APPROACH TO DEVELOPING A GROUND-MOTION DESIGN BASIS FOR FACILITIES IMPORTANT TO SAFETY AT YUCCA MOUNTAIN

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ABSTRACT

The DOE has proposed a methodology for developing a ground-motion design basis for prospective facilities at Yucca Mountain that are important to safety. The methodology utilizes a quasi-deterministic construct called the 10,000-year cumulative-slip earthquake, designed to provide a conservative, robust, and reproducible estimate of ground motion that has a one-in-ten chance of occurring during the preclosure period. This estimate is intended to define a ground-motion level for which the seismic design would ensure minimal disruption to operations; engineering analyses to ensure safe performance in the unlikely event that the design basis is exceeded are a part of the proposed methodology.

INTRODUCTION

The regulations that govern the design of prospective repository facilities at Yucca Mountain specify overall performance objectives, but leave it to the applicant, the U.S. Department of Energy (DOE), to develop design criteria that will lead to satisfactory performance. This paper describes the approach that has been proposed by the DOE for developing a ground-motion design basis for repository facilities that are important to safety.

Title 10, Chapter I, Part 60 of the Code of Federal Regulations (10 CFR 60) specifies performance objectives and general design and siting criteria for mined geologic disposal systems (repositories) which are constructed and operated by the DOE under the provisions of the 1982 Nuclear Waste Policy Act and the 1987 Nuclear Waste Policy Amendments Act. Part 60 specifies that a repository be designed such that, during the preclosure period, protection is afforded against radiation exposures and releases of radioactive material in accordance with standards established by the U.S. Nuclear Regulatory Commission (NRC) in 10 CFR 20 and by the U.S. Environmental Protection Agency (EPA) in 40 CFR 191. Part 60 also requires that emplaced waste be retrievable during the preclosure period.

Part 60 (Section 131(b)(1)) requires that structures, systems, and components important to safety be designed so that natural phenomena and environmental conditions anticipated at the geologic repository operations area will not interfere with necessary safety functions. Here, "important to safety" means those engineered structures, systems, and components essential to the prevention or mitigation of an accident that could result in a radiation dose to the whole body, or any organ, of 0.5 rem or greater at or beyond the nearest boundary of the controlled area, during the preclosure period. This requirement forms the basis for regulatory acceptability of any proposed methodology for developing a seismic design basis for repository facilities that are important to safety.

It is important to note that Part 60 does not rely on or refer to the detailed regulatory guidance the NRC has provided in 10 CFR 100, Appendix A, for developing seismic design bases for nuclear power plants. Rather, Part 60 specifies performance objectives, and it is the applicant's responsibility to develop the seismic design basis and then to demonstrate that the performance objectives will be met.

In addition to the NRC requirements, repository design is subject to DOE Orders. However, NRC requirements supersede DOE Orders where conflicts arise, and, at the time of this writing, it has not been determined to what extent DOE Orders will control development of the ground-motion design basis. DOE Order 6430.1A, General Design Criteria, specifies a methodology for calculating earthquake loads that utilizes a probabilistically defined ground-motion design basis, i.e., earthquake ground motion with a specified return period is used as the design basis, and procedures are prescribed for assuring that a high, specified probability of meeting particular performance goals is attained. However, in light of consistent NRC opposition to purely probabilistically defined ground-motion design bases for nuclear power plants, it seems likely that a variance to some parts of DOE Order 6430.1A will have to be requested.

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This paper describes a proposed approach to developing a ground-motion design basis for facilities important to safety at the prospective Yucca Mountain repository. The approach was introduced by the DOE in its Site Characterization Plan (SCP) for the Yucca Mountain site and utilizes a new construct called the "cumulative slip earthquake" (CSE). The CSE methodology was included in the SCP to help define the parameters which the site characterization program must provide and also to stimulate discussion and consideration of the proposed approach by the NRC and the scientific community. This paper describes the CSE approach and provides a rationale for its usage by delineating the requirements that any design basis must address and then analyzing the CSE approach with respect to those requirements.

Note that this paper does not address the characterization of surface faulting hazards, the development of a ground-motion design basis for the 10,000-yr postclosure waste-isolation period, or potential earthquake interactions with groundwater, all of which will be addressed in future publications by Yucca Mountain Project scientists.

**Requirements for a Ground-Motion Design Basis**

It is argued here that the necessary attributes of any ground-motion design basis are sufficiency, cost effectiveness, reproducibility, and robustness.

**Sufficiency**

Sufficiency embodies the NRC requirement that earthquakes anticipated at the site not interfere with necessary safety functions of facilities that are important to safety. A sufficient ground-motion design basis is taken here to mean one which leads to a design which provides for minimal disruption to operations in the event of earthquake shaking that has a reasonable chance (say, one in ten) of occurring during the facility lifetime, and which protects public health and safety against any credible earthquake ground motion.

**Cost Effectiveness**

While any structure or component can always be made safer, at some point the cost of increased protection becomes unacceptable because of competing demands for financial resources. Cost effectiveness should be determined by evaluating the costs of implementing different design levels versus their efficacy in preventing earthquake damage and in mitigating the consequences of such damage. There may also be engineering tradeoffs in changing the seismic design level that also have to be considered, e.g., making some structures or components stiffer to be more earthquake-resistant may make them more brittle and less able to safely yield under unusual loads that exceed the design basis.

**Reproducibility and Robustness**

The methodology to establish the design basis should provide results that are reasonably reproducible by different workers and results that are "robust." The requirement for robustness means that the design basis which is provided by the methodology should not be sensitive to new information other than major changes in the perception of seismic hazard. Robustness requires that the design basis be conservative in proportion to the amount of uncertainty in the characterization of the seismic hazard, e.g., the greater the uncertainty, the greater the conservatism that is required.

**Realizability?**

It should be noted that a seismic design basis does not have to represent ground motion that would actually be expected should a large earthquake occur, nor need it be physically realizable or correspond to a physically realizable event to provide a seismic design that will accommodate physically realizable and expected events. This fact is illustrated by the seismic designs of U.S. nuclear power plants, each of which is based on a smoothed response-spectrum representation of maximum vibratory ground motion. This representation has a number of advantages, but it is a mathematical fiction which cannot occur in nature.

**The Cumulative-Slip-Earthquake (CSE) Methodology**

The Department of Energy has proposed a design-basis approach which utilizes a new construct called the cumulative-slip earthquake. A CSE is defined as a hypothetical earthquake that would produce the observed or estimated average Quaternary slip rate on a fault, if it were to reoccur at equal, specified time intervals. CSE magnitudes are constrained at the high end to be less than or equal to that of the maximum magnitude earthquake, which is taken here to be the largest earthquake to have occurred on a fault during the Quaternary period. Because CSE magnitudes are defined by slip rates, which are determined by measurements of surface fault displacement, CSE magnitudes are constrained at the low end to be greater than or equal to that of the smallest earthquake that would likely cause surface rupture (magnitude 6 to 6 1/2).

Ten-thousand years has been chosen for the CSE slip-accumulation period with the intent of producing a design basis that has an annual exceedance probability in the range of $10^{-3}$ to $10^{-4}$/yr, i.e., a design basis that, conservatively, has one chance in ten of occurring during the approximately 100-yr lifetime of the preclosure facilities. The CSE methodology is intended to be implemented in conjunction with a comprehensive probabilistic hazard analysis to confirm that the resulting design basis indeed falls within the desired
probability range. If this were found not to be the case, the 10,000-yr slip-accumulation period for the CSE magnitudes would be adjusted accordingly.

To illustrate the estimation of CSE magnitudes, consider the Paintbrush Canyon fault, which is an apparent normal fault, located about 1 km east of the proposed location of the surface waste-handling facilities. Measurements to date indicate that this fault offsets by 4.1 m at a unit dated at 700,000 yr or younger. On this basis, a reasonable preliminary estimate of the average Quaternary slip rate is 0.01 mm/yr. Assuming this value, the 10,000-yr CSE event would be characterized by an average surface displacement of 0.1 m. The corresponding maximum surface displacement can be roughly estimated by tripling the average displacement, i.e., as 0.3 m. The magnitude of an earthquake characterized by this maximum surface displacement can be estimated using published empirical regression curves. Using Ref. 3, for example, a 0.3 m maximum displacement corresponds to a (surface-wave) magnitude value of 6.6.

Much work will be done before final CSE magnitude estimates are made. A comprehensive program of trenching and mapping local Quaternary faults will first be conducted. Published methods of estimating magnitudes from surface displacements will be compared and evaluated and updated regressions will be developed, if warranted. Uncertainties in slip-rate determinations will be estimated explicitly, considering, in particular, potential errors in age determinations of offset units and errors in measuring horizontal displacements. Finally, the possibility of simultaneous distributed faulting on local faults will be considered and factored into the CSE magnitude estimates.

In the proposed methodology, CSE magnitudes are determined for potentially significant local and regional faults, ground motion at the site is estimated for each CSE, and those events which produce the most severe ground motion in any frequency band of significance to repository facilities important to safety are taken to be the controlling events for seismic design. An estimate of the median (50th percentile) ground motion, accounting for any local site effects, is taken as the basis for design. Current information suggests that the Paintbrush Canyon fault will control the seismic design at all frequencies, with a CSE magnitude of about 6 1/2 and a corresponding peak ground acceleration at the site of about 0.5 g.

It is important to note that the CSE methodology is intended to define that earthquake for which the seismic design is to ensure minimal disruption to operation of facilities that are important to safety; the methodology is intended to provide a conservative estimate of ground motion that has a one-in-ten chance of occurring during the facility lifetime. Greater-than-CSE events during the preclosure period are unlikely but possible, and the design of facilities important to safety must therefore also ensure safe performance for such events, including maximum-magnitude earthquakes. Engineering analyses to demonstrate safe performance for earthquake loads which exceed the nominal CSE design basis are an inherent part of the CSE approach to developing a sufficient seismic design.

Sufficiency

Preliminary information indicates that the CSE methodology would, in fact, result in a sufficient seismic design. A recent analysis of alternative seismic design levels for surface waste-handling facilities suggests that the accident risks associated with seismic design levels of 0.2 g or greater would be extremely small. It is estimated, for example, that there is at least a 95 % chance that, if surface waste handling facilities were designed to 0.4 g (the basis of the current conceptual design), they would suffer only light damage in the event of 1.0-g ground motion, with no loss of containment. In other words, the current conceptual design of surface waste-handling facilities appears to provide large margins of safety to accommodate ground motions beyond the design basis. In part, this is because the surface-facility hot cells would be inherently resistant to ground motion due to shielding requirements and the resulting 5-ft-thick shear-wall construction.

Another consideration that suggests sufficiency is that the target range of exceedance probabilities (10^-3 to 10^-4/yr) for the CSE design basis is a range that has been found to correspond to the accepted design bases of a number of U.S. nuclear power plants. Hypothesizing that repository waste-handling facilities would be inherently less vulnerable to earthquakes than are operating nuclear power plants because of the lack of active, complex systems necessary for safe shutdown and the lack of energetic physical mechanisms for widely dispersing radioactive contaminants, the CSE methodology would appear to provide more-than-sufficient conservatism.

Cost effectiveness

The CSE methodology is intentionally quite conservative to accommodate uncertainty and to facilitate regulatory acceptance and, consequently, may not be optimally cost effective. The CSE methodology would likely lead to a peak design acceleration of 0.5 g or more. However, preliminary analysis suggests that increasing the 0.4-g basis of the current conceptual design cannot be justified in terms of avoided accident costs, including the cost of health effects, because the expected accident costs associated with the current design basis are so low that the decrease in avoided accident costs would be several orders of magnitude less
design basis that is unnecessarily conservative, application of the CSE methodology may produce a design basis that is more cost-effective than the cost of increasing the design basis. Thus, current information suggests that application of the CSE methodology may produce a design basis that is unnecessarily conservative, considering design and construction costs and safety benefits. Nevertheless, considering both earthquake and regulatory uncertainties and the potentially extreme costs of licensing delays, it appears prudent to pursue a very conservative approach.

Reproducibility

It is anticipated that the CSE methodology can be applied by different workers with reasonably consistent results. The results of the CSE approach would likely be controlled by slip-rate determinations for one or two of the local Quaternary faults. While certainly subject to interpretation and uncertainty, average Quaternary slip rates should be reasonably determinable by the planned geologic investigations, and residual uncertainties can be accommodated by assuming conservative values. In particular, it is anticipated that the CSE results would be at least as reproducible by different workers as would evaluations of other entities which might be proposed as a basis for seismic design, such as characteristic earthquakes, maximum-magnitude earthquakes, or ground motion corresponding to a particular exceedance probability.

Robustness

The CSE approach is designed to provide a relatively robust design basis. It can be anticipated that application of the CSE methodology will identify one or two local Quaternary faults as being capable of producing the most severe ground motion at the site and, hence, as controlling the seismic design basis. The results of the approach are, thus, expected to depend mostly on the geologic characterization of these one or two faults and, therefore, to be relatively insensitive to new information about the nature of faulting outside the local area or of lesser faults within the local area. To the extent that the Quaternary history (especially, slip rates) of the controlling faults can be determined from the site characterization program, a consensus on the CSE results should be achievable.

As stated above, robustness requires that conservatism be introduced into the design basis in proportion to the degree of uncertainty in the characterization of the seismic hazard. Accordingly, assumptions regarding slip rates on the controlling faults must accommodate the uncertainty that remains following the geologic and seismic investigations of the site.

Realizability

Although, as noted earlier, realizability is not a requirement for a seismic design basis, the topic invariably arises in discussions of the CSE methodology and is, therefore, addressed here.

The occurrence of a CSE-magnitude event may or may not be in accord with expectations of actual fault behavior, depending on the earthquake recurrence model being utilized, but it is unlikely that such an occurrence could ever be ruled out. Certain models of earthquake recurrence, such as an extreme characteristic-earthquake model, hold that faults usually produce surface-rupturing earthquakes that have magnitudes and displacements falling within a limited range. A 10,000-yr CSE event may not fall within this range. For example, if the Paintbrush Canyon fault exhibits strong characteristic-earthquake behavior and has an average earthquake recurrence time of, say, 75,000 years, then release of only 10,000-years-worth of accumulated strain in an earthquake would be statistically unlikely (but not impossible). Such models are motivated by interpretations of offset geologic units in terms of multiple earthquakes, each exhibiting comparable displacements. However, it is axiomatic that it is more difficult to identify and date small offsets than big ones, and it is problematic, therefore, that, the occurrence of small-displacement events can be ruled out on the basis of the geologic record. Consequently, it is anticipated that alternative earthquake recurrence models in which CSE events are and are not consonant with expected fault behavior will remain admissible after the geologic investigations of the site have been completed.

DISCUSSION

The CSE methodology is a quasi-deterministic approach to achieving a reasonable probabilistic result. The methodology shares key attributes of a probabilistically defined design basis, namely primary sensitivity to slip rates and the identification of faults which dominate the seismic hazard. A crucial advantage of the CSE approach over a purely probabilistic approach for use as a design basis is its robustness—its results are less sensitive to new information or speculations about regional tectonics or the characteristics of regional seismic source zones. On the other hand, probabilistic seismic hazard analysis provides an excellent framework for testing the significance of such new information or speculations and for expressing scientific uncertainties about faulting-related parameters. A comprehensive probabilistic seismic hazard analysis is planned in conjunction with the CSE methodology to provide this framework and to assure that the CSE results fall within the desired range of exceedance probabilities. The probabilistic analysis will explicitly address and incorporate, if warranted, alternative conceptual models of regional and local tectonics and alternative, non-Poissonian models of earthquake recurrence.
Despite the fact that the CSE approach is constrained to provide a design basis that is probabilistically equivalent to design bases which have been accepted for nuclear power plants in the United States, concerns are sometimes expressed about the conservatism of the approach because CSE magnitudes may be less than magnitudes estimated for characteristic earthquakes or maximum-magnitude estimates obtained from published fault length-magnitude and fault displacement-magnitude regression relationships. However, these magnitude estimators do not consider fault slip rates and, consequently, are not good indicators of seismic hazard. (A fault which produces a magnitude-7 event every 75,000 years does not pose the same hazard as one which produces a like-magnitude event every 100 years.) The likelihood of the design basis being exceeded and the consequences of the exceedance must be evaluated to assess the conservatism of a seismic design basis. The likelihood of exceeding a CSE design basis would be small (10\(^{-3}\) to 10\(^{-4}\)/yr). Engineering analyses would be performed to assure safe performance in the unlikely event that the design basis is exceeded. The CSE approach is, therefore, considered to be a conservative approach.

Another perspective on the CSE approach can be gained by considering that probabilistic ground-motion estimates are insensitive to the details of the (Poissonian) magnitude-frequency model employed, provided that the slip rates are constrained. In other words, if a random, time-invariant earthquake process is assumed, it matters little whether CSE's, characteristic earthquakes, or maximum-magnitude earthquakes are assumed to actually occur—the calculated hazard levels are about the same for a given average slip rate.

CONCLUSION

Data needs for the CSE methodology and the planned adjunct probabilistic seismic hazard analysis have been used to scope, organize, and prioritize seismic-hazard-related site characterization activities. Together the CSE methodology and the adjunct probabilistic analysis require all the types of information that are generally considered to be material to the characterization of seismic hazard, including data on fault lengths and displacements, slip rates, faulting styles, maximum-magnitude estimates, recurrence-rate estimates, ground-motion attenuation relationships, local site effects on ground motion, local and regional tectonic models, historical seismicity data, and estimates of the uncertainties associated with each of these items. The Site Characterization Plan for Yucca Mountain provides for the acquisition of all of these information items and is considered to be complete with respect to the identification of ground-motion hazards.

The CSE methodology represents the current proposal of the DOE Office of Civilian Radioactive Waste Management for how best to develop a ground-motion design basis for facilities that are important to safety. Whether and to what extent the proposal is implemented will depend on regulatory guidance provided by the NRC and on a determination of the applicability to the repository program of DOE Order 6430.1A and the probabilistically defined design basis prescribed therein.

SUMMARY

The seismic design of prospective repository facilities that are important to safety must meet a general requirement that ground motion anticipated at the site will not interfere with necessary safety functions. The governing regulations specify preclosure performance objectives for repository facilities, but it is left to the applicant (DOE) to develop and apply appropriate design methodologies and to demonstrate that the performance objectives will be met.

The DOE has proposed a quasi-deterministic methodology for developing a ground-motion design basis for repository facilities that are important to safety. The methodology utilizes a new construct called the 10,000-year cumulative-slip earthquake (CSE) that is designed to provide a conservative estimate of ground motion that has a one-in-ten chance of occurring during the (approximately 100-yr) facility lifetime. This ground-motion description is intended to define that ground-motion level for which the seismic design is to ensure minimal disruption to operation of facilities that are important to safety; engineering analyses to ensure safe performance in the unlikely event that the design basis is exceeded are a part of the proposed methodology.

A ground-motion design basis ideally should be sufficient, cost-effective, reproducible, and robust. Expected realizability is sometimes thought to be a necessary attribute of a seismic design basis but, in fact, is not. Based on current information, the CSE methodology appears to be sufficient, reproducible, and robust. The methodology is intentionally quite conservative and may not be optimally cost-effective, but this is considered to be acceptable in light of earth-science and regulatory uncertainties. A CSE design basis might or might not correspond to expectations of actual-fault behavior, but a divergence could probably never be proved and, in any case, would have little bearing on the conservatisn and adequacy of the approach.

The CSE methodology and a planned adjunct probabilistic seismic hazard analysis have been used to help plan related site-characterization investigations. These investigations are believed to be comprehensive, whether the CSE methodology or another methodology is eventually used to develop a ground-motion design basis.
for facilities that are important to safety.
The extent to which the CSE methodology is
implemented will depend on NRC regulatory
guidance and determination of the applicability
of related DOE Orders.

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