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A Performance Goal-Based Seismic Design Philosophy for Waste Repository Facilities

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ABSTRACT

A performance goal-based seismic design philosophy, compatible with DOE's present natural phenomena hazards mitigation and "graded approach" philosophy, has been proposed for high level nuclear waste repository facilities. The rationale, evolution, and the desirable features of this method have been described. Why and how the method should and can be applied to the design of a repository facility are also discussed.

I. INTRODUCTION

Depending on the geographical location and local siting conditions, seismic issues can be significant or even dominant in the design of waste repository facilities. For DOE's Yucca Mountain Site, that is being investigated for site suitability, seismic issues are being evaluated with a level of effort that dwarfs even what is typically done for siting a nuclear power plant. This effort is presently directed at assessing the potential seismic hazards which will be used in repository facility design and performance assessment. As such, it is important that the seismic studies that are presently underway be structured such that hazard assessment is integrated with seismic design of facilities. In fact, it is desirable to integrate these activities not only with seismic design, but also with the other design and accident mitigation considerations. Towards this goal, this paper proposes a performance goal-based seismic design philosophy for the design of high level waste repository facilities. This design philosophy has been developed over the years by DOE, and is being improved continually. It is being considered for endorsement by the ASCE (American Society of Civil Engineers) subcommittee on Seismic and Dynamic Analysis and Design of High Level Nuclear Waste Repositories, of which the author is a member. However, the opinions expressed and positions described here belong to this author and do not represent ASCE's or any of its committee's position.

The rationale and evolution of the proposed seismic design philosophy will be summarized. Why this philosophy is considered superior to conventional methods for designing repository facilities will be discussed. Also, the modifications to the current performance goal-based design method that may be needed for adapting it to the specific repository requirements and configuration will be presented and discussed.

II. EVOLUTION OF PERFORMANCE GOAL-BASED SEISMIC DESIGN METHOD

Before getting into the proposed seismic design philosophy of waste repository facilities, it is necessary to briefly examine how the present day design philosophies and methods for nuclear safety-related structures, systems, and components (SSCs) evolved and why the proposed performance goal-based method is considered a natural evolutionary advancement. In conventional method of SSC design (including the design of safety-related SSCs), the SSC configuration and features are initially determined from the consideration of their intended functions. For example, the layout of a building including the locations and thicknesses of walls, floors, etc., is initially determined ensuring that the building can perform its basic intended functions. Similarly, a piping system is routed and the pipe and fitting sizes are selected so that the basic function of transporting the fluid from one point to the other is satisfied. To facilitate this design process, various civil structures, mechanical, electrical, and chemical engineering standards have been developed over the last century. Initially, these standards primarily dealt with the functional demands of SSCs and the limiting characteristics of the materials of which the SSCs are made (e.g. strength, thermal properties, electrical conductivity, etc.). The standards also considered the fiscal impact of the failure of the SSCs, but safety considerations were not initially included. Gradually, with the increase in the concern for worker, public and environment safety, and pressure from governmental agencies, safety requirements were added. Thus, many of todays industry standards and design codes implicitly recognize, albeit somewhat qualitatively, the consequences of SSC failure in establishing the stringency of design acceptance criteria. Thus, an assembly building, a school building, or a hospital is designed more stringently than a warehouse or a residential building because their failure consequences are relatively more serious. Similarly, the design rules for emergency core cooling system (ECCS) in a nuclear power plant is significantly more stringent than those for an agriculture irrigation system piping. Such differentiation has been made basically through the use of "factor-of-safety" which was varied depending on the SSC failure consequences and the uncertainties in predicting the material strengths and characteristics and analytical processes. However, the numerical values of "factor-of-safety" were not quantitatively correlated with the SSC failure consequences or design uncertainties; the correlation was only qualitative.

Another important parameter was gradually introduced in the industry design codes as well as in the regulatory requirements. That was the probability and the uncertainty of operation related events and natural phenomena hazards to which an SSC may potentially be subjected or for which the SSC may need to be designed. It was recognized qualitatively that the potential risk from a high probability hazardous event is more than that from a low probability event, and this should be accounted for in the design. For simplicity and the ease of design engineers, this event probability was considered in the design rules through the use of "load factors." The loads or demands on the SSCs resulting from the hazardous events were multiplied by these factors. These factors were selected based on consensus judgment of industry experts or regulatory agencies.

Summarizing, it is observed that industry codes and regulatory requirements recognize the following major design considerations:

(1) The magnitude of loads/demands resulting from an event

(2) The configuration of the SSC

(3) The strength and characteristics of the materials with which the SSC is constructed or manufactured.

(4) The uncertainties in the material strength & characteristics.

(5) The uncertainties in predicting the loads and demands resulting from a clearly defined event.

(6) The consequences of the failure of the SSC.

(7) The probability of events that produce loads/demands on the SSC.

Of these the first three are explicitly and quantitatively accounted for in the design process; No. 4 and No. 5 are indirectly recognized through the use of "factors-of-safety"; and the last two are indirectly accounted for using "load factors". This was the state-of-the-art for the nuclear power industry till the mid 1970's, when engineers started seriously looking for ways to eliminate or reduce two major deficiencies in the design method described above, i.e.. the inability of the method to: (a) realistically and more quantitatively account for very low probability events and (b) to establish direct correlation between quantitative safety or risk goals and the design criteria.

In the 70's, engineers designing nuclear power plants observed that the additional design and construction costs of the plants that can be attributed to low-probability external events like earthquake or internal events like loss-of-coolant accident (LOCA) are quite significant. These costs often seemed disproportionate to the risks that the additional design is supposed to reduce. When unrealistically high seismic design and retrofit costs for plants in the seismically inactive (or at best marginally active) eastern and southern parts of the United States were evaluated, it was intuitively felt that, the existing design philosophy, in which the event probability and SSC failure consequences are, at best, crudely and indirectly considered, must change. Many plant owners resorted to probabilistic risk assessment (PRA) to demonstrate that, even if the plants are subjected to seismic levels much higher than what the plant was originally designed for, the potential risk is within acceptable limits. PRA studies brought some sanity to an otherwise wild post-TMI risk-conscious environment.

PRA technique, however, has some limitations. For evaluating the risk potential for an existing plant or an existing design, this technique proved very useful.

It not only identified the vulnerable systems and components in the plants (where attention should be focused), but it also enabled the plant owners to demonstrate to the regulators, environmentalists, and intervenors that the risks from these plants do not add significantly to those already existing in the society. But, efforts to apply this technique directly for designing new plants were not successful because of the following reasons:

(1) The data on the reliability (or failure frequency) of various SSCs, even though to some extent adequate for overall plant-basis PRA, are hardly so for individual SSC design. The overall plant-basis PRA had the advantage of the "integration effect" that reduced the impact of uncertainties associated with insufficient data. The same was not true for individual SSC design.

(2) Conventional PRA technique, if applied directly to SSC design, will lead to an iterative procedure that will be prohibitively expensive.

(3) Application of PRA technique in SSC design will require the existing industry design codes (such as UBC, ASME, AISC, ACI Codes) to be rewritten in "probabilistic" terms (as opposed to what is commonly called "deterministic" terms), which will take years, if not decades, of effort.

(4) Typical design engineers are not familiar with PRA techniques.

As a result, the search for a more suitable seismic design method continued in the 1980's. One such search resulted in the development of DOE's performance goal-based seismic design and evaluation methodology that has the ability to rationally and realistically account for low probability events and hazards, and at the same time it can approximately establish linkage between quantitative safety or risk goals and the design criteria. How these design objectives are met, without encountering the difficulties associated with the use of conventional PRA techniques in the design process, are discussed below while briefly describing the major philosophical features of DOE's performance goal-based seismic design method.

III. DOE's PERFORMANCE GOAL-BASED SEISMIC DESIGN METHOD

DOE's seismic safety program is a part of its overall natural phenomena hazards (NPH) mitigation program. Even though the emphasis on seismic safety at DOE facilities started somewhat later than NRC's systematic program for nuclear power plants, DOE gained from NRC's experience and started its seismic program with a more integrated and rational approach. The primary advantage of this performance goal-based design and evaluation methodology is that it is capable of simultaneously utilizing the state-of-the-art probabilistic or hybrid hazard assessment results and the conventional 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:

(1) It is based on setting target performance goals of SSCs that are expressed as annual probabilities of failure. 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.

(2) The methodology is based on a graded approach such that the seismic hazard level, risk reduction factor, 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.

(3) 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.

(4) The numerical performance goals for various SSC performance categories are set based on experience-based failure rates and past seismic PRA results.

These features were introduced first by Kennedy, et. al. in a University of California publication, UCRL-15910[1] (developed by the Lawrence Livermore National Laboratory as part of DOE's NPH program), and subsequently incorporated in DOE Order 5480.28[2] and DOE draft standard 1020[3]. The following are the key steps for the performance goal-based seismic design and evaluation method presented in these documents:

a. Facility Hazard Classification and Categorization: Facilities are classified/categorized based on their hazard potential without taking into consideration any engineered design features.

b. SSC Safety Classification: SSCs are classified based on their safety and monitoring functions and the consequences of their failures. This classification is not linked with the facility hazard category/class. This classification is often performed by system failure mode and effects analysis (FMEA).

c. SSC Seismic Performance Categorization: It involves assigning performance categories to SSCs based on : (i) facility hazard category/class, (ii) SSC Safety Class, (iii) facility mission, and (iv) SSC repair/replacement cost. Each performance category has been assigned a target numerical performance goal (expressed in terms of annual probability of failure or non-performance, P_F) and a set of corresponding design rules and criteria. The compatibility between the numerical performance goals and the design rules/criteria has been approximately, but rationally, established by benchmarking/comparing these (i.e. numerical performance goals and design criteria) with: (1) those implicit in the Uniform Building Code (UBC), and (ii) the results of a large number (more than 20) of nuclear power plant PRA studies.

d. Determination of Seismic Hazard Level: If the seismic design rules and criteria do not introduce any added conservatism, the hazard exceedance probability, P_H for the design level seismic motion would be the same as the numerical performance goal, P_F for the SSC. However since the design rules and criteria in the existing industry standards and codes have some inherent conservatism, P_H values for various SSC performance categories are not the same as P_F values. These are determined by appropriately accounting for the conservatism in the design rules and criteria. The ratio between P_H and P_F is called risk reduction ratio, R_R (i.e. this is the ratio by which the application of specified design rule/criteria reduces the risk), i.e.,

$$R_R = \frac{P_H}{P_F}$$

Thus, to meet the given target performance goal for an SSC, R_R and P_H can be varied. For example, by adding conservatism to the design rules and criteria (i.e. higher R_R), one can increase the hazard exceedance probability, P_H, but still meet the target performance goal, P_F.

e. Calculation of Seismic Demand and Design of SSC: Once P_H is determined, seismic demands on SSCs are calculated and designs are performed using deterministic and conventional design codes and criteria.

The level of design conservatism for the five seismic performance categories are generally considered comparable to those in the following facility/SSC design:

(i) Nuclear power plant Seismic Category 1 SSCs (for PC-4 SSCs)

(ii) Safety-related SSCs in nuclear fuel processing facilities with no radioactive inventory under high temperature and pressure (for PC-3 SSCs)

(iii) UBC's "Important" class SSCs (for PC-2 SSCs)

(iv) UBC's general use SSCs (for PC-1 SSCs)

(v) PC-0 SSCs are those that require no seismic design from safety, mission, or cost considerations.

Thus, even though existing deterministic and well-established industry design standards and codes are utilized, this method permits explicit and rational gradation of SSCs based on probabilistic performance requirements. Also, it permits the use of improved seismic hazard data and methodology that have been developed in the last decade.

IV. COMPATIBILITY OF PERFORMANCE GOALS WITH NUCLEAR SAFETY POLICY

Even though the use of DOE's performance goal-based seismic design method, as indicated earlier, makes it relatively easy to determine the risks associated with a facility, the present DOE standards and orders do not address the compatibility between the probabilistic target seismic performance goals given in DOE 5480.28[2] and DOE's Nuclear Safety Policy, SEN-35-91[4]. The later states, "DOE has adopted two quantitative safety goals to limit the risks of fatalities associated with its nuclear operations. These goals are essentially the same as those established for nuclear power plants by the Nuclear Regulatory Commission (NRC) and, like the NRC goals, should be viewed as aiming points for performance". Basically, these goals are that the risk of fatality to an average individual in the vicinity of a nuclear facility from accidents or cancer should not exceed 0.1% of the risk to which a member of the general public is exposed.

In a recent study[5], the compatibility between DOE's above-stated safety goal and the numerical performance goals for four seismic performance categories (PC-1 through PC-4) were examined. Using an approximate but simple method, this study showed that if the following offsite dose limits are used as guidelines for the four seismic performance categories, the safety policy goals are adequately met:

PC-4: 25 rem
PC-3: 5 rem
PC-2: 1 rem
PC-1: 0.5 rem

Similar simple studies can be undertaken while developing performance categorization criteria so that seismic design methodology is compatible with the overall performance requirements of the waste repository.

V. APPLICATION OF THE METHODOLOGY TO WASTE REPOSITORY DESIGNS

DOE's seismic design philosophy described above is generic, and can be applied to a wide spectrum of facilities, including waste repository facilities. However, it is recognized that a waste repository, like the one whose feasibility is being investigated at DOE's Yucca Mountain site, will have unique characteristics that will need to be considered. Some of these are briefly discussed here.

A. Performance Goals and Design Criteria for SSCs in Underground Facilities

The performance goal for PC-1 SSCs in DOE 5480.28[2] has been based primarily on the general performance of UBC-designed components, and that for PC-4 SSCs are based on PRA and seismic margin study results of nuclear power plants. PC-3 and PC-2 goals were chosen between PC-1 and PC-4 goals based on a graded approach. For PC-1 SSCs, failures of conventional structural components were primarily considered. For PC-4 SSCs safety-related structures and equipment in typical nuclear power plants were considered. The configuration, design rules, and functional requirements of these SSCs (UBC-designed or nuclear power plant types) are similar to those in the surface facilities of a repository, but the SSCs of the underground facilities are not. As such, the performance goals for the underground facility SSCs will need to be determined in the light of the inherent conservatism in the industry codes and criteria that are applicable for their design. Also, in general, the design criteria and the functioning of SSCs whose failures are not primarily dependent on conventional structural adequacy should be evaluated before establishing facility specific seismic safety performance categories, risk reduction ratios, and design seismic hazard level. 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 repository facility will be concrete tunnel lining, rock bolts, or an unlined tunnel (which may fracture and become unstable during a seismic event).

B. Probabilistic Consideration of Seismic Fault Ruptures

For typical hazardous facilities, it is prudent to locate the facility away from known faults or faults with high or moderate probability of rupture during the facility life. However, the application of this "good practice" rule to some waste repository site may not be judicious, and should be decided based on the advantages and disadvantages of such siting and the costs of the alternatives.

For a nuclear power plant, a fault rupture at or near the plant can potentially cause a core meltdown, containment breach, and unacceptably large and rapid release of radioactive materials. For a waste repository, a fault rupture can potentially cause failure of some waste canisters. But the consequences of canister failure can be significantly mitigated through engineered design and facility layout. Also, even if not mitigated, canister failure consequences are unlikely to be as catastrophic as the core meltdown of a nuclear power plant. The objective should be to estimate the risk in probabilistic term and consider the alternatives. For example, if the fault rupture probability is very low, and when it is combined with a rugged canister design, the resulting risk (from seismic considerations) may be within acceptable limits. In such cases, a site which is otherwise desirable from geological, hydrological, meteorological, and population density considerations should not be rejected because of insignificant seismic risks. The proposed performance goal-based seismic design/evaluation methodology can be easily adapted to permit such rational assessment.

CONCLUSIONS

The design of critical and hazardous facilities that may be subjected to very low probability accidental or natural phenomena events should utilize advanced design philosophy and methods that have been developed in the last decade based on recent experiences and studies. One such evolutionary method is DOE's performance goal-based seismic design method that can be easily adapted for the seismic design of high level nuclear waste repositories. This method lends easily to risk assessment that is essential to demonstrate to the public, the regulators, and the intervenors that the facility would meet the safety goal. By considering the frequency of seismic hazards (including hazards resulting from fault rupture) in a probabilistic way, but utilizing the established design codes and criteria in a deterministic way, this method would permit quantitative determination of risks associated with an seismic event.

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