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An Application of Performance Goal Based Method for the Design and Evaluation of Structures

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An Application of Performance Goal Based Method For the Design and Evaluation of Structures

Thomas J. Conrads[1]

Abstract

This paper describes an application of the U.S. Department of Energy's (DOE) performance goal based method for the design and evaluation of structures, systems, and components (SSCs) at Fluor Daniel Hanford, Inc. (FDH). The philosophy on which DOE's method is based has been employed to construct a graded approach to the minimum structural design and evaluation criteria used at the DOE Hanford Site that complies with the DOE Order 5480.28, *Natural Phenomena Hazards Mitigation*. The FDH structural design and evaluation criteria applies to both nuclear and non-nuclear SSCs that are not covered by a reactor safety analysis report.

Introduction

In 1993, DOE issued Order 5480.28, which reflects its policy to design, construct, and operate DOE facilities so that workers, the public, and the environment are protected from natural phenomena hazards (NPH). This order also underscores DOE's intention that a graded approach be taken for the design and evaluation of an SSC based on its importance to safety. This means that SSCs required to provide a mitigating (safety) feature during an NPH event be designed to ensure the survival of that safety feature. Moreover, such designs that ensure the function of the mitigating feature should be accomplished in a graded fashion commensurate with the SSC's importance to safety.

Application of the Methodology

In order to accomplish this graded approach to the structural design of new SSCs and the evaluation of existing SSCs, DOE has adopted a pseudo probabilistic approach using target performance goals for different classes of SSCs based on their importance to safety. These performance goals (P_f) reflect an annual probability of exceeding acceptable behavior limits. Inherent in this design process governed by performance, are the selection of loading, the evaluation of SSC response, the specification of acceptance criteria and the assumption of ductile detailing.

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Of these elements only the loading is probabilisticly based. The other steps in the design process represent classical deterministic approaches to structural analysis. The following discussion describes how FDH has implemented this cost-effective, graded approach to design and correlated it to both the DOE safety analysis process described in DOE Order 5480.23, *Nuclear Safety Analysis Reports* and practices used by the commercial industry in the design of hazardous and non-hazardous SSC's.

DOE has specified five different performance categories (PC) to describe the graded approach to structural design. These, along with the appropriate performance goals (P_F), i.e., the probability of exceeding acceptable behavior limits, the annual hazard exceedance probabilities, and the risk reduction factors are shown for the seismic hazard in Table 1. By the DOE process, the design basis earthquake (DBE) is defined at a specific hazard probability (P_H) and the SSC is evaluated for the DBE using a conservative acceptance criteria. To meet the target performance goal applicable for the SSC performance category, the acceptance criteria must introduce an additional reduction in the risk of unacceptable performance below the annual risk of exceeding the DBE. The ratio of the seismic hazard exceedance probability (P_H), to the performance goal probability P_F is defined as the risk reduction factor R_R where $R_R = P_H/P_F$. The required degree of conservatism in the deterministic acceptance criteria is a function of the risk reduction ratio.

Table 1: "Seismic Performance Goals & Specified Seismic Hazard Probabilities

PC	Target Seismic Performance Goals, P_F	Seismic Hazard Exceedance Probability, P_H	Risk Reduction Ratio, R_R
0	0	0	N/A
1	$1x10^{-3}$	$2x10^{-3}$	2
2	$5x10^{-4}$	$1x10^{-3}$	2
3	$1x10^{-4}$	$5x10^{-4}$ $(1x10^{-3})^1$	5 $(10)^1$
4	$1x10^{-5}$	$1x10^{-4}$ $(2x10^{-4})^1$	10 $(20)^1$

[1] For sites like LLNL, which are near tectonic plate boundaries.

PC0 category represents that class of SSC that does not require any consideration for seismic loading, i.e., there are no adverse consequences from failure as a result of a seismic event. Whereas the performance goals for PC1 SSCs are consistent with goals of model building codes for standard facilities, the performance goals for PC2 SSCs are slightly more conservative than the goals of model building codes for important or essential facilities. For seismic design and evaluation, model building codes utilize equivalent static force methods, except for very unusual or irregular facilities, for which a dynamic analysis method is employed. The performance goal for PC3 SSC's is consistent with DOE essential facilities and plutonium handling facilities. The performance goal for PC4 SSC's approach that used for nuclear power plants. For these reasons, the DOE Order and its standards specify seismic design and evaluation criteria for PC1 and PC2 SSCs corresponding closely to model building codes, and seismic design and evaluation criteria for both PC3 and PC4 SSC's are based on dynamic analysis methods consistent with those used for similar nuclear facilities.

So far, the discussion has focused on fundamentals used to define the performance goal (P_F) the annual exceedance probability (P_H), the risk reduction factor (R_R), and the PC. The obvious question is how does one establish the PC? Tables 2 and 3 are excerpts from DOE Standard 1020-94 and provide qualitative descriptions of both the safety significance and the component damage state expected for the various performance categories. Therefore, a key to cost-effective design is to establish an understanding of what safety function is required of an SSC and what design features are being relied upon to ensure these features are being preserved during NPH events. It is also necessary to determine the consequences of an items failure so it can be ranked (PC1, PC2, etc.) according to its importance to safety.

Now that the PC of the SSC has been established, it is necessary to determine the quantitative hazard level to which it should be designed. As seen from Table 1, this level is directly proportional to the exceedance probability P_H, which is a result of a probabilistic hazard assessment. Realizing that the inverse of P_H is the annual hazard return period, the sites that do not have a need to confine a hazard probably will not have structures classified as PC3 or PC4, and will not have to prepare probabilistic hazard assessments. These sites can use the Uniform Building Code to obtain the 500 year return period DBE for PC1 and other model building codes for the 1000 year return period DBE for PC 2.

For these organizations that find it necessary to ensure a confinement, which is usually associated with an off-site consequence, a probabilistic seismic hazard curve will have to be developed. The seismic hazard curve for the Hanford Site is shown in Figure 1. This curve then provides the seismic hazard for return periods associated with PC1 through PC4 SSCs for different locations on the Hanford Site.

Figure 2 depicts the process used by FDH to effect a graded approach for the design and evaluation of all SSCs. This is FDH's interpretation of the DOE policy to ensure the workers and public are protected against the effects of natural phenomena. The first two rows depict the hazard evaluation process, which is facility based and does not drive design criteria. It does influence the type of safety analysis required, the approval levels for the safety analysis, and the rigor required of the supporting analyses. The next three rows describing the safety analysis, mission importance, and cost importance, are drivers which directly influence the selection of the PC. Once the PC is known, NPH design levels are obtained from hazards curves and methods for structural evaluation are given in DOE Standard - 1020-94.

The above process yields the necessary information that engineers can use to apply a graded approach to the structural design of SSCs having a broad spectrum of safety applications. Yet this information only provides one-half of the design equation. Once the project establishes the functional design criteria and has identified the design loads from the above process, the other information that is needed for a complete design specification is the set of codes and standards to be employed. These dictate the quality level required for the design.

Table 4 is the FDH proposed correlation between safety classification and codes/standards for various components. For Safety Class (SC) SSCs, it invokes codes and standards normally reserved for nuclear reactor applications. For General Services SSCs, it invokes codes and standards associated with standard commercial practice. For the Safety Significant Category, the direction is to employ the commercial practice code and standard and compliment it with provisions of the nuclear industry codes and standards that will enhance the feature of interest.

Summary

The process described above provides a graded approach to the design and evaluation of SSCs based on the DOE policy to protect workers and public from the effects of NPH. It requires that the engineer makes a conscientious decision which SSCs are important from a safety, mission, and cost perspective, rank these appropriately and select the loads, codes, and standards necessary to assure functionality during and following a natural phenomena event. This process can also be extended to address a graded approach to quality assurance, surveillance and in-service inspection, procurement, etc.

Experience to date has demonstrated the cost effectiveness of such an approach in that it eliminates redundancy where it is not needed, and allocates the appropriate level of resources for designing SSCs based on their importance to the project.

Table 2, "Structure, System, or Component (SSC) NPH Performance Goals for Various Performance Categories

PC	Performance Goal Description	NPH Performance Goal Annual Probability of Exceeding Acceptable Behavior Limits, P_F
0	No Safety, Mission, or Cost Considerations	No requirements
1	Maintain Occupant Safety	$\sim 10^{-3}$ of the onset of SSC[1] damage to the extent that occupants are endangered
2	Occupant Safety, Continued Operation with Minimum Interruption	$\sim 5 \times 10^{-4}$ of SSC damage to the extent that the component cannot perform its function
3	Occupant Safety, Continued Operation, Hazard Confinement	$\sim 10^{-4}$ of SSC damage to the extent that component cannot perform its function
4	Occupant Safety, Continued Operation, Added Confidence of Hazard Confinement	$\sim 10^{-5}$ of SSC damage to the extent that the component cannot perform its function

(1) These performance goals are for each NPH (earthquake, wind, and flood)
(2) SSC refers to structure, distribution system, or component (equipment)

Table 3, "Qualitative Seismic Performance Goals"

PC	Occupancy Safety	Concrete Barrier	Metal Liner	Component Functionality	Visible Damage
1	No structural collapse, failure of contents not serious enough to cause severe injury or death, or prevent evacuation	Confinement not required	Confinement not required	Component will remain anchored, but no assurance it will remain functional or easily repairable	Building distortion will be limited but visible to the naked eye
2	No structural collapse, failure of contents not serious enough to cause severe injury or death, or prevent evacuation	Concrete walls will remain standing but may be extensively cracked, they may not maintain pressure differential with normal HVAC. Cracks will and provide a tortuous path for material release. Don't expect largest cracks greater than 1/2 inch	May not remain leak tight because of excessive distortion of structure	Component will remain anchored and majority will remain functional after earthquake. Any damaged equipment will be easily repaired	Building distortion will be limited but visible to the naked eye
3	No structural collapse, failure of contents not serious enough to cause severe injury or death, or prevent evacuation	Concrete walls cracked, but small enough to maintain pressure differential with normal HVAC. Don't expect largest cracks greater than 1/8 inch	Metal liner will remain leak tight	Component anchored and functional	Possibly visible local damage but permanent distortion will not be immediately apparent to the naked eye
4	No structural collapse, failure of contents not serious enough to cause severe injury or death, or prevent evacuation	Concrete walls cracked, but small enough to maintain pressure differential with normal HVAC. Don't expect largest cracks greater than 1/8 inch	Metal liner will remain leak tight	Component anchored and functional	Possibly visible local damage but permanent distortion will not be immediately apparent to the naked eye

Figure 1, "Hanford Site Seismic Hazard Curves"

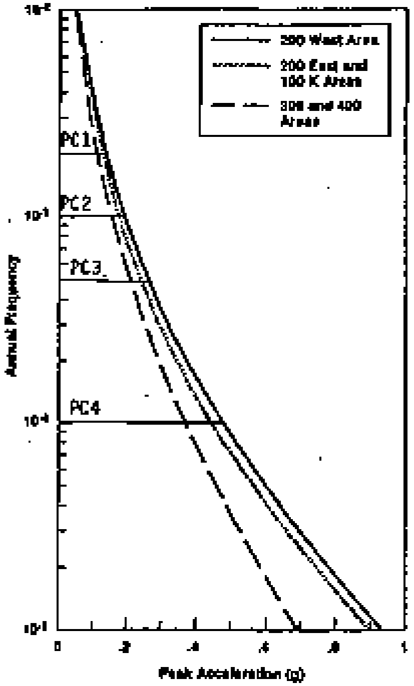

Figure 2, "Safety and Performance Category Correlation"

This table depicts the step by step safety analysis process that culminates with the selection of performance category. Hazard categories and classes are shown for completeness but do not correlate directly to safety designation or performance category

Facility Type	Reactor or PSD designated	Hazardous or Essential Non reactor Facility			General Facilities	No Safety Function
Hazard Category	HC 1	HC 2	HC 3	Radiological		
Hazard Class		High (HH)	Moderate (MH)	Low (LH)		

Categorizing the Hazard as depicted above does not directly influence the safety classification process nor the category

Structures Systems Components Safety Designation and Mitigating Features	Safety Class		Safety Significant			General Services	
	Performs or preserves reactor safety function	Prevents or mitigates rad consequences above risk guidelines to	Prevents or mitigates toxic chemical or rad consequences above risk guidelines to		Worker safety. Prevents or mitigates serious injury not controlled by Institutional Safety Program (ISP) to	Occupant & worker safety controlled by building code and ISP	
		Offsite public	Offsite public (toxic only)	Onsite worker (toxic chemical)	Facility worker	Any occupant	No occupant
	SC-1			SC 2	SC 3	Non Safety Class	
Mission Importance	Mission Importance Criteria TBD				Historic or UBC essential	Not essential	None
Cost Imp	Cost Importance Criteria TBD						None
Performance Category	PC4	PC3		PC2	PC1		PC0
	Goal 1X10^{5}	Goal 1X10^{4}		Goal 5X10^{4}	Goal 1X10^{3}		No Goal

Table 4, "Guidance for Selecting National Codes and Standards

This table was developed by the Westinghouse Maintenance and Operations Nuclear Facility Safety/Engineering Joint Subcommittee

Category/Application	General Services (GS)	Safety Significant	Safety Class
Structural	UBC ACI 318 AISC UCRL 15910 AWS D1 1	same as GS	ACI 349 ANSI N690
	Guidance on applicable codes and standards is also provided by Performance Category per DOE STD 1021		
Process Equipment Vessels & Tanks	ASME VIII API AWWA D100 UL 58 142	same as GS	ASME III *
Process Equipment Piping & Valves	UPC ASME VIII ASME B 16 et B31 1 B 31 3 B 31 9 AWWA Hydraulic Institute Standards	same as GS	ASME III* ANSI N278
Process Equipment Pumps	API ANSI/ASME B73 1M 2M ASME VIII Hydraulic Institute Standards AWWA AFBMA	same as GS	ASME III*
Process Equipment Heat Exchangers	ASME VIII TEMA ASHRAE	same as GS	ASME III*
Process Equipment Ducts & Fans	ASHRAE SMACNA	same as GS	same as GS
Process Equipment Pre and HEPA Filters	ASHRAE 52 68 ASME/ANSI 509 510 Mil F 51068C	same as GS	same as GS
Mechanical Handling Cranes	CMAA ANSI B30 et ASME NOG 1	same as GS	CMAA Nuclear Sections
Mechanical Handling Other Equipment	ANSI 16 et AISC	ANSI N14 6	same as safety significant
Electrical	NEC NESC IES Lighting Handbook	IEEE 577	IEEE 308 338 379 38[illegible] 603 (Section 5 III)
Instruments and Controls	ISA ANS 8 3 N42 18 N13 1	same as GS	ANSI N320 ISA S67 04 NQA 2 IEEE 497
Fire Protection	NFPA	same as GS	same as GS
Chemical & Toxicological Hazards	OSHA AIChE Safety Standards API Safety Standards ACGIH Requirements NFPA	same as GS	same as GS
All applicable Equipment	OSHA UL Local and State Standards AWS NEMA ASTM ANSI NFPA	same as GS	same as GS

* ASME III or other comparable safety related codes and standards that are appropriate for the system being designed

Appendix

References

DOE Order 5480.28, *Natural Phenomena Hazard Mitigation*

DOE Order 5480.23, *Nuclear Safety Analysis Report*

DOE Standard 1020-94, *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities*

UBC Uniform Building Code

DOE Order 5481.1B, *Safety Analysis and Review System*

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Key Words: performance goals, natural phenomena hazard evaluation, structural analysis, safety analysis, design basis earthquake, exceedance probability, annual return period, U.S. Department of Energy Orders.