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Study Plan Number 8.3.1.17.3.5

Study Plan Title GROUND MOTION AT THE SITE FROM CONTROLLING SEISMIC EVENTS

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PREFACE

This study plan extends the discussions of Study 8.3.1.17.3.5 in the Site Characterization Plan (SCP). Sections 1, 4, and 5 are taken largely from the SCP and from related Project documents. Sections 2 and 3 discuss the bases for the planned tests and the plans themselves in greater detail than is found in the SCP.

The study is part of the preclosure tectonics program. It is one of a series of related studies that collect and synthesize information about earthquake sources and underground nuclear explosions (UNEs) in the site region in order to estimate the vibratory ground motion hazard relative to the proposed repository. Stephen Hartzell is the principal author of the study plan. Frances R. Singer prepared sections 4 and 5, and assisted in writing section 1.

ABSTRACT

Study 8.3.1.17.3.5 will identify those 10,000-yr cumulative slip earthquake sources, other maximum magnitude events, and underground nuclear explosions (UNEs) that would generate the most severe ground motions at the Yucca Mountain site, in the frequency band from 0.5 to 33 Hz. When these controlling seismic events have been identified, the best methods from among five alternatives for calculating the ground motions will be determined, based on the availability of recorded ground motions for small events and knowledge of the local velocity structure. The time histories and response spectra at the Yucca Mountain site will then be computed using the best method(s).

Identification of controlling seismic events and resulting ground motions are required to design the repository in accordance with tentative design goals for predicting the performance of the repository.

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STUDY 8.3.1.17.3.5
GROUND MOTION AT THE SITE FROM CONTROLLING SEISMIC EVENTS

Study 8.3.1.17.3.5 consists of two activities:

- Identify controlling seismic events
- Characterize ground motion from the controlling seismic events

The study is part of the preclosure tectonics program (fig. 1-1), and is included in Investigation 8.3.1.17.3, Studies to provide required information on vibratory ground motion that could affect repository design or performance (fig. 1-2).

1. PURPOSE AND OBJECTIVE OF THE STUDY

The objectives of this study are to: (1) identify the controlling seismic events at the repository site, and (2) calculate the ground motions from the events. Objectives specific to each activity are discussed in sections 3.1 and 3.2, respectively.

1.1 Information to be obtained and how that information will be used

Information for identifying controlling seismic events will be obtained primarily from Studies 8.3.1.17.3.1, Relevant earthquake sources, and 8.3.1.17.3.2, Underground nuclear explosion sources (fig. 1-2). Controlling-event ground motions will be characterized by suites of strong-motion time histories that are representative in terms of expected amplitude, frequency content, and duration. Different methodologies for constructing these time histories will be evaluated. The calculations will also use information provided by Study 8.3.1.17.3.4, Effects of local site geology on ground motions, which incorporates possible amplification and attenuation effects specific to the site.

The specific information to be obtained in each activity is discussed in sections 3.1.1 and 3.2.1. The results will be used for measuring repository performance against performance measures as discussed in section 1.2; uses of the information for supporting other studies are discussed in section 4.

1.2 Rationale and justification for the information to be obtained--why the information is needed

This study is needed as a basis for evaluating the hazards posed by those underground nuclear explosions (UNEs) or 10,000-yr cumulative slip earthquakes and other maximum magnitude events that would generate the most severe ground motions at the site, at frequencies of engineering significance. Identification of these controlling seismic events and resulting ground motions are required to design the repository in accordance with tentative design goals for predicting the performance of the repository, and for measuring the predicted performance against tentative goals associated with performance measures.

Information on potential earthquake sources that may control ground motion at frequencies within the range of engineering significance are needed to design repository facilities to withstand the effects of vibratory ground motions. This information serves as a basis for assessing the likelihood of seismic ground motions that could directly or indirectly affect the surface or underground facilities both during operation of the repository and after closure (see figures 1-2 and 1-3).

The information to be obtained in this study is also needed to satisfy certain regulatory requirements, most specifically those embodied in Design Issue 4.4 (Technologies for repository construction, operation, closure, and decommissioning; SCP section 8.3.2.5); and 1-12 (Seal characteristics; SCP section 8.3.3.2).

For Issue 4.4, information from this study is needed to satisfy the tentative goals associated with two performance measures: (1) the locations of surface facilities important to safety (FITS) and (2) the ability to continue preclosure operations and retrieve waste (see SCP tables 8.3.2.5-1 and 8.3.2.5-2). The goals for those performance measures deal with the locations of underground and surface facilities important to safety (see SCP tables 8.3.1.17-5b, -5a, -6b, -6a; 8.3.2.5-1 and -2). The results of the study will be used to support design and performance parameters bearing on (1) the development of a seismic design-basis for FITS, and (2) the identification of credible accidents that might be initiated by seismic events and lead to the release of radioactive materials.

For Issue 1.12, information obtained from the present study will be used to evaluate the design and performance parameter bearing on seismic response spectra at selected areas in shafts, ramps, and the underground facilities. Specifically, information on design-basis ground motion time histories and corresponding spectra will be used to evaluate the behavior of selected sealing components under realistic in situ conditions as well as under unlikely conditions at site specific locations. The data will be used to satisfy tentative postclosure design goals associated with limiting or restricting the amount of water entering shafts, ramps, and the underground facility (see SCP tables 8.3.3.2-1 and 8.3.3.2-4).

Study 8.3.1.17.3.5: Ground motion at the site from controlling seismic events

Finally, information from this study will contribute indirectly to the resolution of performance issues 1.1, 1.8, 1.9, and 1.11 (SCP sections 8.3.5.13, 8.3.5.17, 8.3.5.18 and 8.3.2.2 respectively; this study plan, fig. 1-3) through its contributions to the preclosure tectonics program.

2. RATIONALE FOR SELECTING THE STUDY

This study brings together much of the information obtained in other studies dealing with ground motions from earthquake and UNE sources (8.3.1.17.3.1, Relevant earthquake sources; 8.3.1.17.3.2, Underground nuclear explosion sources; 8.3.1.17.3.3, Ground motion from regional earthquakes and underground nuclear explosions; 8.3.1.17.3.4, Effects of local site geology on ground motions) (fig. 1-2). However, unlike study 8.3.1.17.3.3, which is primarily concerned with peak ground motion parameters as a function of magnitude and distance, this study focuses on generating time histories and response spectra for those specific sources (UNEs and 10,000-yr cumulative slip earthquakes) that will generate the most severe ground motion at the site at frequencies of engineering interest.

2.1 Activity 8.3.1.17.3.5.1 Identify controlling seismic events

2.1.1 Rationale for the type of test selected

The single test for this activity--identify controlling seismic events--follows directly from the determination of the 10,000-year cumulative slip earthquakes and other maximum magnitude events on relevant sources in Study 8.3.1.17.3.1, the identification of potential future UNEs in Study 8.3.1.17.3.2, the earthquake and UNE ground motion models developed in Study 8.3.1.17.3.3, and the local site correction factors developed in Study 8.3.1.17.3.4.

2.1.2 Rationale for selecting the number, location, duration, and timing of tests

Site ground motion parameters, including peak ground acceleration and velocity, duration, and response spectral ordinates at 1 Hz intervals, will be calculated for each of the 10,000-yr cumulative slip earthquakes and other maximum magnitude events and for the closest and largest potential UNEs that are determined to produce the most severe ground motions at the site at frequencies of engineering interest. The locations of the events to be tested as controlling will come directly from Studies 8.3.1.17.3.1 (Relevant earthquake sources) and 8.3.1.17.3.2 (Underground nuclear explosion sources). Much of the work will be done after receiving input from Studies 8.3.1.17.3.1 and 8.3.1.17.3.2 on the location and type of significant sources, and Studies 8.3.1.17.3.3 and 8.3.1.17.3.4 on the ground motion attenuation as a function of distance and magnitude and effects of local site geology on ground motion. However, most of the software development needed to perform the required computer simulations can be done before obtaining this information. Also, the collection of required empirical Green's functions or empirical source functions for the calculation of ground motion at the site (discussed in section 3), should proceed before the completion of the above studies.

2.1.3 Constraints: Factors affecting selection of tests

The choice of test methods for this activity was not affected by the following factors: impact on the site, simulation of repository conditions, limits of analytical methods, capability of analytical methods, scale and applicability, interference with other tests, or interference with exploratory shaft. The accuracy and precision with which the controlling seismic events can be selected will depend on the accuracy and precision of the methods used to calculate the ground motion parameters under Activity 8.3.1.17.3.5.2. If several seismic sources are identified as controlling events, calculation of the ground motion time histories will determine which sources are the most important at specific frequencies. In this case, the accuracy and precision of the methods used to calculate ground motion time histories will be a contributing factor.

2.2 Activity 8.3.1.17.3.5.2 Characterize ground motion from the controlling seismic events

2.2.1 Rationale for the types of tests selected

As stated in the SCP, two general approaches are possible for the calculation of ground motion for the controlling seismic events: (1) scale or otherwise apply a transfer function to existing strong motion records so they represent the correct magnitude, distance, and site conditions for Yucca Mountain, or (2) apply a Green's function summation technique using either empirical or theoretical Green's functions. Other methods have also been used which combine different aspects of these two general approaches. The approach in this activity is to pursue several different techniques to better evaluate the uncertainty in the final ground motion parameters (see sec. 3.2). Calculation of ground motion for a UNE source does not present the degree of difficultly that an earthquake source does. This simplification occurs because a UNE can to treated as a point source. Also, if a UNE source is determined to be a controlling event, a set of existing strong motion records from previous UNE sources at the Nevada Test Site can be used to estimate the required time histories of ground motion.

2.2.2 Rationale for selecting the number, location, duration, and timing of tests

Five approaches are identified as being potential methods of calculating the ground motion for a controlling seismic event:

- **Method 1 (Scaling)** - Scaling of existing records with respect to distance, site condition, and source size using local magnitude (Guzman and Jennings, 1976; Heaton et al., 1986)

- **Method 2 (Transfer)** - Convolution of existing records with a transfer function, which is designed to correct the ground motion for the conditions of the site at which it was recorded to the conditions of the site under study. The transfer function is obtained by deconvolving an appropriate small event in the Yucca Mountain region from a seismogram of a small event in the region for which there is data (Gomberg and King, in press).

- Method 3 (Theoretical) - Summation of theoretical Green's functions over a finite fault (Hartzell et al., 1978; Imagawa et al., 1984).
- Method 4 (Empirical) - Summation of empirical Green's functions over a finite fault (Hartzell, 1978; Kanamori, 1979; Irikura, 1983; Hadley and Helmberger, 1980).
- Method 5 (Semi-empirical) - Convolution of empirical source functions with theoretically computed propagation path effects in a finite fault summation (Wald et al., 1988a; 1988b).

The final selection of the preferred technique or techniques will depend on the location and mechanism of the controlling seismic events, the availability of empirical Green's functions, and the existence of appropriate strong motion records for scaling or transfer. For an earthquake source, methods 3, 4, 5, and possibly method 2 will require specification of the slip distribution on the fault plane of the controlling earthquake. The distribution of slip is a major source of uncertainty. Two approaches are possible for the specification of the distribution of slip: (1) use the slip distribution for another earthquake (or average of other earthquakes) of similar magnitude (Hartzell and Heaton, 1983, 1986; Mendoza and Hartzell, 1988, 1989; Hartzell, 1989; Hartzell and Iida, 1990); and (2) use a randomly generated slip distribution, which has the characteristics of distributions determined for actual earthquakes (Joyner, 1984; Joyner et al., 1988).

For UNE sources, considerable work has already been done. Estimation of ground motion at Yucca Mountain from UNE sources is facilitated by a large number of recordings from appropriate events (Vortman and Long, 1982a, b; Vortman, 1986). These data can be used as empirical high-frequency (0.5 to 33Hz) estimates of the ground motion from future UNE sources. Phillips (1988) has calculated pseudo relative velocity response spectra (PSRV) for a large number of surface and downhole ground motion records at Yucca Mountain, and made predictive fits with multiple linear regression techniques. The ability to model UNE time-domain waveforms has also been demonstrated by Walck and Phillips (1990), and Barker et al (1991). These studies have been used to produce one- and two-dimensional estimates of the local velocity structure which complement the velocity model information based on refraction studies (Hoffman and Mooney, 1983; Ackerman et al, 1988). These velocity models can be used to calculate theoretical ground motions for UNE or earthquake sources along propagation paths of particular interest.

With regard to location, duration, and timing, the discussion of these topics in section 2.1.2 is applicable to this section.

2.2.3 Constraints: factors affecting selection of tests

The choice of test methods for this activity was not affected by the following factors: impacts on the site, simulation of repository conditions, limits of analytical methods, capability of analytical methods, scale and applicability, interference with other tests, and interference with exploratory shaft. It should be noted, however, that this study requires input from the other studies mentioned in previous sections. Also, the test methods were selected to encompass the currently used methodologies of simulating ground motion to high frequencies (0.5 to 33 Hz) and are recognized to encompass the current state-of-the-art.

3. DESCRIPTION OF TESTS AND ANALYSES

3.1 Activity 8.3.1.17.3.5.1 Identify controlling seismic events

The objective of this activity is to identify those UNEs or 10,000-yr cumulative slip earthquakes and other maximum magnitude events that would produce the most severe ground motions at the site at frequencies of engineering significance.

3.1.1 General approach

The controlling seismic events will be identified on the basis of the following ground motion parameters; peak ground acceleration, and velocity, duration, and response spectral ordinates at 1 Hz intervals within the range of interest (0.5 to 33 Hz). The list of candidate sources will come from Studies 8.3.1.17.3.1 (Relevant earthquake sources) and 8.3.1.17.3.2 (Underground nuclear explosion sources), including data on (1) earthquake magnitude and epicentral location; (2) fault strike, dip, and expected slip direction; and (3) distance, azimuth, depth, and yield of controlling UNEs, if any.

Previous work has concentrated on analysis of UNE ground motion records and probabilistic approaches to the estimation of earthquake-generated, peak-ground-motion parameters. Phillips (1988, 1991) has done regression fits to a large number of surface and downhole UNE velocity response spectra at Yucca Mountain. Peak ground motion parameters (acceleration, velocity, displacement) from UNE sources have been tabulated by Vortman and Long (1982a, b) and Vortman (1986). Probabilistic seismic hazard modeling has been used by URS/John Blume (1986) to estimate 500-year and 2,000-year return period peak ground motions at Yucca Mountain for earthquake sources. A primary objective of this study is to use scaling and/or deterministic methods to obtain time-domain estimates of ground motion. Because of the large data base of UNE ground motion records at Yucca Mountain, which can serve as empirical estimates of ground motion for future UNE sources, the work of this study will need to concentrate on earthquake sources.

3.1.2 Test method and procedures

No procedures are required, inasmuch as this activity will compile and synthesize data from other studies.

3.1.3 QA requirements

Quality Assurance (QA) requirements for this activity will be specified in a Yucca Mountain Project QA Grading Report, which will be issued prior to the start of work as a separate controlled document. All procedures applicable to this activity will be identified on the basis of the findings in the Grading Report and will be prepared in accordance with applicable QA requirements.

3.1.4 Required tolerances, accuracy, and precision

No explicit requirements for tolerance, accuracy, or precision have been specified for this activity. It is, however, subject to the tolerances, accuracies, and precisions of the studies from which it receives input.

3.1.5 Range of expected results

This activity will identify the 10,000-year cumulative slip earthquakes, other maximum magnitude events, and UNE sources that are expected to generate the most severe ground motion at the Yucca Mountain site.

3.1.6 Equipment

The equipment needed for this activity includes a high-speed, modern computer similar to a SUN4 or the equivalent. In this activity, software to simulate high-frequency radiation (0.5 to 33 Hz) from a finite fault will be developed and certified for use via a software QA program.

3.1.7 Data-reduction techniques

A variety of computer-generated earthquake and UNE sources will be calculated as described section 3.2.

3.1.8 Representativeness of results

The representativeness of the results of this activity will depend on the accuracy of the information obtained in Studies 8.3.1.17.3.1, 8.3.1.17.3.2, 8.3.1.17.3.3, and 8.3.1.17.3.4 and on the accuracy of the computer simulations in Activity 8.3.1.17.3.5.2.

3.1.9 Relations to performance goals and confidence levels

Controlling seismic events must be identified in order to assess the impact of ground motion from the 10,000-year cumulative slip earthquakes and other maximum magnitude events and UNE's on the design of the Yucca Mountain repository (see sec. 1.2).

3.2 Activity 8.3.1.17.3.5.2 Characterize ground motion from the controlling seismic events

The objective of this activity is to generate suites of strong-motion time histories and corresponding response spectra that are representative in amplitude, frequency content, and duration of site ground motions that could be generated by the controlling seismic events.

3.2.1 General approach

No simple procedure is currently recognized as the best for calculating high-frequency seismic energy radiated from a hypothetical finite fault; accordingly, this activity will pursue five methods (described below) which encompass the state-of-the-art. This approach allows estimation of the error in the ground motion parameters, taken from the spread in the estimates derived from the different methods. Also, these different methods require different input data, which may not all be obtainable in the desired amounts. After initial investigations and field activities, a subset of the five methods may dominate as the most effective.

The methods described below are presented in terms of the calculation of the time histories of ground motion from a finite earthquake source. However, if the controlling event should be a UNE, obvious simplifications can be made for sources of this type.

3.2.2 Test method and procedures

Method 1 (Scaling)

Following the work of Guzman and Jennings (1976) and Heaton et al. (1986), this method uses existing strong motion records, and scales them on the basis of local magnitude, distance, and site conditions.

The reliability of this method improves as the size of the strong motion data base increases. The seismic source in question is characterized in terms of the length and width of the rupture surface and the average stress drop. A moment magnitude is calculated from these parameters. The moment magnitude is converted to local magnitude, ML, with a correction factor for tectonic setting (intra-plate, subduction zone, or transform margin). A site correction factor, Cs, is determined; for example, Trifunac and Brady (1976) set Cs=0.15 for soft, 0.0 for intermediate, and -0.15 for hard sites. These values may not be the most appropriate for the Yucca Mountain site. Study 8.3.1.17.3.4, Effects of Local Site Geology on Ground Motions, will supply the most relevant values. Following the work of Jennings and Kanamori (1983), Hutton and Boore (1987), and Bakun and Joyner (1984), a local magnitude-distance correction factor, Ao, is determined for the closest distance of the rupture surface to the site. The expected amplitude on a Wood-Anderson seismometer is then calculated using the formula,

$$A_S = A_0 10^{(M_L + C_S)} \quad (1)$$

A similar procedure is then followed for all strong motion records in the data base that were recorded for earthquakes of similar magnitude, distance, and tectonic setting to the hypothesized event. For each record, the moment magnitude is determined and converted to local magnitude. The site correction factor, Csi, and the distance correction factor, Aoi, are determined for each record. Next, the expected amplitude on a Wood-Anderson seismometer is calculated for each record,

$$A_i = A_{oi}\, 10^{(M_{Li} + C_{si})} \tag{2}$$

Finally, the i-th record is multiplied by the scaling factor, Si,

$$S_i = A_s / A_i \tag{3}$$

The result of this scaling process is a suite of records that should be representative of the motions that could be expected at the site in question. To minimize possible errors in the above scaling process, records should be used that require the least amount of scaling. Although there are no local recordings of significant earthquakes in the region of the proposed repository, several studies have compiled ground motion records from western United States earthquakes (Joyner and Boore, 1981; Campbell, 1985; 1989a, b; 1991; and Somerville and Yoshimura, 1990). A subset of these records, carefully screened for appropriate path and site properties would give the best estimate by this method.

Method 2 (Transfer)

Following Gomberg and King (in press), this method empirically estimates the filter or transfer function that translates recordings of ground motion from one region to another. Consider the situation where we wish to estimate the ground motion in region A, for which there are no records of an appropriate size. The transfer function, T(r,t), is obtained by deconvolving the recording of a small event in region B, designated b(r,t), from a recording of a small event in region A, a(r,t). Records from earthquakes of the desired size in region B, designated B(r,t), are then transferred to region A by convolution with the transfer function such that,

$$A(r,t) = B(r,t) * T(r,t)$$

where $\mathfrak{F}(T(r,t)) = \tilde{T}(r,\omega) = \dfrac{\tilde{a}(r,\omega)}{\tilde{b}(r,\omega)}$ (4)

and $\mathfrak{F}$ indicates Fourier transform.

The focal mechanisms of the smaller earthquakes should be similar to the mechanisms of the larger events. Also, the source-time functions of the smaller earthquakes should be similar. This requirement is met by using small enough sources such that the time functions are approximately delta functions. Additional corrections can be made to the transfer function. For example, the transfer function can be low-pass filtered, if it is known that earthquakes in region

A have lower stress drops than earthquakes in region B. In the absence of appropriate data to produce the empirical transfer functions, they can be synthesized theoretically using estimates of the velocity structures from regions A and B.

If significant spatial variations in transfer function over the source region can be resolved, equation (4) can be replaced with a summation of sub-events where,

$$A(r,t) = \sum_{i}^{n} b(r,t)_i * f(r,t)_i * T(r,t)_i \qquad (5)$$

In equation (5), n is the number of regions with different transfer functions and is equal to the number of sub-events. f(r,t)i is a small earthquake record from the i-th portion of region B, and T(r,t) is the transfer function appropriate to the i-th portion. It is assumed that all of the source complexity of the large earthquake in region B (B(r,t)) can be represented by n source-time functions, f(r,t)i, which can be solved for by a least-squares or similar analysis of recordings of B(r,t).

Method 3 (Theoretical)

The displacement due to a slip dislocation over a fault surface S can be expressed (Burridge and Knopoff, 1964) by:

$$\vec{u}^{i}(\vec{y},t) = \int_{-\infty}^{\infty}\int_{S} \vec{s}(\vec{x},\tau) \cdot \vec{G}^{i}(\vec{x},t-\tau,\vec{y})\, d\vec{x}\, d\tau \qquad (6)$$

where u(y,t) is the i-th component of displacement at a location y and time t, s(x,τ) is the slip discontinuity across the fault surface at a position x and time t=τ , and G(x,t-τ,y) is the stress tensor as a function of position x and time t due to an impulsive point force applied at position y in the i-th coordinate direction at time t=τ. G(x,t-τ,y) may also be taken as the i-th component of displacement at the receiver position y due to a point dislocation at x on the fault, or in other words, the Green's function or impulse response of the medium. Equation (6) states that the displacement is the convolution of the slip distribution with the Green's function, integrated over the fault surface. Equation (6) can be discretized by replacing the integral over the fault surface with summations, and the integral over time with a convolution,

$$\vec{u}^{i}(\vec{y},t) = \frac{1}{n_L n_w} \sum_{1}^{n_L} \sum_{1}^{n_w} \vec{s}(\vec{x},t) * \vec{G}^{i}(\vec{x},t-t_r-t_T,\vec{y}) \qquad (7)$$

where n_L and n_W are the number of point sources along the length of the fault and down the width of the fault, respectively. t_r is the rupture time delay, and t_T is the travel time delay from the source to the receiver. In equation (7) we have normalized the total moment by the number of point sources in the summation. This method has been used by Hartzell et al. (1978) and Imagawa et al. (1984), as well as many other authors.

The application of equation (7) requires a knowledge of the velocity structure, which must be more detailed for the accurate computation of higher frequencies. Some effects, such as scattering and lateral heterogeneity, are hard to incorporate, due to the difficulty in calculating the required Green's functions. To more accurately simulate complexities in the real earth, it is desirable to incorporate an element of randomness in equation (7). A small component of randomness can be added to the rupture delay time, or to the spatial and temporal description of the slip distribution, s(x,t). Also, it is an observational fact that radiation pattern nodes are not well defined at frequencies higher than about 2 Hz (Liu and Helmberger, 1985). Therefore, application of a maximum cutoff frequency for radiation pattern terms is advisable.

Method 4 (Empirical)

If the velocity structure is not well known, or even if it is well known but too complex to allow computation of adequate Green's functions, recordings of small earthquakes can be used as empirical Green's functions. This method has been used in numerous studies (Hartzell, 1978; Kanamori, 1979; Irikura, 1983; Hadley and Helmberger, 1980; Heaton and Hartzell, 1989). The expression for the i-th component of displacement at location y is then,

$$\vec{u}^{i}(\vec{y},t) = c \sum_{1}^{n_L} \sum_{1}^{n_w} \sum_{1}^{n_\tau} \frac{\mathcal{R}'(\theta,\phi)}{\mathcal{R}(\theta,\phi)} \cdot \frac{R}{R'} \cdot \dot{s}(\vec{x},t) * \vec{G}^{i}(\vec{x},t-t_r-t_T-t_\tau,\vec{y})$$

where $c = \dfrac{M_0'}{n_L n_w n_\tau M_0} = 1$, if self-similar (8)

$$\tau = \frac{16\,S^{1/2}}{7\pi^{3/2}\beta}, \text{ rise time}$$

$$n_\tau = \tau'/\tau$$

Primed quantities refer to parameters for the large event to be simulated. S and β in the expression for rise time are the fault area and shear wave velocity at the source, respectively.

$G(x,t-t_r-t_T-t_\tau,y)$ is the ground motion at y due to a small earthquake at x. n_L and n_W are the number of small earthquakes needed to span the dimensions of the rupture area of the large event, which can be determined on the basis of a relationship between magnitude and fault area, such as $\log A = 1.07M_L - 4.71$ (Wyss, 1979). A third summation is added to equation (8) to account for the difference in rise times between the small and large events. The expression for rise time, τ, above is from Geller (1976), and is one of several theoretical expressions that could be used (Kanamori and Anderson, 1975; Day, 1982; Heaton and Hartzell, 1989; Heaton, 1990). n_τ empirical Green's functions are lagged and summed over the rise time of the large event.

This summation can also be replaced with a convolution with a function that corrects for the difference in rise times. Two additional terms appear in equation (8) to correct the empirical Green's function for radiation pattern and geometrical spreading. They are $\mathcal{R}(\Theta,\phi)$ and R. These corrections are needed in a finite fault summation process, because one seldom has an empirical Green's function at the exact location, and with the correct mechanism, as required. Spudich and Miller (1990) have developed a more accurate method of interpolating between Green's function. However, this method is computationally intensive, and still requires a good distribution of empirical Green's functions with known source parameters to interpolate between.

As with the use of theoretical Green's functions, randomness should be added to avoid systematic periodicities in the summation process and to better approximate real world complications. Randomness can be added to the rupture delay time, t_r, the rise time delay, t_r, and the slip distribution, s(x,t). Use of equation (8) avoids the need to know the velocity structure, but one must have a set of well recorded earthquakes of the appropriate size and spatial distribution.

Method 5 (Semi-empirical)

The semi-empirical method of Wald et al. (1988a, 1988b) includes a combination of theoretical and empirical aspects of source and propagation effects. The gross propagation effects are calculated theoretically. Details of the source radiation and propagation are included empirically with empirical source functions. The ground motion at location y and time t can be expressed as,

$$\vec{u}^{i}(\vec{y},t) = c \sum_{1}^{n_L} \sum_{1}^{n_w} \sum_{1}^{n_\tau} \frac{\eta'}{\eta} \cdot \vec{g}(\vec{x},t) * \vec{G}^{i}(\vec{x},t-t_r-t_T-t_\tau,\vec{y}) \tag{9}$$

where c, n_L, n_W, and n_τ are the same as in equation (8). $G(x,t-t_r-t_T-t_\tau,y)$ is the theoretical Green's function with no receiver function or radiation pattern. g(x,t) is the empirical source function. g(x,t) is obtained from the close-in recording of a small earthquake, where the epicentral distance is similar to the source depth, and need not necessarily be from the same region as the large earthquake to be simulated. With this distance restriction, the empirical source function can be adequately corrected back to the source by simply removing the effect of geometrical spreading. Assuming that most attenuation occurs near the surface, g(x,t) includes an estimate of the effective attenuation of propagation. By recording several g(x,t) functions for a single event, a look-up table of empirical source functions is obtained which empirically includes a frequency dependent radiation pattern. Finally, the empirical source function is corrected for the receiver function, indicated in equation (9) by the ratio, η'/η, where the primed quantity refers to the large event to be simulated.

The semi-empirical method may have an advantage over the purely empirical method, since a good distribution of empirical Green's functions from the source region is not needed. The frequency dependence of the radiation pattern is also included. However, one must have a well recorded set of empirical source functions, which can be obtained from one appropriately sized event, recorded at a sufficient number of stations to adequately sample the radiation pattern.

Boore (1983) presents another approach to the estimation of strong ground motions. The method uses a stochastic simulation process to generate acceleration time histories by requiring the radiated energy to match a given spectral shape. Following Aki (1967) and Brune (1970), Boore (1983) uses the ω^2 source spectrum. Ground motion time series are calculated by first filling an array with random, white, Gaussian noise, with zero expected mean and variance chosen to give unit spectral amplitude on the average. A transient accelerogram is obtained by using a shaping window, whose length is controlled by the source duration. The signal is then transformed into the frequency domain and multiplied by the model spectrum. The model spectrum includes the effects of anelastic attenuation, Q, and the observation that acceleration spectra often show a sharp decrease with increasing frequency, above some cutoff frequency, f_{max} (Hanks, 1982). The model spectrum is scaled by 1/R for geometrical spreading, the moment of the source, an average radiation pattern term, and a factor to account for amplification due to the free surface. Transformation back to the time domain gives the desired time series. Boore (1983) shows this estimator to compare favorably with average values of peak acceleration, peak velocity, and Wood-Anderson instrument response, as a function of magnitude. However, there is a large scatter in the data from which these average values are derived, due to variations in source, path, and site effects, which this method does not address. Since whole-space, point-source Green's functions have been used with this technique, it does not produce variations in frequency content with time, such as would be observed between body waves and surface waves. Also, the method is a point source approximation, and may break down for predictions of motions close to large earthquakes. For these reasons, the Boore (1983) method is considered to be less appropriate as a primary method of calculating ground motions at the Yucca Mountain site, than the methods discussed above. However, the Boore (1983) method could be useful as a means of calculating average ground motion estimates for controlling events, depending on their size and distance from the site.

Methods 3, 4, and 5 above all require a random component to the source description for the high frequencies, which can not be modeled deterministically. Methods 4 and 5, as presented, also set the number of small events to be summed by the ratio of the moments of the small and large earthquakes. If N events are summed in a random manner, the low frequency spectral amplitude will scale like N, while the high frequency spectral amplitude will scale like $\sqrt{N}$. This spectral scaling is not consistent with the often observed ω^2 source model for earthquakes. To preserve both low and high frequency levels, Joyner and Boore (1986) proposed a summation procedure in which $N^{4/3}$ events are summed and scaled by the factor $N^{-1/3}$. Wennerberg (1990) proposed another summation scheme which more accurately represents energy near the spectral corner. A related observation was make by Heaton and Hartzell (1989), in the simulation of ground motion for large subduction zone earthquakes, with magnitude greater than 8.0. Using Method 4, they found that a smaller number of events was required in the summation, than indicated by the ratio of the moments, to obtain the proper high frequency amplitude. However, the methods of Joyner and Boore (1986) and Wennerberg (1990) are of limited application to the estimation of ground motion at the Yucca Mountain site. This conclusion comes from the fact that they are formulated for a point source, not an extended fault, with a single function being lagged and summed randomly. There are no variations in slip amplitude, radiation pattern, or rupture propagation effects with these formulations. In recent applications of Method 5 by Wald et al. (1988a), Somerville et al. (1991), and Cohee et al. (1991), the moment ratio of the small and large events was used to set the number of sources in the summation. They simulated a magnitude 8.0 event using a magnitude 6.9 empirical source function and up to a magnitude 7.2 event using a magnitude 5.2 empirical source function, and obtained good overall agreement with observed data. But at the highest frequencies, these summations may appear random, and care must be exercised in the simulation of ground motions for Yucca Mountain to ensure that the high frequency spectral amplitude is not over estimated.

The calculation of ground motion at a subsurface site, such as the nuclear waste repository inside Yucca Mountain, requires an additional correction to the time histories of ground motion, not outlined in the above methods. The methods discussed above require Green's functions recorded at the site of interest, which in this case is below the earth's surface. Since these records would be difficult to obtain, the estimates of ground motion at the surface must be corrected to the desired depth. Two competing effects take place as seismic waves approach the free surface: amplification due to lower rigidities, and attenuation due to lower Q. Either effect may dominate in a particular frequency band, but peak amplitudes are usually smaller at depth. In a unique study of damage to underground facilities during the 1976 Tang-Shan earthquake, Jing-Ming (1985) observes an exponential decrease in damage with depth to 500 m, and constant damage below this depth. A plane-layer Haskell model has been shown to accurately predict surface ground motions using borehole records as input (Joyner et al., 1976; Seale and Archuleta, 1989). This technique has also been successful at estimating ground motion on soft soil sites using records from hard rock sites as input (Seed et al., 1988; Joyner et al., 1981). The same plane-layer Haskell method can be used to estimate ground motions at depth using surface records as input.

For UNE sources there is a considerable number of simultaneous measurements of ground motion from borehole and surface sensors (Vortman and Long, 1982a, b). These data have been analyzed in terms of time-domain waveforms and response spectral ratios by Long et al, (1982), and Phillips (1988, 1991), who found good repeatability of results at a particular station but insufficient data to develop a general depth-attenuation model for Yucca Mountain. The empirical measurements and theoretical calculations should complement each other in the estimation of ground motions at depth.

The empirical Green's function methods assume that low strain records can be added and scaled to produce large strain records (in other words, that linearity holds). Under high strains, theoretical and laboratory models of nonlinear soil behavior predict that rigidity decreases and damping increases. The change in damping usually dominates, and the ground response is shifted to longer periods with lower amplitudes. Examples of catastrophic nonlinear behavior, in the form of liquefaction of soils, are well known (Ishihara, 1985). Ishihara et al. (1981) documented a less dramatic example of nonlinear site response in which they show an increase in pore fluid pressure, presumably caused by volume changes in the soil, coincident with strong shaking on a hydraulic-fill island in Tokyo Bay. In this case the site conditions are unusual and very different from the dry environment of Yucca Mountain. Also, numerous studies (Celebi, 1987; Aki, 1988; Rogers et al., 1985; Tucker and King, 1984; Joyner et al., 1981; Jarpe et al, 1988) have found no evidence of nonlinearity in strong motion records, and conclude that small motions at a site can be used to predict large motions. Since earthquake-caused occurrences of nonlinear soil behavior are rare, it is difficult to assess under what conditions and what levels of shaking it becomes important. If nonlinear soil response is determined to be important at Yucca Mountain, the calculated ground motions can be modified to simulate its effects (Seed et al., 1986; American Society of Civil Engineers, 1985; Sun et al., 1988).

At the current stage of planning for this activity, the need for technical procedures is not anticipated. The five methods to be employed and evaluated are well documented in published papers, and the discussions given in the foregoing paragraphs suffice to detail their application to the present study.

3.2.3 QA requirements

See Section 3.1.3.

3.2.4 Required tolerances, accuracy, and precision

No explicit requirements for tolerance, accuracy, or precision have been specified for this activity; however, it is subject to the tolerances, accuracies, and precisions of the studies from which it receives input. Since it is difficult to evaluate the accuracy of the methods outlined in section 3.2.2, the best evaluation of the results is expected to come from a comparison of the different methods. It may be decided, based on the availability of empirical Green's function or empirical source functions, or on knowledge of the local velocity structure, that a subset of the five methods listed above represents the best alternative. Within the application of a particular method, an approach similar to that of Abrahamson et al. (in press) could be used to estimate errors. In this approach, the free source parameters are probabilistically varied to estimate the error associated with the uncertainty in each model parameters.

3.2.5 Range of expected results

This activity will calculate the ground motion time histories in the frequency range 0.5 to 33 Hz and the corresponding response spectra at 1 Hz intervals at the Yucca Mountain site. These calculations will be done for the 10,000-year cumulative slip earthquakes and other maximum magnitude events on nearby faults, or maximum potential underground nuclear explosions that would control site ground motion at any frequency between 0.5 and 33 Hz.

3.2.6 Equipment

The equipment needed for this activity includes a high-speed, modern computer similar to a SUN4 or the equivalent. In this activity, software to simulate high-frequency radiation (0.5 to 33 Hz) from a finite fault will be developed and certified for use via a software QA program.

3.2.7 Data-reduction techniques

A variety of computer-generated earthquake and UNE sources will be calculated as described in section 3.2.2.

3.2.8 Representativeness of results

The representativeness of the results of this activity will depend upon several factors: the accuracy of the information obtained from Studies 8.3.1.17.3.1 through 8.3.1.17.3.4, the accuracy of the computer simulations described in section 3.2.2, the availability of empirical Green's functions and empirical source functions, and knowledge of the local velocity structure.

The first two methods of estimating ground motion discussed in section 3.2.2 (Scaling and Transfer) require far less calculations and knowledge of the source structure and propagation effects. There is also no particular computational difficulty in making estimates of ground motion at high frequencies (0.5 to 33 Hz) using these two methods. However, they have their own limitations. The Scaling Method requires a data base of strong motion records from similar magnitude events located in similar tectonic settings with similar source to station distances and site conditions as the hypothesized event. Also, the method ignores source complications such as slip distribution, rupture mode (unilateral or bilateral), and rupture velocity, other than the range in effects of these parameters represented in the data base. The Scaling Method also makes no explicit corrections for frequency content or duration. However, if appropriate records are scaled (i.e., those with similar path and site conditions), these effects will be included. The Transfer Method requires recordings of smaller events of broad dynamic range and low noise level, from both the source region of the hypothesized event and the source region from which data is to be transferred. Given sufficient time and equipment, these records could be obtained, but they may not exist at present. Like the Scaling Method, this method is limited to the source parameters of the earthquakes for which there is data.

The third method mentioned in section 3.2.2 (Theoretical) is perhaps the least attractive for the computation of high frequency ground motion above 2 Hz. (This statement is not true for UNE sources, which can be considered to be point sources, and whose ground motion is considerably less complex at distances of a few tens of kilometers.) Below 2 Hz, numerous studies have demonstrated the ability to deterministically predict ground motion, on average, to within less than a factor of two. Much of the scatter in amplitudes has been ascribed to local site effects. Above 2 Hz, source and path complexities, make a purely theoretical approach difficult. Even if the structure could be accurately described in terms of a laterally homogeneous medium, computation of the required Green's functions for an extended source to 33 Hz would be impractical. There is also the difficulty of describing the source processes to 33 Hz. As mentioned above, a stochastic description of the source must be used at these frequencies.

The fourth method (Empirical) is the most desirable, provided that numerous, well-distributed, broadband empirical Green's functions are available for the source region of the hypothesized event. With these data, propagation path complexities are completely and accurately described, assuming the empirical Green's functions are recorded at the same location as the proposed site. However, one must still describe the source (rupture mode, rupture velocity, distribution of slip). Again, a stochastic description must be used at high frequencies.

The fifth method (Semi-empirical) was developed to take advantage of aspects of both the Theoretical and Empirical approaches. Seldom are their sufficient quality and number of empirical Green's functions. With this method, the gross propagation effects are calculated theoretically. Some of the source effects and propagation effects are included by using empirical source functions. Preferably, these empirical source functions would come from the source region of the hypothesized event, but need not. As with the Theoretical and Empirical approaches, the source description must be specified, and a stochastic model is used at high frequencies.

Considerable information is available on ground motion at Yucca Mountain from UNE sources. These data can be used to make reasonable estimates of surface ground motion for future UNE sources in the manner of Vortman (1986) and Phillips (1988). For estimating ground motions at depth, given the availability of subsurface recordings, the best approach is a combination of theoretical modeling techniques (Joyner et al, 1976; Seal and Archuleta, 1989) with empirical observations (Vortman and Long, 1982a, b; Phillips, 1988, 1991). The more difficult task is the estimation of ground motion from earthquake sources, due to the lack of recordings of appropriate-sized events in the study region. Some of the methods described in this study require information on propagation path velocity structures. This information is best obtained from the modeling of available UNE records (Walck and Phillips, 1990; Barker et al, 1991), and from local refraction studies (Hoffman and Mooney, 1983; Ackerman et al, 1988). The uncertainty in the more empirical methods will depend on the availability of empirical Green's functions.

Abrahamson et al. (1990) have considered the errors involved in estimating strong ground motions. They separate the total uncertainty in the prediction of strong ground motion into three parts: modeling uncertainty (differences between the actual physical process that generated the strong ground motion and the simulation of those processes in the numerical procedure), random uncertainty (detailed aspects of the earthquake source and wave propagation that cannot be modeled deterministically), and parametric uncertainty (uncertainty in the values of source parameters). They estimate the combined modeling and random uncertainty by applying the

Semi-empirical Method to recorded earthquake data. The parametric uncertainty is estimated from a suite of ground motions produced by probabilistically varying the free source parameters. As an example, they estimated a total standard error of a factor of 1.66 in the ground motion estimate between 3.0 and 8.5 Hz for a magnitude 7.2 earthquake at a distance of 4.5 km. Dan et al (1990) have performed a similar estimation of the uncertainties in the summation of magnitude 3.4 to 4.9 Green's functions to stimulate a magnitude 6.7 event in Japan. Besides comparing the ground motion estimates obtained from the different methods chosen to be applied in this study, the uncertainly in the ground motion can be estimated for any one method using a procedure similar to Abrahamson et al. (1990) and Dan et al (1990).

3.2.9 Relations to performance goals and confidence levels

Ground motion time histories for the controlling seismic events are needed to assess the viability of the repository design (see sec. 1.2).

4. APPLICATION OF RESULTS

This section identifies other studies within both the preclosure and postclosure tectonics program that will use information obtained in the present study. Related discussions in section 1.2 draw on section 8.3.5 of the SCP to consider the uses of information from the study in the context of issue resolution and performance goals. Data regarding the locations, timing, and magnitudes of 10,000-yr cumulative slip earthquakes, other maximum magnitude events, and UNE's, as supplied by other studies in Investigation 8.3.1.17.3 (Studies to provide required information on vibratory ground motion that could affect repository design or performance), will be used in the present study to identify those controlling seismic events and resulting ground motions that could impact design or performance of the waste facility. Through its contribution to postclosure Activity 8.3.1.8.2.1.5 (Assessment of postclosure ground motion in the subsurface; fig. 1-3); information from this study will be used in conjunction with Study 8.3.1.17.3.6 (Probabilistic seismic hazards analyses) to characterize ground motions that have a probability of less than 0.1 of being exceeded in the minimal 1,000-yr waste package lifetime. Time histories representative of the estimated ground motions at the repository horizon will be prepared for use in the engineering evaluations.

5. SCHEDULE AND MILESTONES

Figure 5-1 shows the principal milestones for this study and its scheduling ties to other studies. This information is abstracted from the most current and complete schedule information available.

REFERENCES

Abrahamson, N.A., Somerville, P.G., and Cornell, C.A., 1990, Uncertainty in numerical strong motion predictions: Proceedings of 4th U. S. National Conference on Earthquake Engineering, Palm Springs, CA, v. 1, pp. 407-416.

Ackerman, D., Mooney, W.D., Snyder, D.B., and Sutton, V.D., 1988, Preliminary interpretation of seismic-refraction and gravity studies west of Yucca Mountain, Nevada and California, in Carr, M., and Yount, J., eds., Geologic and Hydrologic Investigations of a Potential Nuclear Waste Disposal Site at Yucca Mountain, Southern Nevada: U.S. Geological Survey Bull. 1790, p. 23-34.

Aki, K., 1967, Scaling law of seismic spectrum: Journal of Geophysical Research, v. 72, pp. 1217-1231.

______ 1988, Local site effects on ground motion: Earthquake Engineering and Soil Dynamics II-Recent Advances in Ground-Motion Evaluation, Proceedings of the American Society of Civil Engineers Specialty Conference, June 27-30, Park City, Utah, pp. 103-155.

Bakun, W.H., and Joyner, W.B., 1984, The ML scale in central California: Bulletin Seismological Society of America, v. 74, pp. 1827-1843.

Barker, J., Hartzell, S., Burdick, L., and Helmberger, D.V., 1991, Analysis of local seismic waveforms from underground nuclear explosions: I. Forward modeling for effective source functions at Pahute Mesa: Journal of Geophysical Research, v. 96, pp. 10129-10143.

Boore, David M., 1983, Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra: Bulletin Seismological Society of America, v. 73, pp. 1865-1894.

Brune, J.N., 1970, Tectonic stress and the spectra of seismic shear waves from earthquakes: Journal of Geophysical Research, v. 75, pp. 4997-5009.

______ 1971, Correction: Journal of Geophysical Research, v. 76, p. 5002.

Burridge, R., and Knopoff, L., 1964, Body force equivalents for seismic dislocations: Bulletin Seismological Society of America, v. 54, pp. 1875-1888.

Campbell, Kenneth, 1985, Strong-motion attenuation relations: A ten-year perspective: Earthquake Spectra, v. 1, p. 759-804.

____, 1989a, Empirical prediction of near-source ground motion for the Diablo Canyon Power Plant Site, San Luis Obispo County, California: U.S. Geological Survey Open-File Report 89-484.

____, 1989b, The dependence of peak horizontal acceleration on magnitude, distance, and site effects for small-magnitude earthquakes in California and eastern North America: Bulletin of the Seismological Society of America, v. 79, p. 1311-1346.

____, 1991, An empirical analysis of peak horizontal acceleration for the Loma Prieta, California, earthquake of 18 October 1989: Bulletin of the Seismological Society of America, v. 81, p. 1838-1858.

Celebi, M., 1987, Topographical and geological amplifications determined from the strong-motion and aftershock records of the 3 March 1985 Chile earthquake: Bulletin Seismological Society of America, v. 77, pp. 1147-1167.

Cohee, B.P., Somerville, P.G., and Abrahamson, N.A., 1991, Ground motion from hypothesized M=8 subduction earthquakes in Washington and Oregon: Bulletin Seismological Society of America, v. 81, pp. 28-56.

Dan, K., Watanabe, T., Tanaka, T., and Sato, R., 1990, Stability of earthquake ground motion synthesized by using different small-event records as empirical Green's functions: Bulletin of the Seismological Society of America, v. 80, p. 1433-1455.

Day, S.M., 1982, Three-dimensional simulation of spontaneous rupture; the effect of nonuniform prestress: Bulletin Seismological Society of America, v. 72, pp. 1881-1902.

Dobry, R., Henke, B., Higgins, N., Jamiolkowski, M., Ko, H., Ladd, R., Prakash, S., Saada, T., and Sirles, P., 1989, Low-and High-Strain Cyclic Material Properties, in Proceedings of workshop on Dynamic Soil Property and Site Characterization, sponsored by the National Science Foundation and the Electric Power Research Institue, Palo Alto, California, November 9-10, 1989.

Geller, R.J., 1976, Scaling relations for earthquake source parameters and magnitudes: Bulletin Seismological Society of America, v. 66, pp. 1501-1523.

Gomberg, J., and King, G., in press, Re-evaluation of the basic assumptions used for the prediction of strong ground motion: the use of empirical transfer functions: Pure and Applied Geophysics.

Study 8.3.1.17.3.5: Ground motion at the site from controlling seismic events

Guzman, R.A., and Jennings, P.C., 1976, Design spectra for nuclear power plants: Journal of the Power Division, American Society of Civil Engineers, v. 102, No. P02, Proceedings Paper 12521, pp. 165-178.

Hadley, D.M., and Helmberger, D.V., 1980, Simulation of strong ground motions: Bulletin Seismological Society of America, v. 70, pp. 617-630.

Hanks, T.C., 1982, fmax: Bulletin Seismological Society of America, v. 72, pp. 1867-1879.

Hartzell, S.H., 1978, Earthquake aftershocks as Green's functions: Geophysical Research Letters, v. 5, pp. 1-4.

____ 1989, Comparison of seismic waveform inversion results for the rupture history of a finite fault: application to the 1986 North Palm Springs, California, earthquake: Journal of Geophysical Research, v. 94, pp. 7515-7534.

Hartzell, S.H., Frazier, G.A., and Brune, J.N., 1978, Earthquake modeling in a homogeneous half-space: Bulletin Seismological Society of America, v. 68, pp. 301-316.

Hartzell, S.H., and Heaton, T.H., 1983, Inversion of strong ground motion and teleseismic waveform data for the fault rupture history of the 1979 Imperial Valley, California, earthquake: Bulletin Seismological Society of America, v. 73, pp. 1553-1583.

____ 1986, Rupture history of the 1984 Morgan Hill, California, earthquake from the inversion of strong motion records: Bulletin Seismological Society of America, v. 76, pp. 649-674.

Hartzell, S.H., and Iida, M., 1990, Source complexity of the 1987 Whittier Narrows, California, earthquake from the inversion of strong motion records: Journal of Geophysical Research, v. 95, pp. 12475-12485.

Heaton, T.H., 1990, Evidence for and implications of self-healing pulses of slip in earthquake rupture: Physics of the Earth and Planetary Interiors, v. 64, pp. 1-20.

Heaton, T.H., and Hartzell, S.H., 1989, Estimation of strong ground motions from hypothetical earthquakes on the Cascadia subduction zone, Pacific Northwest: Pure and Applied Geophysics, v. 129, pp. 131-201.

Heaton, T.H., Tajima, Fumiko, and Mori, A.W., 1986, Estimating ground motions using recorded accelerograms: Surveys in Geophysics, v. 8, pp. 25-83.

Study 8.3.1.17.3.5: Ground motion at the site from controlling seismic events

Hoffman, Lynn, and Mooney, W.D., 1983, A seismic study of Yucca Mountain and vicinity of southern Nevada; data report and preliminary results: U.S. Geological Survey Open-File Report 83-588.

Hutton, L.K., and Boore, D.M., 1987, The ML scale in southern California: Bulletin Seismological Society of America, v. 77, pp. 2074-2094.

Imagawa, K., Mikami, N., and Mikumo, T., 1984, Analytical and semi-empirical synthesis of near-field seismic waveforms for investigation the rupture mechanism of major earthquakes: Journal Physics of the Earth, v. 32, pp. 317-338.

Irikura, K., 1983, Semi-empirical estimation of strong ground motions during large earthquakes: Bulletin of the Disaster Prevention Research Institute, Kyoto University, v. 33, pp. 63-104.

Ishihara, K., 1985, Stability of natural deposits during earthquakes: Proceedings of the International Conference on Soil Mechanics and Foundation Engineering, 11th, Rotterdam, Netherlands, Balkema.

Ishihara, K., Shimizu, K., and Yamada, Y., 1981, Pore water pressures measured in sand deposits during an earthquake: Soils Foundation, v. 21, pp. 85-100.

Jarpe, S.P., Cramer, C.H., Tucker, B.E., and Shakal, A.F., 1988, A comparison of observations of ground response to weak and strong motion at Coalinga, California: Bulletin Seismological Society of America, v. 78, pp. 421-435.

Jennings, P.C., and Kanamori, H., 1983, Effect of distance on local magnitudes found from strong-motion records including records from the 1979 Imperial Valley, California, earthquake: Bulletin Seismological Society of America, v. 73, pp. 265-280.

Jing-Ming, Wang, 1985, The distribution of earthquake damage to underground facilities during the 1976 Tang-Shan earthquake: Earthquake Spectra, v. 1, pp. 741-757.

Joyner, W.B., 1984, A scaling law for the spectra of large earthquakes, Bulletin Seismological Society of America, v. 74, pp. 1167-1188.

Joyner, William, and Boore, David, 1981, Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley, California, earthquake: Bulletin of the Seismological Society of America, v. 71, p. 2011-2038.

Joyner, W.B., and Boore, D.M., 1986, On simulating large earthquakes by Green's function addition of smaller earthquakes, in Das, S., Boatwright, J., and Scholz, C., eds., Earthquake Source Mechanics: American Geophysical Union, Geophysical Monograph 37 (Maurice Ewing 6), pp. 269-274.

Joyner, W.B., Campbell, K.W., and Harmsen, S.C., 1988, Near-source simulation of earthquake ground motion based on the stochastic omega-square model: Seismological Research Letters, v. 59, p. 10.

Joyner, W.B., Warrick, R.E., and Fumal, T.E., 1981, The effect of quaternary alluvium on strong ground motion in the Coyote Lake, California, earthquake of 1979: Bulletin Seismological Society of America, v. 71, pp. 1333-1349.

Joyner, W.B., Warrick, R.E., and Oliver, A.A., 1976, Analysis of seismograms from a downhole array in sediments near San Francisco Bay: Bulletin Seismological Society of America, v. 66, pp. 937-958.

Kanamori, H., 1979, A semi-empirical approach to prediction of long-period ground motions from great earthquakes: Bulletin Seismological Society of America, v. 69, pp. 1654-1670.

Kanamori, H., and Anderson, D.L., 1975, Theoretical basis of some empirical relations in seismology: Bulletin Seismological Society of America, v. 65, pp. 1073-1095.

Kanamori, H., and Jennings, P.C., 1978, Determination of local magnitude, ML, from strong motion accelerograms: Bulletin Seismological Society of America, v. 68, pp. 471-485.

Liu, H.L., and Helmberger, D.V., 1985, The 23:19 aftershock of the October 1979 Imperial Valley earthquake; more evidence for an asperity: Bulletin Seismological Society of America, v. 75, pp. 689-708.

Long, J.W., Sabisch, K.A., Stearns, S.D., Vortman, L.J., 1983, Prediction of downhole waveforms: SAND82-2478, Sandia National Laboratories, Albuquerque, New Mexico.

Mendoza, C., and Hartzell, S.H., 1988, Inversion for slip distribution using teleseismic P waveforms: North Palm Springs, Borah Peak, and Michoacan earthquakes: Bulletin Seismological Society of America, v. 78, pp. 1092-1111.

Mendoza, C., and Hartzell, S.H., 1989, Slip distribution of the 19 September 1985 Michoacan, Mexico, earthquake: near-source and teleseismic constraints: Bulletin Seismological Society of America, v. 79, pp. 655-669.

Phillips, J.S., 1988, Prediction of pseudo relative velocity response spectra at Yucca Mountain for underground nuclear explosions conducted in the Pahute Mesa testing area at the Nevada Test Site: SAND88-3032, Sandia National Laboratories, Albuquerque, New Mexico.

______, 1991, Analysis of component surface/downhole ground motions at Yucca Mountain from underground nuclear explosions in Pahute Mesa: SAND87-2381, Sandia National Laboratories, Albuquerque, New Mexico.

Rogers, A.M., Tinsley, J.C., and Borcherdt, R.D., 1985, Predicting relative ground response, in Ziony, J., ed., Evaluating Earthquake Hazards in the Los Angeles Region-An Earth-Science Perspective: U.S. Geological Survey Professional Paper 1360, pp. 221-247.

Seale, S.H., and Archuleta, R.J., 1989, Site amplification and attenuation of strong ground motion: Bulletin Seismological Society of America, v. 79, pp. 1673-1696.

Seed, H.B., Wong, R.T., Idriss, I.M., and Tokimatsu, K., 1986, Moduli and damping factors for dynamic analyses of cohesionless soils: Journal Geotechnical Engineering, v. 112, pp. 1016-1032.

Seed, H.B., Romo, M.P., Sun, J.I., Jaime, A., and Lysmer, J., 1988, The Mexico earthquake of September 19, 1985-relationship between soil conditions and earthquake ground motions: Earthquake Spectra, v. 4, pp. 687-729.

Somerville, P.G., Sen, M.K., and Cohee, B.P., 1991, Simulation of strong ground motions recorded during the 1985 Michoacan, Mexico and Valparaiso, Chile earthquakes: Bulletin Seismological Society of America, v. 81, pp. 1-27.

Somerville, Paul, and Yoshimura, Joanne, 1990, The influence of critical Moho reflections on strong ground motions recorded in San Francisco and Oakland during the 1989 Loma Prieta earthquake: Geophysical Research Letters, v. 17, p. 1203-1206.

Spudich, P., and Miller, D.P., 1990, Seismic site effects and the spatial interpolation of earthquake seismograms: results using aftershocks of the 1986 North Palm Springs, California, earthquake: Bulletin Seismological Society of America, v. 80, pp. 1504-1532.

Trifunac, M.D., and Brady, A.G., 1976, Correlation of peak acceleration, velocity, and displacement with earthquake magnitude, distance, and site conditions: International Journal of Earthquake Engineering and Structural Dynamics, v. 4, pp. 455-472.

Tucker, B.E., and King, J.L., 1984, Dependence of sediment-filled valley response on input amplitude and valley properties: Bulletin Seismological Society of America, v. 74, pp. 153-165.

Study 8.3.1.17.3.5: Ground motion at the site from controlling seismic events

URS/John A. Blume and Associates, 1986, Ground motion evaluations at Yucca Mountain, Nevada, with applications to repository conceptual design and siting: SAND85-7104, Sandia National Laboratories, Albuquerque, New Mexico.

Vortman, L.J., 1986, Ground motion produced at Yucca Mountain from Pahute Mesa underground nuclear explosions: SAND85-1605, Sandia National Laboratories, Albuquerque, New Mexico.

Vortman, L.J., Long, J.W., 1982a, Effects of repository depth on ground motion, the Pahute Mesa data: SAND82-0174, Sandia National Laboratories, Albuquerque, New Mexico.

____, 1982b, Effects of repository depth on ground motion, the Yucca Flat data: SAND82-1647, Sandia National Laboratories, Albuquerque, New Mexico.

Walck, Marianne, and Phillips, James, 1990, Two-dimensional velocity models for paths from Pahute Mesa and Yucca Flat to Yucca Mountain: SAND88-3033, Sandia National Laboratories, Albuquerque, New Mexico.

Wald, D.J., Burdick, L.J., and Somerville, P.G., 1988a, Simulation of acceleration time histories close to large earthquakes, in Von Thun, J.L., ed., Proceedings of the Earthquake Engineering and Soil Dynamics II Conference: American Society of Civil Engineers, Geotechnical Special Publication, No. 20, pp. 430-444.

Wald, D.J., Somerville, P.G., and Burdick, L.J., 1988b, The Whittier Narrows, California earthquake of October 1, 1987--simulation of recorded accelerations: Earthquake Spectra, v. 4, pp. 139-156.

Wennerberg, L., 1990, Stochastic summation of empirical Green's functions: Bulletin Seismological Society of America, v. 80, pp. 1418-1432.

Wyss, M., 1979, Estimating maximum expectable magnitude of earthquakes from fault dimensions: Geology, v. 7, pp. 336-340.

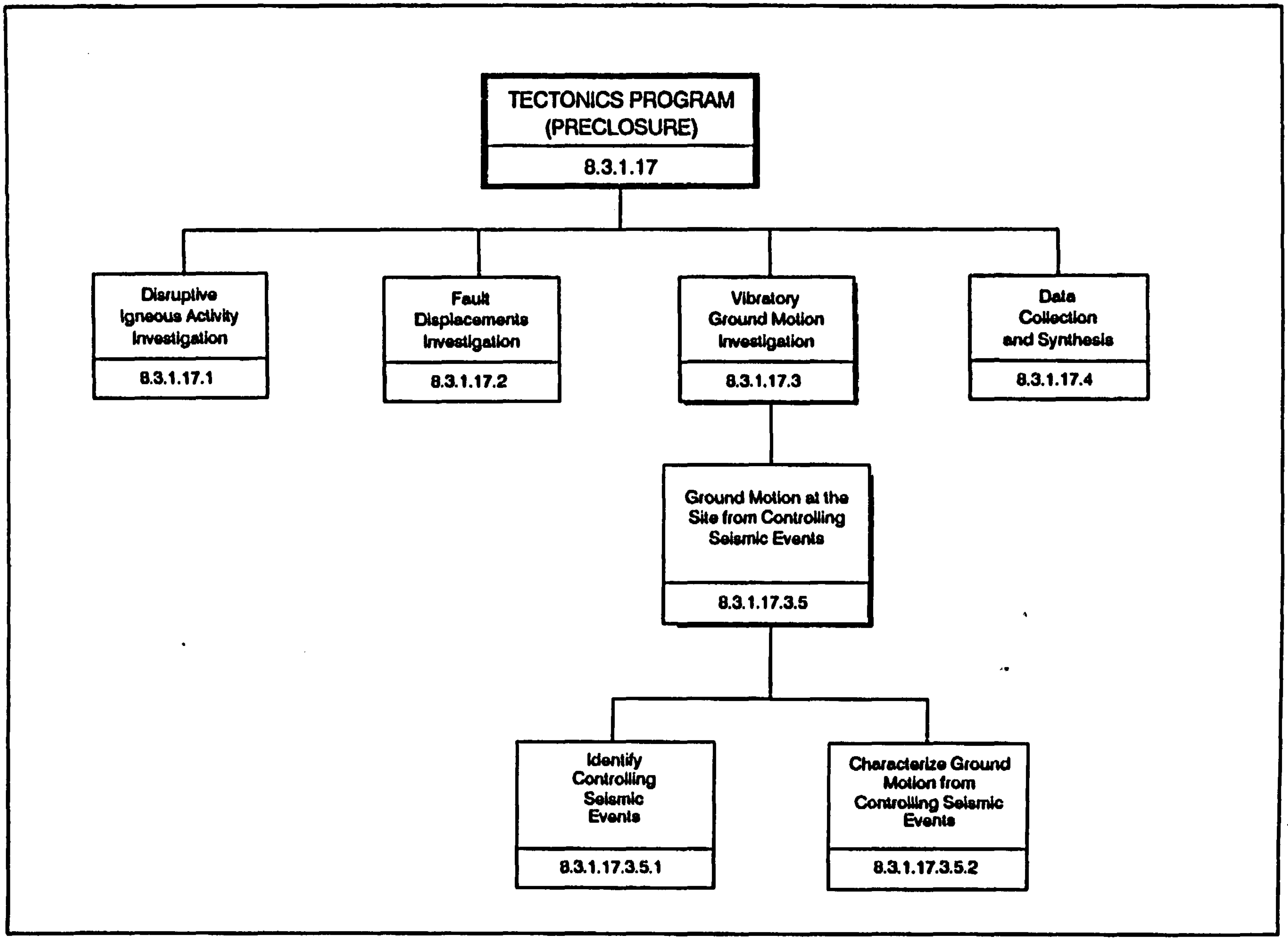
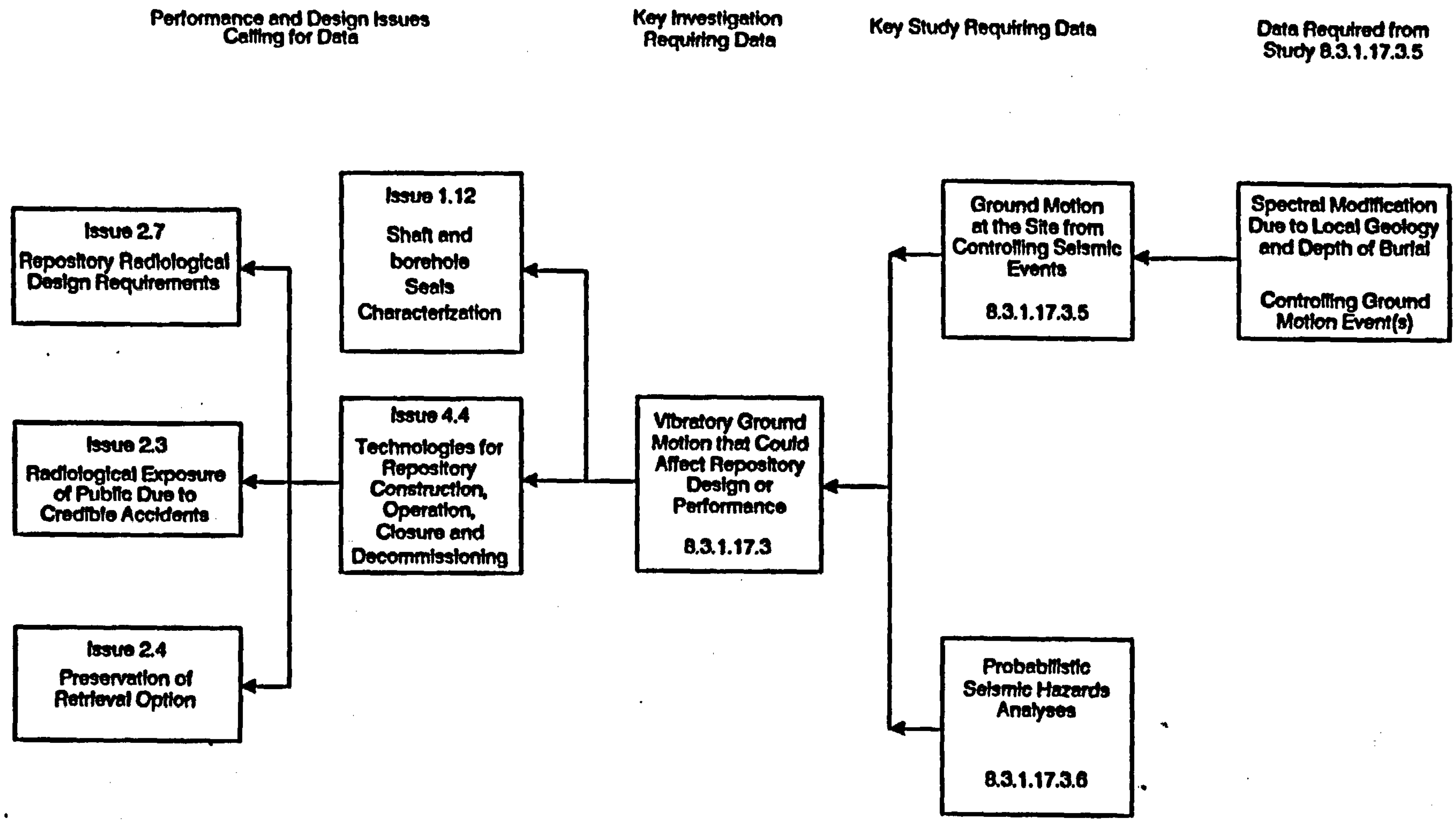
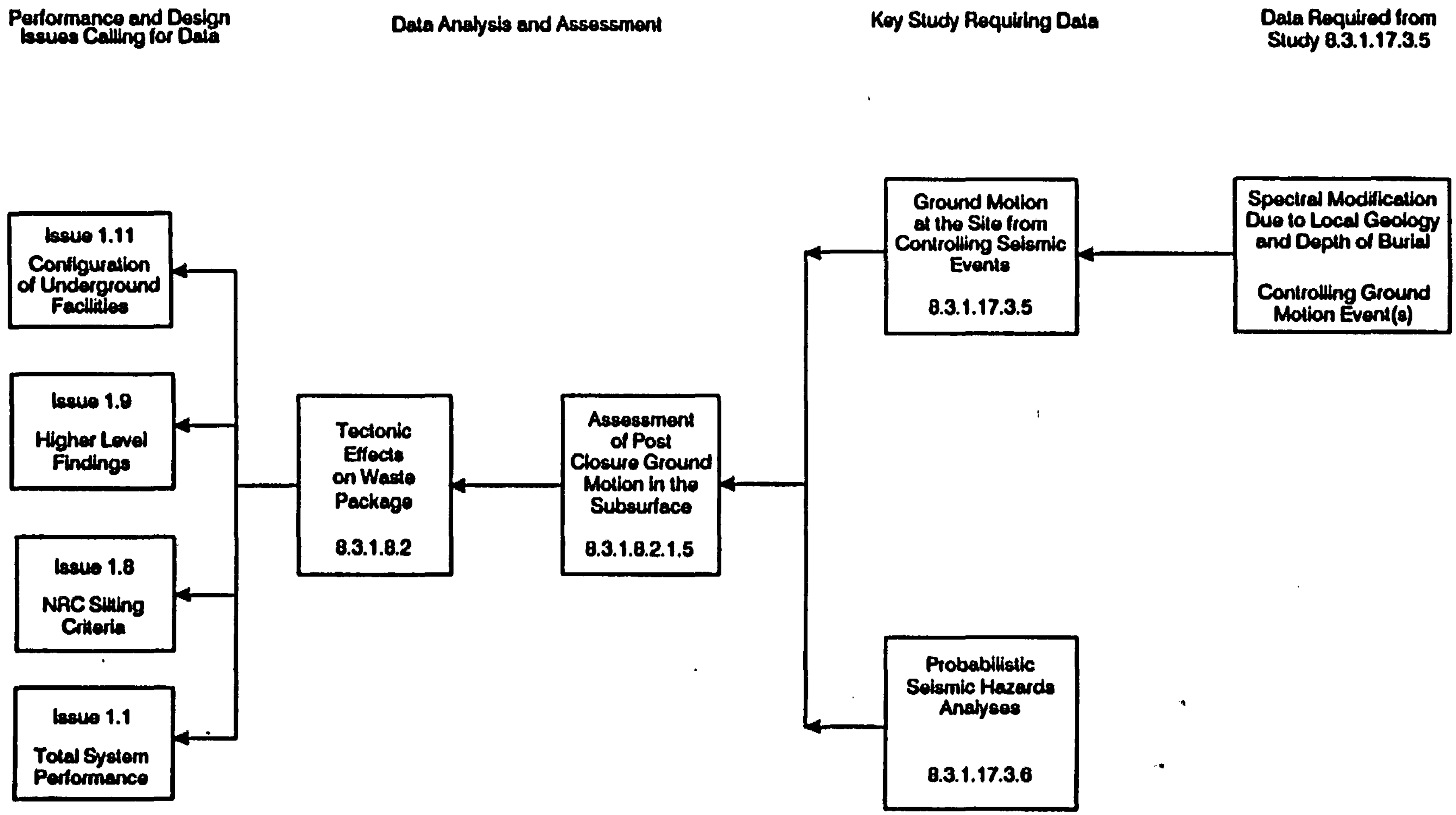


Figure 1-1.--Relation of Study 8.3.1.17.3.5 to the preclosure tectonics program.



Sources of information:
For Investigation 8.3.1.17.3, modified from SCP Figures 8.3.1.17-1 and 8.3.1.17-5.

Figure 1-2.--Information required from Study 8.3.1.17.3.5 for issue resolution through studies in the preclosure tectonics program.



Sources of information:
For Investigation 8.3.1.8.2, modified from SCP Figures 8.3.1.8-1 and 8.3.1.8-4.

Figure 1-3.--Information required from Study 8.3.1.17.3.5 for issue resolution through the postclosure tectonics program.

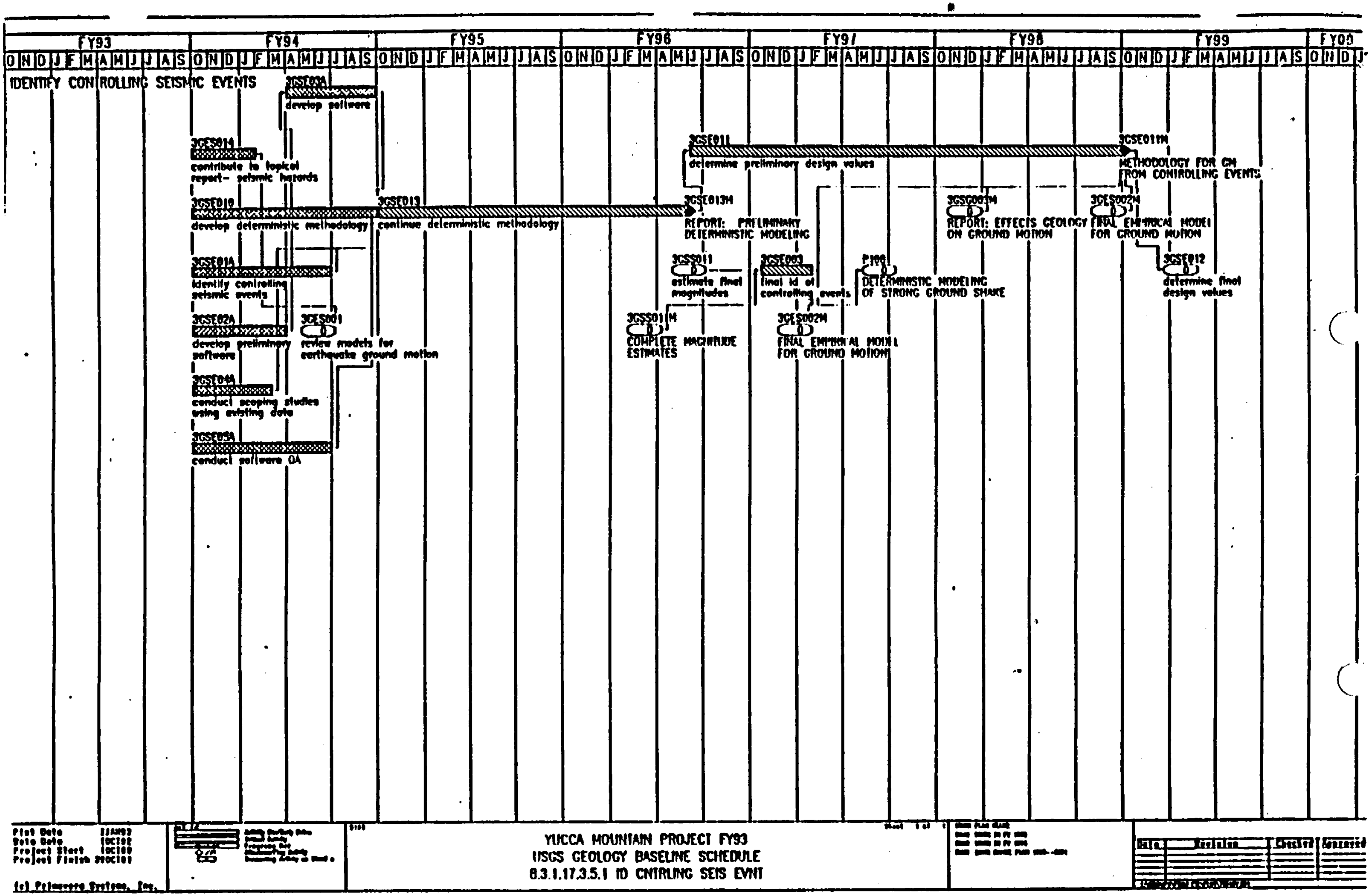


Figure 5-1. Detailed schedule and milestones (numbers ending with "M") for Study 8.3.1.17.3.5.

SP 8.3.1.17.3.5, R0