Transactions, SMiRT-26
Berlin/Potsdam, Germany, July 10-15, 2022
Division III

SOFTWARE COMMERCIAL GRADE DEDICATION GUIDANCE FOR NONLINEAR SEISMIC ANALYSIS

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ABSTRACT

Seismic analysis, including the consideration of soil-structure interaction (SSI), is an important and required step in the design and licensing of nuclear power plant structures, systems, and components (SSCs) that are important to safety. Historically, the SSI analysis of nuclear structures has been performed using equivalent linear methods. However, there has been considerable industry exploration of alternative seismic design and analysis approaches, such as nonlinear seismic analysis, to reduce the construction cost of new reactors.

Many next generation reactors are characteristically very different from previous designs, including features such as liquid metal or molten salt coolant, stacked graphite block reflectors, solid pebble fuels, and seismically isolated SSCs. Nonlinear seismic analysis may offer a more realistic approach to capture the physics of next generation designs with inherently nonlinear design features and/or performance criteria. As defined herein, nonlinear seismic analysis refers to an integrated seismic analysis of the site and structure in the time domain where nonlinear behavior in one or more parts of the system is explicitly modeled. Nonlinear seismic analysis tools offer the ability to capture the dynamic coupling between components/subsystems, including SSI effects, while considering nonlinear response in one or more parts of the soil-structure system. However, commercial grade dedication (CGD) of the nonlinear seismic analysis software represents a costly hurdle to implementation within the regulatory framework.

To reduce duplicate effort and the overall burden on reactor developers, an industry initiative was undertaken to develop software dedication guidance for nonlinear seismic analysis tools. The guidance is intended to assist a commercial software user seeking to perform nonlinear seismic analysis of a nuclear facility whose quality assurance requirements necessitate CGD. The developed CGD guidance focuses on the nonlinear features and underlying physical behaviors expected to be important to many reactor designs in order to achieve tools relevant to many reactor developers. The guidance includes a test matrix, which defines physical responses and software features that are mapped to corresponding test cases. The test matrix and test cases help benchmark the specific software features within an end-user's CGD process. These tools can also be leveraged to alleviate the regulatory scrutiny associated with a first-of-a-kind technical approach as they support technical benchmarking of the nonlinear seismic analysis methodology.

This paper discusses the dedication process and how the developed guidance [Doulgerakis et al. (2021)] can support advanced reactor design and licensing. The paper identifies the location of the publicly accessible guidance document and accompanying tools. The guidance and test cases are designed to be technology neutral to support designers of all advanced reactors and other nuclear facilities.

INTRODUCTION

In the 1970s while significant SSI research and technical progress were establishing the foundation for modern nuclear seismic regulation, computer programs emerged to solve the soil-structure system response based upon the direct method and the substructuring method [Kausel (2010)]. Although the direct method of solution in the time domain was praised for proper treatment of nonlinear behavior to the extent it could be described mathematically, the substructuring approach was attractive for the enabling savings in computer time and storage [Idriss et al. (1979)]. Consequently, SSI analysis precedence within the nuclear industry was established based upon extensive application of the substructuring approach, considering an equivalent-linear approximation of the soil-structure system, and from this experience, lessons learned, best practices, and general confidence developed. In the last few decades, nonlinear seismic analysis has become computationally feasible for project-scale analysis and is increasingly adopted within the building, oil and gas, water infrastructure, and transportation industries. However, this adoption and advancement of nonlinear seismic analysis initiated during the time period when the U.S. nuclear power industry was relatively dormant.

As nuclear reactor designs are evolving into smaller, cheaper, and more versatile power plants, so must the nuclear power industry in its broader approaches to plant licensing and design. Many next generation reactors are characteristically very different from previous designs, including features such as liquid metal or molten salt coolant, stacked graphite block reflectors, solid pebble fuels, and seismically isolated SSCs.

Given the advancement in reactor designs and licensing approaches, seismic analysis of future nuclear reactors should also consider modern analysis tools, including nonlinear seismic analysis. As defined herein, nonlinear seismic analysis refers to an integrated seismic analysis of the site and structure in the time domain (i.e., the direct method) where nonlinear behavior in one or more parts of the system is explicitly modeled. Nonlinear seismic analysis contrasts with decoupled approaches that define an artificial boundary or handoff between the soil-structure system (analysed using the substructuring approach) and the structure or subsystems for which nonlinear response must be explicitly modeled. Nonlinear seismic analysis can explicitly account for nonlinearities in the soil and at the soil-structure interface. However, nonlinear seismic analysis may also consider an equivalent-linear approximation of the soil response with nonlinear behavior considered within another part of the system.

Nonlinear seismic analysis software may offer more realistic tools to capture the physics of next generation designs with inherently nonlinear design features and/or performance criteria. Some examples of reactor design and licensing considerations that may benefit from nonlinear seismic analysis include:

- Structures not required to perform a safety-related confinement or containment function – The US NRC risk-informed, performance-based approach to seismic design [Chokshi et al. (2020)] allows inelastic response in these structures, and permits assigning a corresponding limit state (i.e., Limit State A, B, or C as defined in ASCE 43-19). Nonlinear seismic analysis can realistically capture the response of the inelastic structural component(s) to support structural design, in-structure response generation, and displacement demands.

- Liquid metal/molten salt reactors – Liquid metal/molten salt reactors operate at lower pressures and higher temperatures than reactors in the operating fleet. Thermal stresses resulting from the higher temperatures are mitigated by a thinner vessel wall, which is made possible by the lower operating pressure. However, seismic demands can become the controlling accident scenario, and overly conservative analyses may challenge optimization of the reactor vessel thickness. A coupled nonlinear analysis is needed to realistically capture the response of the system given the significant volume of coolant in the reactor vessel, often located within a smaller building structure than those associated with traditional light water reactors. Nonlinear seismic analysis offers the ability to predict the dynamic response of the fluid-vessel-internals system coupled with the response of the larger system and site.

- Seismically isolated structures, components, or skids – Seismic isolation has the potential to increase the seismic safety of nuclear power plants and to reduce the cost and time to build them [Kammerer et al. (2018)]. Seismic isolation has previously been used in the design and construction of nuclear power plants and related infrastructure in France, South Africa, and Japan, and it is currently being considered for nuclear facilities in the U.S. [Kammerer et al. (2018)]. According to Kammerer et al. (2018), nonlinear seismic analysis is the preferred method for seismic analysis of isolated structures.

However, application of nonlinear seismic analysis within the nuclear regulatory framework represents a first-of-a-kind approach. US NRC regulation requires CGD for the nonlinear seismic analysis software tool when it has not been designed and manufactured under an appropriate quality assurance program [US NRC (2019)], [US NRC (2020)], representing a considerable cost to reactor developers. In order to alleviate these costs, an industry initiative developed software dedication guidance to reduce the burden associated with implementing nonlinear seismic analysis in a licensing application.

COMMERCIAL GRADE DEDICATION

For the purpose of this paper, software CGD refers to the overall process that satisfies the definition of dedication provided in 10CFR, Part 21 [US NRC (2020)] to demonstrate a commercial grade item will perform its intended safety function. As defined by 10CFR, Part 21 [US NRC (2020)]:

> "Dedication is an acceptance process undertaken to provide reasonable assurance that a commercial grade item to be used as a basic component will perform its intended safety function and, in this respect, is deemed equivalent to an item designed and manufactured under a 10CFR, Part 50, Appendix B, quality assurance program."

Guidance for dedication of safety-related design and analysis software is provided in EPRI (2013), endorsed by the US NRC in Regulatory Guide 1.231 [US NRC (2017)]. EPRI 3002002289 defines the CGD process in terms of two key elements: the technical evaluation and the acceptance process. In the technical evaluation, the dedicating entity defines the software safety function, critical characteristics, software intended use / types of calculations to be performed, and the range of intended use. The acceptance process includes the tests, inspections, and reviews that demonstrate reasonable assurance the requirements or critical characteristics are met. There are four methods identified in EPRI 3002002289 for demonstrating acceptance. However, acceptance method 1, special tests and inspections, encompasses verification and validation activities and is often the only practical means for verifying certain software critical characteristics [EPRI (2013)].

Herein, software verification and validation refer to software testing that provides evidence of the correctness of the software and the results obtained from it. Simplistically, from Oberkampf and Roy (2010), it demonstrates the software is solving the right equations and solving them correctly. Software verification and validation can and does support a significant portion of the CGD process—and specifically the acceptance process—but is not equivalent to software CGD. To provide impactful dedication support in a manner that is software platform neutral, the guidance primarily focuses on verification and validation of key software features and capabilities expected to be important to safety for the next generation of reactors.

DEDICATION GUIDANCE FOR NONLINEAR SEISMIC ANALYSIS

The guidance [Doulgerakis et al. (2021)] is intended to assist a commercial software user seeking to perform nonlinear seismic analysis of a nuclear facility whose quality assurance requirements necessitate CGD. The CGD guidance includes a test matrix, which defines physical responses and software features that are mapped to corresponding test cases. The following sections summarize the developed guidance and its intended use. For more detailed information and use, readers are directed to the full guidance document and accompanying tools, which are publicly accessible and available at: <https://cgd.linksolutions.com/>.

Purpose and Scope

The purpose of the guidance document is to reduce the software dedication, verification, and benchmarking burden required to meet US regulatory expectations for nonlinear seismic analysis. Further, the guidance document is intended to support many reactor developers considering a wide range of software tools capable of performing nonlinear seismic analysis. The guidance primarily focuses on the technical aspects of CGD, rather than the programmatic or administrative considerations, and specifically the verification and validation of key software features and capabilities expected to be important to safety for the next generation of reactors. To achieve the greatest impact most efficiently, the guidance is focused, considering:

1. The intersection of quality assurance requirements and US regulatory review expectations
2. The technical characteristics / intended uses that are common across reactor designs
3. The dedication activities that can be applied across different users (and specifically users of different software platforms)

The dedication process fundamentally consists of (1) identifying critical characteristics and (2) demonstrating the critical characteristics are met. Filtering through the aforementioned considerations results in a subset of critical characteristics and a single acceptance method (method 1, special tests and inspections) that serve as the focus for this work. Acceptance method 1 (special tests and inspections) is often the only practical means for verifying certain software critical characteristics [EPRI (2013)]. Further, special tests and inspections document comparisons to simplified models and experimental data, which would also support a US NRC case-specific review of nonlinear seismic analysis methods.

The generic critical characteristics in EPRI 3002002289 that serve as the focus of this work are:

- Validity of scientific basis
- Accuracy of the output
- Precision of the output
- Output parameters
- Range of input parameters

Additionally, focus is placed on verification and validation activities that build upon the comprehensive software testing typically executed at the elemental level as part of internal software development. It should be noted that the designation of commercial-grade software does not imply the absence of quality assurance practices in the software development process. Rather, the quality assurance practices have not been confirmed and qualified against the requirements in 10 CFR Part 50, Appendix B, and the burden of demonstrating reasonable assurance lies with the dedicating entity rather than with the software developer or vendor.

Many commercially-sold software tools that could be used for nonlinear seismic analysis undergo considerable testing and quality assurance protocols, with verification and validation testing typically exercising the fundamental features and solution algorithms of finite element method. Testing performed by the software developer can be leveraged by the dedicating entity by either crediting the testing already performed by the developer (via method 2) and/or recreating and performing the test cases (or subset thereof) within the intended environment (via method 1).

Thus, the detailed guidance is developed to demonstrate the generic critical characteristics given above specifically for unique reactor design features expected to be outside of a typical software vendor verification and validation testing program. The purpose of the tools and test cases presented in the following sections is to help establish reasonable assurance that a nonlinear seismic analysis software can appropriately predict the identified behaviors.

Analysis-Specific Critical Characteristics

To efficiently develop impactful dedication support applicable to many reactor designs, the test matrix and test cases are developed for key software features and capabilities identified as important for next generation nuclear power reactors. The tools and test cases presented in the guidance document can be applied to help demonstrate that a nonlinear seismic analysis software produces the expected response for the identified features/capabilities.

The capabilities of many nonlinear seismic analysis tools are vast, and exhaustive characterization of nonlinear response and the corresponding mapping to software features and test cases is far beyond the scope of this work. The key nonlinear physical behaviors (or required functionality) are selected based upon a review of design features proposed for the next generation of nuclear reactors. The most important dataset used to inform this review is the data collected as part of the industry initiative from surveys and interviews of reactor developers, as well surveys of supporting designers/consultants. The dataset is compiled from 56 survey responses and individual interviews with 14 reactor developer/designer entities.

The following summarizes the key conclusions from this review that shaped the selection of nonlinear physical behaviors included herein:

- Many reactor designs have reactor vessels that make up a considerably larger portion of the overall “structure” mass compared to historical plants. Thus, decoupling the reactor vessel (and specifically the nonlinear behavior of the reactor vessel) from the overall soil-structure system analysis may not be appropriate.

- Many reactor designers are considering large volumes of liquid coolant, including liquid metals or molten salts, which may have a large mass relative to the overall structure mass. The seismic response of the liquid coolant and its effect on the reactor vessel and submerged components is inherently nonlinear and is typically important to these designs.

- Many reactor designs are considering seismic isolation and damping devices to support the reactor vessel, other large components, and/or the reactor building. The seismic demand on a seismically isolated component is inherently nonlinear. Many types of isolators are characterized by a nonlinear response to a seismic event, and modelling the nonlinear response is important to demonstrating seismic safety.

- Many reactor designs are considering gapped, bumper-type, or other nonlinear supports for the reactor vessel (or other large components) to accommodate thermal expansion associated with high operating temperatures. Thus, the seismic response of the reactor vessel is nonlinear as it is dependent upon the instantaneous configuration of the vessel and support at any given time.

- Many reactor designs are considering more deeply embedded structures (or portions of the structure). Seismic response of more deeply embedded structures is sensitive to nonlinearities in the soil material and the soil-structure interface (e.g., soil-structure separation, lateral soil pressure, wave-passage effects), which may not be appropriately captured considering an equivalent-linear approximation of the soil or bonded contact at the soil-structure interface.

- Many reactor safety cases do not rely on the structure to perform a containment or confinement function. Considering a performance-based approach, the safety function of the structure does not necessitate that the structure remain essentially elastic, as has been the case for large light-water plants. Thus, the structural response under design basis shaking may be nonlinear. In such a case, characterization of the nonlinear structural response is necessary to determine the seismic demands on SSCs supported within the structure.

- Many reactor designers are considering a risk-informed and performance-based approach to seismic design. For some risk-informed and performance-based approaches, seismic design may be based upon multiple seismic hazard levels (i.e., seismic design may consider the plant response under various earthquake intensities). The historical approach considering an equivalent-linear approximation of the soil and the structure is conditional upon a given earthquake intensity. Nonlinear characterization of the soil and structure provides a seismic analysis model that is independent of the seismic hazard level and can be applied with varying earthquake intensities.

From the review of design features for next generation nuclear reactors, the key physical behaviors or analysis-specific critical characteristics considered in the test matrix includes:

Critical Characteristic	**Example Design Feature or Behavior**
Fluid response and fluid-structure (and/or component) interaction	• Component submerged within fluid • Component/structure containing fluid • Fluid within annulus space between structures/components • Fluid volume with free surface • Floating particles/pebbles within fluid
Response at the interface between components, structures	• Sliding and/or uplift of unanchored equipment • Nonlinear supports (e.g., gapped, tension-only or bumper-type, compression-only supports) • Impact and pounding between adjacent structures • Rattling and uplift of components supported within sleeves, racks, or rails with no structural connection
Response of the combined/integrated soil-structure system	• Soil-structure interaction effects (kinematic and inertial) • Displacement of foundation walls due to lateral earth pressure (especially for deeply embedded structures) • Sliding, gapping/separation between structure and geomaterial
Response of seismic isolation and/or damping devices	• Seismically isolated reactor vessel with elastomeric isolators (e.g., low damping rubber and lead rubber bearings), sliding isolators (e.g., single, double, or triple concave friction pendulum bearings), or spring-based isolators • Equipment supports with fluid viscous dampers (shock absorbers) • Metallic yielding dampers (e.g., buckling restrained braces)

Response of structural materials beyond the linear-elastic region	• Softening of reinforced concrete structural members (including steel-plate composite walls) due to cracking, reinforcing bar yielding, concrete crushing • Yielding of structural steel members • Local/global buckling of structural steel members • Strain hardening response of structural steel
Response of geomaterials (soil and/or rock)	• Nonlinear material response of soil (soil properties independent of shaking intensity / hazard level) • Equivalent-linear strain-compatibility of geomaterial for a given strain demand or hazard level (e.g., strain-compatible soil properties from iteration in SHAKE or similar software) • Large strain response of geomaterial with material shear strength consideration • Horizontal discontinuities in geomaterial (e.g., spatially non-uniform soil layers, cavities/weak zones) • Wave propagation through layered or non-homogeneous soil deposits/profiles • Surface topography effects and slope stability • Soil liquefaction, cyclic softening, and/or cyclic settlement

Test Matrix

As defined in 10CFR, Part 21, CGD is an acceptance process to provide reasonable assurance that a component's safety function will be met. Reasonable assurance is an engineering determination with inherent subjectivity [EPRI (2014)] unique to each software dedication. The intermediate steps in the software dedication process given by EPRI (2013) are key to define reasonable assurance for a given CGD:

1. Identify critical characteristics for acceptance
2. Document safety function(s), failure modes and effects analysis (FMEA), critical characteristics
3. Select acceptance methods

The text matrix supports these intermediate dedication steps by mapping a subset of critical characteristics to an acceptance method (Method 1) and specific test cases. Recognizing that the outcome is a justifiable (not absolute) level of confidence, the acceptance plan should be defined considering the required extent of testing, the software features that should be tested, the critical output parameters, and the necessary acceptance criteria. To that end, the test matrix facilitates more detailed definition of the types of modeling and analysis features, software capabilities, and outputs that will likely be important and should be considered in the software dedication process.

The test matrix (Table 3 and Table 4 in the guidance document [Doulgerakis et al. (2021)]) provides a tool to identify key nonlinear physical responses to be predicted by the software tool and translate the individual physical behaviors to software features and test cases. Table 3 of the guidance document helps the dedicating entity identify what types of behavior and corresponding software features may be important to the safety-related nonlinear seismic analysis. The extent of nonlinear behaviors considered in the test matrix is identified in the previous section (Analysis-Specific Critical Characteristics). Table 4 of the guidance document helps the dedicating entity identify test cases for each software feature selected from Table 3. Each software feature is further defined by specific response modes and response parameters of interest. The response modes and response parameters describe the detailed behavior and output parameters that may be important for a given software feature. Based on the intended use and types of calculations to be performed, the dedicating entity selects the response mode(s) (and corresponding test cases) that are expected to be important. Excerpts from Table 3 and Table 4 of the guidance document are provided below for illustration purposes.

Table 1: Excerpt from Table 3 of Doulgerakis et al. (2021) – important nonlinear response, required software functionality, software features

Req'd Functionality	**Examples**	**Software Feature**
Fluid response and fluid-structure (and/or component) interaction	• Component submerged within fluid • Component/structure containing fluid • Fluid within annulus space between structures/components • Fluid volume with free surface • Floating particles/pebbles within fluid	• Fluid element • Fluid-structure coupling algorithm
Response at the interface between components, structures	• Sliding of unanchored equipment • Uplift of unanchored equipment • Nonlinear supports (e.g., gapped, tension-only or bumper-type, compression-only supports) • Impact and pounding between adjacent structures • Rattling and uplift of components supported within sleeves, racks, or rails with no structural connection	• Contact algorithm
Response of the combined/integrated soil-structure system	• Soil-structure interaction effects (kinematic and inertial) • Displacement of foundation walls due to lateral earth pressure (especially for deeply embedded structures) • Sliding, gapping/separation between structure/foundation and geomaterial	• Geomaterial constitutive model • Structural materials/elements • Contact algorithm

Test Cases

Contained within Appendix A of the guidance document [Doulgerakis et al. (2021)] are 25 unique test cases. Each test case consists of an objective, problem description, reference solution, and acceptance criteria. The problem descriptions are intended to be sufficiently specific to define all key input parameters for performing an analysis compatible with the reference solution, while accommodating alternate modeling/implementation approaches across various software platforms. For example, the physical material properties typically required for a structural steel material model may be given (e.g., stress-strain relationship, reloading/unloading rules), but no specific constitutive model is identified.

Table 2: Excerpt from Table 4 of Doulgerakis et al. (2021) – software features, response modes, and test cases

Software Feature	Response Mode	Response Parameter	Test Case
Fluid element	Impulsive (acoustic)	Frequency and magnitude of pressure waves	1, 2, 8, 9, 10, 11
	Convective (sloshing)	Frequency and magnitude of fluid displacement	1, 8, 9, 10
Fluid-structure coupling algorithm	Normal	Force/stress resultant on flexible structure	1, 2, 8, 9, 10, 11
Geomaterial constitutive model	Cyclic pure shear (Simple shear)	Cyclic shear stress-strain	4, 17
	Wave propagation/SRA, equivalent linear	Free-field response spectra, strain/acc. profile with depth	15, 20, 21, 22
	Inertial/kinematic SSI response, equivalent linear	In-structure response	20, 21
	Wave propagation/SRA, nonlinear	Free-field response spectra, strain/acc. profile with depth	16, 22
	Inertial/kinematic SSI response, nonlinear	In-structure response	20*
	Lateral soil pressure	Disp. of earth-retaining element	TBD
	Triaxial compression/ extension	TBD	TBD
Contact algorithm	Normal	Nonlinear compressive and tensile response	23
	Tangential Friction	Static and dynamic contact force	7

The reference solutions are developed from a variety of sources: experimental data, simplified mathematical models, closed form solutions, and alternate software analysis results. Reference solutions based upon experimental data are powerful for demonstrating a software's ability to appropriately replicate physical response. However, some parameters of the experiment may be less controlled or not as well characterized, which can challenge translation of the experiment into a numerical model suitable for comparison with tight acceptance criteria. Additionally, in the absence of larger datasets from which to derive mean response, there may be considerable uncertainty and variability of response inherent to the experimental reference solution. Thus, experimental reference solutions typically provide a stronger demonstration of the validity of scientific basis than of accuracy.

In contrast, the other reference solution sources (alternate software analysis results in particular) offer relatively controlled problem definitions that can typically be well translated into numerical models within a given software. Mathematical models, closed form solutions, and alternate software results also offer the possibility to create multiple realizations of the same test case to align with and exercise a range of input parameters. Where possible within the test cases in Appendix A of the guidance document [Doulgerakis et al. (2021)], the basis for the expected results includes the equations or source references that allow a dedicating entity to reproduce the reference solution for the range of input parameters appropriate for their intended use.

ACKNOWLEDGEMENTS

This material is based upon work supported by the Department of Energy under Award Number DE-NE0008857. The authors would like to recognize Dr. Ching-Ching Yu, Mr. Faizan Ul Haq Mir, Mr. Sharath

Parsi, Dr. Asa Bassam, and Mr. Michael Perez for their contributions toward the test cases included in the guidance document. The authors would also like to recognize the additional SC Solutions engineers and the community of software developers, reactor developers, and structural engineers who contributed to and provided feedback on this body of work. Finally, the guidance document and accompanying tools are publicly accessible thanks to the support from the Department of Energy Office of the Chief of Nuclear Safety and Dr. Stephen McDuffie.

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