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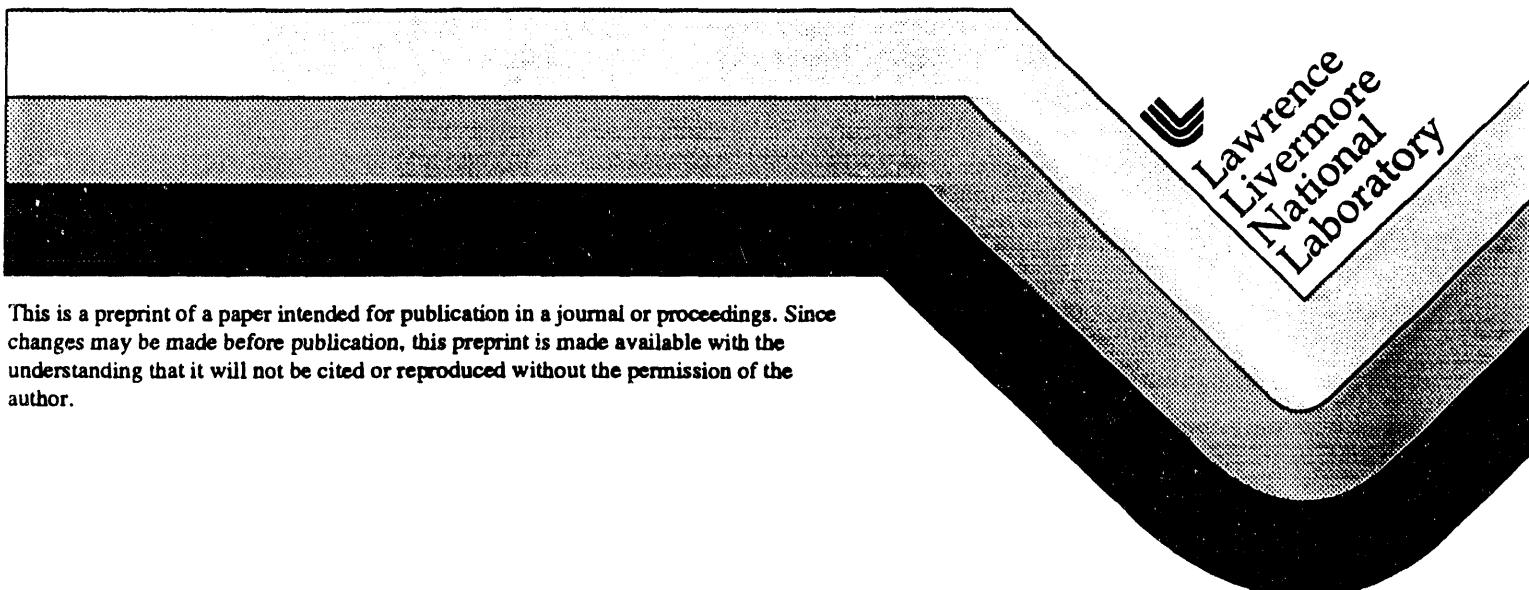
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Seismic Design & Analysis Considerations for High Level Nuclear Waste Repositories

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ABSTRACT

A high level nuclear waste repository, like the one at Nevada's Yucca Mountain that is being investigated for site suitability, will have some unique seismic design and analysis considerations. These are discussed, and a design philosophy that can rationally account for the unique performance objectives of such facilities is presented. A case is made for the use of DOE's performance goal-based seismic design and evaluation methodology that is based on a hybrid "deterministic" and "probabilistic" concept. How and to what extent this methodology should be modified to adopt it for a potential site like Yucca Mountain is also outlined. Finally, the issue of designing for seismic fault rupture is discussed briefly, and the desirability of using the proposed seismic design philosophy in fault rupture evaluation is described.

INTRODUCTION

For a facility design, an ideal method should be such that the design acceptance criteria and codes are compatible with the facility mission, functional requirements, and safety goals. The design method should also recognize the uncertainties associated with the selection and prediction of internal and external events (including seismic events) that determine the magnitude of the design loads, and the uncertainties in characterizing and predicting fragilities or capacities of structures, systems, and components (SSCs) that comprise the facility.

In conventional design methods, basic facility and SSC configuration are primarily determined by their mission and functional requirements. Typically, safety requirements are met in the design by conforming to the provisions of applicable industry-accepted design codes and regulatory requirements. Examples of such codes are Uniform Building Code (UBC) for building structures and components, American Concrete Institute (ACI) code for concrete structures, American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code for reactor vessels, steel containments, and piping components. The term "deterministic" is commonly used to describe such conventional design methods. It implies that the maximum anticipated loads or demands are used to design the SSCs, and that the effects of the uncertainties in determining the loads and in the capacities of the SSCs are definitely accounted for by applying safety factors consistent

with accepted practice. Consequently, the use of a "deterministic" design method sometimes gives an erroneous impression that the design loads are maximum and that, if the acceptance criteria of the design codes are satisfied, for all practical purposes, the SSCs will never fail, because "adequate" safety factors have been provided in the design codes.

The above-described deterministic design method has been in use for many decades. The safety factors that are built into the design codes have evolved through industry's experience. These factors were introduced primarily to account for the uncertainties in the prediction of SSC strengths or capacities; the uncertainties in the loading itself are not explicitly accounted for. Thus, for SSCs or facilities in which the anticipated loads are well defined, or can be predicted with relatively very little uncertainty, the long established deterministic design methods are well suited, except that these methods do not lend to easy determination of risks associated with a facility. Also, when deterministic methods are used, consensus on the actual risk associated with a design is often difficult to achieve when loading from rare events, such as earthquakes, must be considered.

Since the late 1970s, because of these two inadequacies of conventional deterministic design methods, i.e. the inability to realistically account for very low probability loads and the inability to establish direct correlation between safety goals and design codes, the nuclear industry has been searching

for new design methods. At first, the search resulted in the use of load factors and variable acceptance criteria to indirectly account for the variation in the probability of occurrence of the loading events. The use of probabilistic risk assessment (PRA) also came into vogue. Load factors and variable acceptance criteria were used to design the SSCs and also to evaluate their adequacies, but PRA was used only to estimate the risks associated with critical facilities (e.g., nuclear power plants) that were already built or designed. The use of load factors and variable acceptance criteria are simple and convenient, but cannot explicitly account for the variation in the probability of occurrence of loading events. On the other hand, the use of PRA in an iterative design process is not practical, because it requires: (a) the development of component fragility curves, (b) probabilistic assessment of facility failure resulting from a large number of component failure scenarios, and (c) it requires specialized design and evaluation experience that the average design engineers do not possess. So, the search for a more suitable method continued in the 80's.

This search resulted in the development of a performance goal-based design and evaluation methodology that has been outlined in two Department of Energy (DOE) documents, UCRL-15910 [Reference 1] and the draft DOE-STD-1020-XX [Reference 2], and in two recent technical papers, one by Kennedy [Reference 3] and the other by Nelson [Reference 4]. This author recommends that the general philosophical basis of the methodology presented in these documents be used in the seismic design and evaluation of a high level nuclear waste repository (HLNWR).

PERFORMANCE GOAL-BASED SEISMIC DESIGN & EVALUATION METHOD

The primary advantage of the performance goal-based design and evaluation methodology described in the documents referenced above is that it is capable of utilizing the state-of-the-art probabilistic or hybrid hazard assessment results and the deterministic design codes and criteria in the national consensus standards, thus making the implementation process suitable for average design engineers. The other major features of this methodology are as follows:

- a. It is based on setting target performance goals of SSCs that are expressed as annual probabilities of failure (defined as probabilities of exceedance of acceptable behavior limits or unacceptable performance) resulting from seismic events. The performance goal for an SSC is set based on the effects of its postulated failure

on various factors such as health and safety of people on or off site, risks to the environment, facility mission or production goal, and repair and replacement costs. SSCs are grouped into four performance categories based on these factors, and each performance category is assigned a performance goal.

- b. The methodology is based on a graded approach such that the seismic hazard level, risk reduction ratio, the level of sophistication of seismic response analyses, and the stringency of design acceptance criteria and codes are compatible to the performance goal of the SSC being designed or evaluated. (Risk reduction ratio is the ratio of hazard exceedance probability to numerical performance goal.)
 - c. The methodology uses the site specific probabilistic seismic hazard curve, the SSC performance goal, and the applicable risk reduction factor to determine the design basis earthquake. For SSCs with less stringent performance goals, it permits the use of seismic zone maps from the UBC (or equivalent model building codes) to define design seismic loads.
 - d. The methodology provides a set of deterministic seismic design or evaluation acceptance criteria that are based on national consensus standards or codes, e. g. ACI-349, ASCE-4, UBC, etc. One such set of criteria is specified for each SSC performance category.
 - e. The numerical performance goals for various performance categories are set based on estimated failure rates of UBC - designed components (for lowest performance category SSC) and the seismic PRA results of about 30 nuclear power plants (for highest performance category SSCs).
- Thus, for each SSC performance category, a general description of mission, safety, and cost requirements are provided; a numerical target performance goal is assigned; and a set of design acceptance criteria is specified. In general, the application of the method for seismic design requires the following basic general steps:
- Step 1: Determine the performance category of the SSCs in the facility.
 - Step 2: Perform a site-specific hybrid seismic hazard assessment to develop the seismic hazard curve and response spectra shape

applicable for the site.

Step 3: From Step 1 and Step 2 results, define the applicable Design Basis Earthquake (DBE) motion.

Step 4: Perform seismic response analyses and design evaluations using analyses methods and design acceptance criteria applicable for the SSC performance category.

APPLICATION OF PERFORMANCE GOAL BASED METHOD FOR HLNWR DESIGN

The performance goal-based seismic design and evaluation methodology outlined above is generic in nature and is applicable to a wide spectrum of facilities and SSCs ranging from general use buildings to nuclear facilities. The general philosophical basis of this methodology can also be used in the seismic design and evaluation of a HLNWR. However, since a HLNWR will have several unique characteristics, and since it is likely to be subjected to a unique regulatory process, it will be prudent for the facility owner (i.e. the DOE) to develop a performance goal based seismic design criteria and methodology document that would address the seismic design related issues unique to a HLNWR. A list of such issues together with a brief discussion and recommendations on each issue is provided below.

Compatibility between Seismic Performance Goals and Design Criteria

In the performance goal-based method presented in references 1 through 4, the target seismic performance goals, the seismic hazard levels, and the seismic design criteria are set such that these are compatible with each other. To achieve this, it was necessary to estimate the approximate seismic failure rates of SSCs when these are designed in accordance with the specific seismic criteria. For example, the failure rate for PC-1 (i.e. Performance Category 1) SSCs was estimated from UBC-designed component performance, and that for PC-4 SSCs was estimated from the results of PRA and seismic margin studies of nuclear power plants. Following a graded approach, the performance goals for PC-2 and PC-3 SSCs were selected in between those for PC-1 and PC-4 SSCs.

The seismic performance goal value selected for PC-1 represents the probabilistic failure rate of UBC-designed (or equivalent) conventional structural components whose failures are defined in terms of stresses, strains, forces, or displacements. This is appropriate for facilities whose seismic performance is defined primarily by the structural adequacy of

typical building components such as beams, columns, slabs, etc. But, in a HLNWR facility, especially in the underground part of the facility, there will be some SSCs whose mission, safety, and cost significance may be equivalent to PC-1, but their design may not be covered by UBC (or equivalent) type of design criteria, and hence may not be compatible with PC-1 numerical performance goal.

The seismic performance goal value selected for PC-4 represents an overall or average probabilistic failure rate of various types of safety-related SSCs in a typical nuclear power plant that contribute to the overall risk of core meltdown or containment breach. The design criteria and failure modes of these SSCs vary with their types. For example: (a) building components and other major structural systems are designed by American Concrete Institute (ACI), American Institute of Steel Construction (AISC), or American Society of Civil Engineers (ASCE) codes and standards; (b) Piping and other mechanical components are designed by American Society of Mechanical Engineers (ASME) codes, and (c) Electrical and control equipment are designed by Institute of Electrical and Electronic Engineers (IEEE) codes. Failure modes of these various types of components may be different. It is likely that the probabilistic failure rates of these of SSCs designed by various industry codes and criteria are also different. So, even though the general design criteria used in the design of safety-related SSCs in a nuclear power plant is compatible with PC-4 numerical performance goal, the same may not be true for SSCs in a HLNWR, whose mission, safety, and cost significance may be equivalent to PC-3 or PC-2. This equivalency needs to be studied and consensus has to be reached, especially for those SSCs whose failures are not primarily dependent on conventional structural adequacy. Their design criteria may need to be modified, if necessary, to make these compatible with numerical performance goal values applicable for the seismic performance category. This recommendation applies also to SSCs whose failures are primarily defined by their structural adequacy, but whose configuration and failure modes are different from conventional structural components. Examples of such components in a HLNWR will be concrete tunnel lining, rock bolts, or an unlined tunnel (which may fracture and become unstable during a seismic event).

Performance Categorization of Safety-Related SSCs in a HLNWR

In the performance-goal based design method of reference 1 through 4, the performance category of a safety-related SSC is determined based on the hazard category of the facility. Since the hazard category of a nuclear facility depends

primarily on its inventory of radioactive materials, all safety-related SSCs in a facility with a large inventory of radioactive material may be placed into Performance Category 4, irrespective of the failure consequences of the SSC being categorized. For small facilities, this categorization method leads to a simple and conservative design process. But, for a HLNWR this may result in excessive and unnecessary conservatism. This may be especially significant for the SSCs in the underground facility. If an inventory-based SSC categorization method is used, many of these SSCs will be placed into PC-4 category, even though the failure of these SSCs may have very little adverse radiological consequences. As such, it is recommended that the facility owner develop a procedure for categorizing SSCs in a HLNWR using a graded approach such that the numerical performance goal of an SSC is approximately proportional to the risk associated with its failure. Thus, if the failure of an SSC can potentially result in a large offsite dose or a large leakage to the ground water, the SSC would belong to a higher performance category requiring the use of an appropriately lower probability design seismic event. On the other hand, if the SSC failure results in a very small or insignificant release or the probability of the release is very low, it should be permissible to place the SSC in a lower performance category, even though the facility may have a large inventory of radioactive materials.

Implementation of such a procedure need not be very rigorous and time consuming. The principle can be applied on a system level first, instead of at a component level, and all the components of the system can be conservatively placed in a performance category commensurate with the consequence of its failure. However, if designing some components to the applicable system performance category is found not to be cost-effective, these components can be placed into lower performance category if a system analysis indicates that their failures have less severe consequences. Thus, a dose-based criteria would provide the flexibility necessary for a cost-effective seismic evaluation program. Even an approximate (but conservative) estimation of the failure consequences of a system or a component for the purpose of gradation and performance categorization will be enormously useful.

Designing Facilities for Seismic Fault Ruptures

A seismic event causes vibratory ground motions over a large area, and the facilities located within the affected area are designed to withstand the loads associated with such vibratory motions. The performance-goal based design method of references 1 through 4 addresses SSC and facility design for

such seismic vibratory motions.

A seismic event may also cause ground rupture (differential offset) in the immediate vicinity of a facility or through a facility. It is a customary and prudent practice to locate Nuclear Power Plant type facilities sufficiently away from existing fault lines or from areas where the potential for ground rupture at existing fault lines is significant. However, for certain sites with large facilities, like DOE's Yucca Mountain Site, for the reasons stated below, it may not be cost-effective or may not be technically prudent to try to locate all facilities and SSCs away from all potential fault lines:

- (i) The failure mode and consequences of failure of a HLNWR resulting from a fault rupture are significantly different from those of a nuclear power plant. For a nuclear power plant, a fault rupture can potentially damage the reactor resulting in a core meltdown, containment breach, and sudden release of large amounts of radioactivity in the area surrounding the plant. For an underground repository, a fault rupture, unless mitigated through engineered design, can potentially cause failure of waste canisters resulting in the spilling of the radioactive materials into the drifts. Keeping the potential low for these radioactive materials to reach the ground water is the primary mission of a repository project. Thus, if this mission can be satisfied by appropriately considering in the design the consequences of a fault rupture, this should be permitted. For surface facilities also, the consequences of a fault rupture (say, from the structural failure of a hot cell), can be kept limited to localized spillage and the potential risks can be kept within permissible range through engineered design.
- (ii) The long term objective of isolating the waste from reaching the environment will be achieved primarily through geologic barriers. Thus, the geologic and hydrological characteristics of a site are of utmost importance. Potential seismic events are likely to be small contributors to the overall risk, or risks from them can be kept within permissible limits by engineered barrier systems. Hence, a geologically and hydrologically desirable site should not be rejected because of seismic concerns.

Thus, instead of summarily rejecting a potential site because of nearby faults, following a "graded approach" philosophy, a design should

properly weigh the probability of ground rupture, the relative vulnerabilities of SSCs subjected to the forces that may result from the rupture, and the consequences of failures resulting from the rupture. If the ground rupture probability is insignificant, or if the combination of (i) SSC design robustness, (ii) SSC failure consequences, and (iii) the probability of ground rupture is such that the potential risk is insignificant, the SSC can be located on or near potential fault lines.

The design method of references 1 through 4, even though based on the same "graded approach" philosophy, does not explicitly address SSC and facility design for seismic fault rupture. It is recommended that the HLNWR facility owner develop a criteria document addressing the design issues associated with fault rupture. Specifically, the document should address the following issues:

- (a) Assessment of site specific hazards associated with seismic fault ruptures.
- (b) The effects of fault rupture induced forces or displacements on the functionality and failure modes of safety-related SSCs.
- (c) Design acceptance criteria for SSCs when subjected to fault rupture induced forces or displacements.

CONCLUSION

A HLNWR project will consist of facilities ranging from surface facilities with conventional design life of 50 to 100 years to some sub-surface facilities or components with unconventional performance requirements for up to 10,000 years. The performance goal-based seismic design methodology outlined above will be especially suitable for use in designing such facilities for the reasons listed below:

- (a) This method permits determination of seismic hazard level, analysis and evaluation requirements, and design acceptance criteria that are consistent with the overall safety goal. In such design methods, the linkage with the safety goal, even though approximate, is distinct, traceable, and rationally established. Since the method is based on a graded approach, it has the potential to render the design and construction cost of a facility consistent with the societal risk resulting from its postulated failure. A purely deterministic and conventional seismic design method, by comparison, is either unable to rationally

account for relative mission and safety significance of facilities and unconventional performance requirements, or at best accounts for these in an indirect and arbitrary way.

(b) Some of the SSCs in the subsurface facilities of a HLNWR that constitute the engineered barrier system (EBS) may have 10,000 year performance requirements. The design of such SSCs will require consideration of very low probability seismic events. But, if the selection of the design basis earthquake (DBE) for such facilities is done without taking into account the relative magnitude of societal risk and the cost effectiveness of risk reduction through EBS, the DBE may be set at an unrealistic and arbitrary value. The use of performance goal-based design method would eliminate such a possibility.

(c) A potential HLNWR site may have faults with a very low, but finite probability of being active over a span of 100 years of surface facility life or 10,000 years of subsurface facility life. Purely deterministic treatment of such low probability occurrences in facility design will not be appropriate. On the other hand, the performance goal-based method of design is ideally suited to account for events associated with such low activity faults.

(d) The use of performance goal-based seismic design method will permit quantitative assessment of repository seismic performance (quantity and frequency of release) with relative ease, and will facilitate the overall facility performance assessment.

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