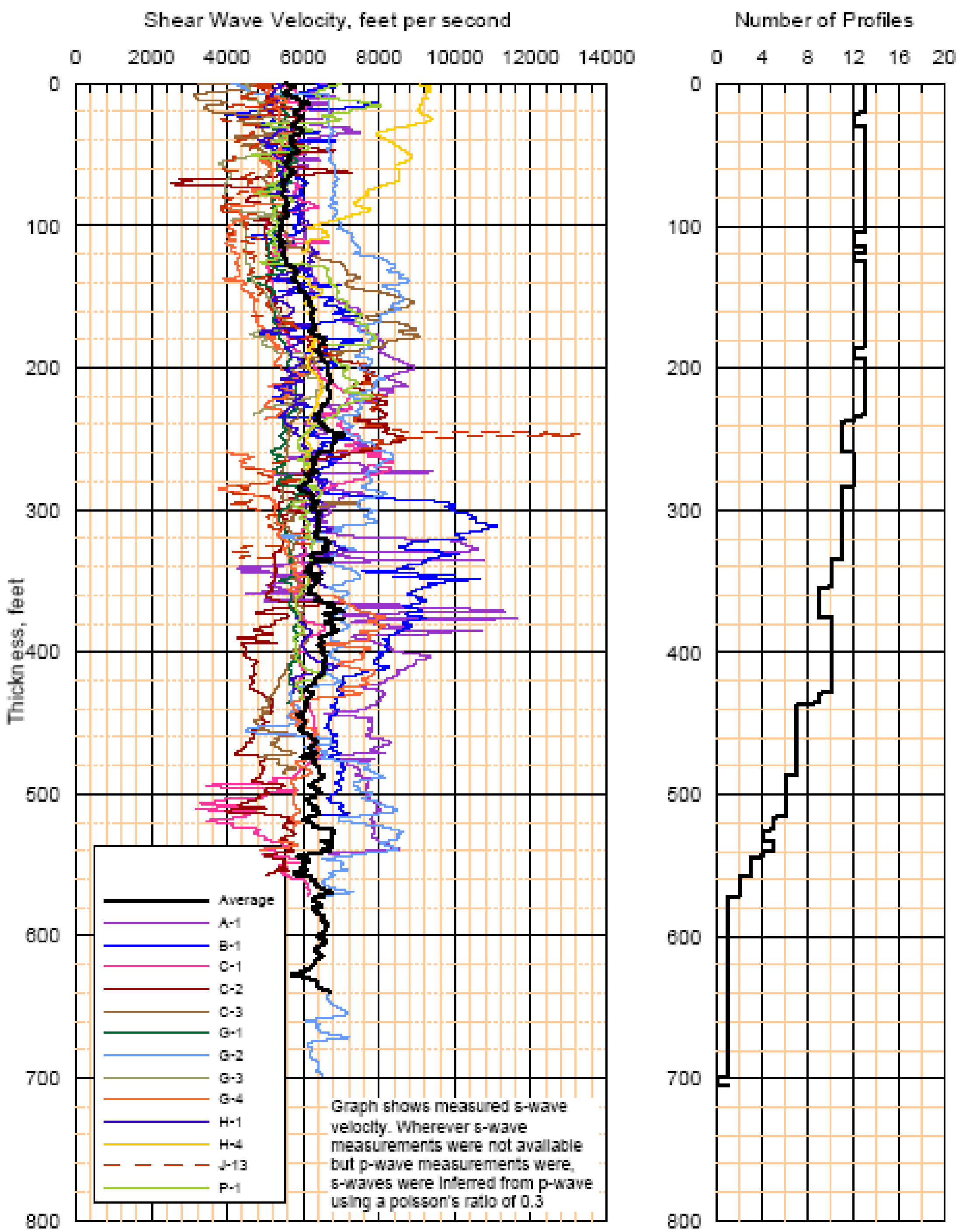
For alluvium and tuff of the Timber Mountain and Paintbrush Groups, assumed values for density are taken from BSC (2004 [DIRS 170027], Section 6.2.3.7). As described in that report, the value for alluvium is based on gamma-gamma density measurements in two boreholes at the SFA. The value for tuff is based on gamma-gamma measurements from the Tiva Canyon Tuff and on dry bulk density for core samples from the Topopah Spring Tuff middle-nonlithophysal and lower-lithophysal units. More recent measurements of density for core samples from the Topopah Spring Tuff (SNL 2008 [DIRS 183779], Table 6.5-3) are consistent with the assumed value.

For tuff underlying the Paintbrush Group, an increase in density is assumed to 2.4 g/cm^3 (150 pcf). The increase is to reflect an assumed effect of increasing confining pressure. Note, however, dynamic properties of small samples from the Calico Hills Formation and Prow Pass Tuff show little effect of confining pressures up to about 3 MPa (e.g., SNL 2008 [DIRS 183779], Figure 6.5-8). Mean densities for core samples from the Calico Hills Formation and Prow Pass Tuff range from about 1.5 to 2.0 g/cm^3 (94 to 125 pcf) (Flint 1998 [DIRS 100033], Table 7; SNL 2008 [DIRS 183779], Table 6.5-3). While the assumed value for in situ conditions is high relative to laboratory measured values, given the lack of ground motion sensitivity to the value of density used, an assumed value of 2.4 g/cm^3 is acceptable.



Source: Nelson et al. 1991 [101272]

Figure 5-1. Shear-wave Velocity Data for the Calico Hills Formation



Source: Nelson et al. 1991 [101272]

Figure 5-2. Shear-wave Velocity Data for the Prow Pass Tuff