Workshop on

Nonlinear Analysis for Nuclear Installations

SMiRT-26

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Boris Jeremić	Stephen McDuffie
Civil and Environmental	Office of the Chief of Nuclear Safety
Engineering Department	Central Technical Authority staff
University of California	Office of Environmental Management
Davis CA 95616, USA	U.S. Department of Energy
	Richland WA 99352, USA

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Executive Summary

- The main outcome of the "Workshop on Nonlinear Analysis for Nuclear Installations" is a summary of participant opinions and workshop discussions, provided in Section 2, on page 7,
- Other sections of this report, as listed in Introduction, on page 5, provided details about the premises and background for workshop organization, verbatim participant opinions and participant slides.

Contents

Chapter 1

Introduction

Due to a significant increased interest in nonlinear analysis of soils, structures and their interaction (SSI), and significant increase in use of nonlinear analysis of SSI, for static and dynamic loads, a workshop was organized at the 26th Structural Mechanics in Reactor Technology (SMiRT-26) conference in Potsdam, Germany in July 2022. Workshop was well attended with a number or presentations and discussions by attendees, In addition to the in-person workshop at the SMiRT conference, an online discussions forum was organized before and after the conference so that participants can share their opinions. By request, online forum opinions were anonymized, and are provided toward the end of this report.

This report very briefly introduces nonlinear analysis of nuclear installations workshop premise and reports on workshop discussions and presentations. Report is organized in sections, as described below:

- A number of important points, that resulted from presentations and discussions among participants are summarized in section 2, on page 7.
- Invitation flyer, that was sent to a number of potential participants is presented in section 3, on page 10.
- Overview of empirical evidence of nonlinear behavior of rock, soil and structures is briefly presented in section 4.1, on page 14,
- Overview of nonlinear analysis approaches are briefly presented in section 4.2, on page 15,
- Overview of available programs for nonlinear analysis is presented in section 4.3, on page 15,

- Participant opinions, collected in an online discussion forum, before and after the workshop, and anonymized by request, are presented in section 5, on page 19.
- Nonlinear workshop participants slides are provided at the end, in section 6 (pages 48–).

Chapter 2

Summary of Main Points

Summary of main points and conclusions is provided below:

1. There exist overwhelming empirical evidence that behavior of soil, rock, structures and components is nonlinear, inelastic, elastic-plastic, elastic-damage-plastic, with permanent, plastic deformation at the end of loading for all loads of interest. Only for small loads, some structural components have a linear elastic response, however for most service loads and for all hazard loads, the response is inelastic, nonlinear, elastic-plastic,

2. Numerical modeling of nuclear installation soil-structure systems performance for static and dynamic loads should follow physics/mechanics as close as possible,

3. Assessment of performance of nuclear installation soil-structure systems, has to be performed using realistic modeling, where modeling/epistemic uncertainties are controlled and reduced as much as possible,

4. Nonlinear analysis programs that are used for design and assessment of nuclear installation performance for static and dynamic loads should have available all the modeling (mechanics) and simulation (computer science) features that are necessary for obtaining high quality results,

5. Quality assurance of nonlinear analysis is necessary in order to obtain high quality results, and it consists of two components, listed below,

   (a) Quality assurance of nonlinear analysis requires detailed verification and validation of analysis program used,

(b) Quality assurance of nonlinear analysis requires substantial engineering expertise in nonlinear analysis for engineers, analysts performing analysis,

6. Most commercial analysis programs do not provide publicly available quality assurance. Commercial analysis programs provide a number of benchmark examples, however, as noted by Oberkampf and Trucano (2008), the main goal of those examples is to demonstrate the "engineering accuracy" of the program, and not to quantify the numerical error in the solution. Quantification of numerical error in the solution is the primary goal of verification,

   Two commercial programs that are used for analysis of nuclear installations have developed detailed verification and validation suite:

   - Linear analysis, the SASSI program (Lymser, 1988; Lysmer et al., 1988; Ostadan, 2007a,b; Costantino et al., 2016), and
   - Nonlinear analysis, the Real-ESSI Simulator (Jeremić et al., 1988-2023, 1989-2023).

7. One of the main detriments in performing realistic, nonlinear/inelastic assessment of static and dynamic behavior of nuclear installations is the lack of expertise within nuclear regulatory agencies and engineering consulting companies. There are positive example of national nuclear regulatory agencies and engineering consulting companies that are actively pursuing realistic assessment of nonlinear behavior of nuclear installation, for example engineering companies and agencies from South Korea, Switzerland, France, Slovenia, Russia, and others. Their presentation slides are provided at the end of this report,

8. Use of linear elastic behavior assumption does not, in general, lead to safe design of structures. This is due to the fact that stiffer linear elastic components attract more forces. This means that yielding limits of those stiffer components would have to be proportionally higher so that additional forces they attract do not results in components yielding before other, softer components. In addition, once yielding occurs, there will be a redistribution of forces within a soil-structure system, and that redistribution will affect different structural components in a different way, and potentially lead to collapse. Currently used linear elastic analysis cannot predict such behavior,

9. Use of linear elastic behavior assumption leads to an over-design of many structural components, resulting in increase in use of concrete and steel, and thus increasing carbon footprint

of the soil-structure system. Production of one metric ton of concrete produces 280kg of carbon and production of one metric ton of steel produces one metric ton of carbon. However, over-design does not necessarily lead to safer design, as noted above,

10. General comment/observation after the workshop by participants, about status of nonlinear SSI analysis within USA agencies: US-DOE and US-NRC currently do NOT use nonlinear analysis programs for modeling static and dynamic SSI behavior for nuclear installations,

11. It was also noted that other countries do follow, look up to work of UC-NRC and US-DOE, and yet there is no work in the area of nonlinear analysis of static and dynamic SSI, and this was deemed very unfortunate,

12. In addition, it was noted that other countries have shown great interest in, do recognize benefits of and do work on high fidelity nonlinear analysis of nuclear installations, for example engineering companies and agencies from South Korea, Switzerland, France, Slovenia, Russia, and others. Some of that work is presented in slides at the end of this report,

13. Workshop participant opinions and participant presentation slides are attached at the end of this report.

Chapter 3

Invitation Flyer

Workshop on
Nonlinear Analysis for Nuclear Installations

A workshop is organized to continue and extend discussion on static and dynamic nonlinear analysis of soils and structures and their interaction for nuclear installations. Workshop organizers are Dr. Stephen McDuffie (US-DOE) and Dr. Boris Jeremić (UCDavis). Workshop will be organized in three parts.

1. Identify important points and issues, communicate to organizers for posting online, Dec2021 - Feb2022:
   - Analysis user community, designers, consultants, owners, regulators, energy agencies: participants are asked to prepare a list of important issues related to nonlinear static and dynamic analysis in their line of work, suggested strategies for implementation and use of nonlinear analysis. Possible discussion topics:
     - Benefits of and problems with nonlinear static and dynamic analysis for soils, structures and SSI
     - Practicality of analysis approaches, availability of different levels of sophistication
     - Universality, that is, many features versus specialty numerical tools
     - Availability and importance of documentation, training, education and example models

- Importance of quality assurance procedures
- Importance of analysis program management procedures
- Analysis program availability: commercial, public domain, open-source, etc.
- Any other related topic that you consider important

- Analysis program developer community: participants are asked to develop a list of available analysis program modeling and simulation features for static and dynamic nonlinear analysis of soils and structures and their interaction for nuclear installations. Possible discussion topics:
  - Availability: commercial, open-source, public domain
  - Pre- and Post- processing tools and approaches
  - Modeling features: material models, elements, loads, staging, ...
  - Simulation features: sequential/parallel-HPC, explicit/implicit-equilibrium, operating system, ...
  - Quality assurance, verification/validation, development and maintenance procedures
  - Documentation and examples
  - Training and education
  - Acceptance of user feedback, suggestions and requests
  - Any other related topic that you consider important

2. An online, written discussion forum will be organized on issues/points from the above topics, Jan2022 - Jul2022.

3. In-person forum to further discussion about nonlinear analysis and a final report development, at the 26th SMiRT in Berlin/Potsdam, in July 2022. Depending on global traveling regulations in July 2022, remote participation will also be organized. The final report will document the discussions, the issues raised and the possible paths to resolving them.

Invited Workshop Participants. Invitation emails were sent to a number of colleagues that have expressed interest in nonlinear analysis over years.

— Consultants

Alain Pecker, France

James Johnson, USA

Pierre Alain Nazé, France

Greg Mertz, USA

Pierre Labbé, France

Peter Rangelow, Switzerland

Nilesh Chokshi. USA

Annie Kammerer, USA

Alexander Tyapin, Russia

Victor Kostarev, Russia

Farhang Ostadan, USA

Carl Constantino, USA

Natalie Doulgerakis, USA

Andrew Whittaker, USA

Francisco Beltran, Spain

Ben Kosbab. USA

Payman Khalili Tehrani, USA

Greg Hardy, USA

Mohamed Talaat, USA

— Utilities/Owners

Mathhieu Caudron, EDF, France

Philippe Renault, SwissNuclear, CH

Donald P. Moore, Vogtle Electric Generating Plant, Waynesboro GA

John Richards, EPRI, USA

Emmanuel Viallet, EDF. FR

— Regulators

José Pires, (NRC) USA

Tadeusz. Szczesiak, ENSI, CH

George Stoyanov, CNSC/CCSN, CAN

Djordje Vojnovic, SNSA, SLO

Raoul Awad, UAE

Dr. Bishnoi, IND

Dr. Richard Fowler, UK

— National and International Agencies

Catherine Berge-Thierry, CEA, France

Ayhan Altinyollar, UN-IAEA

Shunicchi Suzuki, METI, Japan

— Vendors

Luben Todorovski, GE, USA

Haydar Karaoglu, NuScale Power, USA

Yuri Volkov, RossEnergoAtom, Russia

Michael Cohen, TerraPower, USA

Haydar Karaoglu, NuScale Power, USA

— Analysis Program Developers

e-FrontISTR, Muneo Hori, Japan

OpenSees, Francis McKenna, USA

Mastodon, Chandu Bolisseti, USA

ACS SASSI, Dan Ghiocel, USA

Modulate, Kristel Meza, France

code_aster, Philippe Martinuzzi, France

SW4-ESSI(?), David McCallen, USA

Real-ESSI Simulator, Boris Jeremić, USA

Chapter 4

Nonlinear Analysis, Background

4.1 Nonlinear Behavior, Empirical Evidence

There exists significant empirical evidence, observations from experiments and from behavior of real objects during monotonic and cyclic loading, that material response for soil, rock, steel, and concrete is inelastic (Drucker and Prager, 1952), (Muir Wood, 1990), (Wood, 2004), (Crisfield, 1991), (Crisfield, 1997), (Scott, 1988), (Lade, 1989), (Stavrogin et al., 2001), (Fairhurst, 2003), (Mogi, 2006), (Desai and Siriwardane, 1984), (Desai, 1981). (Lemaitre and Chaboche, 1990). Moreover, there exists a theoretical proof that all material made from particles can only experience (non-) linear elastic behavior for pure compression, while as soon as there is shear present, particulate materials do undergo inelastic, elastic-plastic deformation (Mindlin and Deresiewicz, 1953).

Recent Evidence of Inelastic Response of NPPs. The official report of The Fukushima Nuclear Accident Independent Investigation Commission, developed for the The National Diet of Japan (Kurokawa et al., 2012) presents evidence of significant nonlinear, inelastic response of the Fukushima NPP, including structures, systems and components, well before the actual tsunami inundated the NPP during Tohoku earthquake in 2011. There is also recent evidence (Morita et al., 2021) that nonlinear response of nuclear installations soil-structure systems also had some beneficial effects during the same earthquake.

4.2 Nonlinear Behavior, Modeling Approaches

The main modeling and simulation approach for analysis of nonlinear behavior of soils, structures and their interaction is based on incremental elastic-plastic finite element method (Zienkiewicz and Taylor, 1991a,b; Bathe, 1996; Crisfield, 1991, 1997). It noted that analysis approaches based on elastic (linear elastic, equivalent linear, nonlinear elastic, etc.) are also used. It is very important to note that approaches that are based on elastic assumption can sometimes fit the curve, that is they can match some part of the nonlinear, inelastic response, however they cannot be used to predict and inform, as they essentially rely on wrong physics (elasticity) to model inherently inelastic behavior of soil and structural materials. Therefor nonlinear analysis of static and dynamic nuclear installation soil-structure system behavior has to be based on proper mechanics, and that is incremental elasto-plasticity.

4.3 Nonlinear Analysis Programs

4.3.1 Quality Assurance of Analysis Programs

Verification and Validation (V&V) of analysis programs is very important. The V&V efforts are described in some details by a number of authors, with major contributions by the US-DOE (Oberkampf et al., 2002b; Roy and Oberkampf, 2011; Oberkampf and Roy, 2010; Oberkampf and Trucano, 2008; Oberkampf et al., 2002a, 2007; Oberkampf and Pilch, 2017)

4.3.2 Program Licensing Options

Programs for performing linear and nonlinear analysis of soils, structures and their interaction are available, distributed using different types of licenses, as described below:

a) Commercial software license is purchased from a commercial company, and has features and capabilities usually determined by the commercial license. Commercial programs usually only guarantee accurate working for examples provided in the manual. Commercial programs also usually do not provide verification and validation suite, as noted by Oberkampf and Trucano (2008).

b) Open-source software license is a license that guarantees that the software source code and derivative source code will always be available as open-source. The open-source programs usually do not guarantee quality to external users/developers due to legal reasons (liability). Locally, within the development team, quality control procedures might exist, however that is not guaranteed, and usually not the case, particularly for research open-source programs.

c) Restricted-source software license is a restricted version of an open source software. The difference is that developers/owners can restrict source code distribution, so a revised open source license is used.

d) Open-use software license makes program executables freely available, however source code is usually closed or restricted.

e) Public-domain software license, is a license where the source code and/or executables are distributed with no restrictions whatsoever. The original developer/owner relinquishes all or his/her rights with respect to sources and/or executables. Usually such software does not and cannot provide quality assurance as anybody is free to take the source code, make changes, additions, publish results using new program while still using the original program name.

4.3.3 Available Programs

There exist a number of programs for performing linear and nonlinear analysis of soils, structures and their interaction for nuclear installations, as described by Pecker et al. (2022). Listed below are all/most available programs for analysis of soils, structures and soil-structure interaction:

- ABAQUS, (`http://www.3ds.com`)
- ADINA, (`http://www.adina.com`)
- ALGOR/AutoDesk simulation, (`http://www.autodesk.com`)
- ANSYS, (`http://www.ansys.com`)
- CLASSI, (`https://www.lstc.com`)
- GT STRUDL, (`https://hexagonppm.com`)
- LS-DYNA, (`http://www.lstc.com`)

- NASTRAN, (http://www.mscsoftware.com)
- FLUSH, (https://www.geoengineer.org)
- SAP2000, (https://www.csiamerica.com)
- SASSI 2010, (http://sassi2000.net)
- ACS SASSI, (http://www.ghiocel-tech.com)
- SMACS, (https://www.osti.gov)
- GT STRUDL, (https://ce.gatech.edu)
- SOFISTIK, (http://www.sofistik.com)
- PLAXIS, (http://www.plaxis.nl)
- FLAC, (http://www.itascacg.com)
- DYNAFLOW, (https://blogs.princeton.edu)
- Zsoil, (http://www.zsoil.com)
- FEAP, (http://www.ce.berkeley.edu)
- DEEPSOIL, (http://deepsoil.cee.illinois.edu)
- SIMQKE, (http://nisee.berkeley.edu)
- OpenSees, (http://opensees.berkeley.edu)
- Real ESSI, (http://real-essi.us)
- Code_ASTER, (http://www.code_astair.org)
- SHAKE91, (http://nisee.berkeley.edu)
- EERA and NEERA, (http://www.ce.memphis.edu)
- DESRA-2
- SUMDES

- D-MOD
- TESS

Chapter 5

Participant Comments, Views, Opinions

Invited participants provided comments and views about nonlinear analysis as used for static and dynamic analysis of nuclear installations. Since some participants asked for anonymity, it was decided that all opinions will be anonymized, that is all opinions are provided below, however author details are removed.

5.1 Participant No 1

Implicit non-linear dynamic analyses Multi-physics and CFD coupling. For more specific cases like assessing seismic dissipation devices, the use of non-linear dynamic analyses is inevitable. At such examples often more complex contact problems are involved and integrated in models.

There is increasing development of small and medium sized nuclear installations with enhanced modularity (or small modular reactors-SMRs). Some variants of such installations utilize pool submerged reactors. In case of investigating possible seismic isolation of such installations we might be in need to implement analyses not only accounting elastic, plastic deformation but also hydrodynamic phenomenon (CFD, Navier Stokes eq.). In case of (implicit) non- linear dynamic analyses with contact problem beside solid to solid interaction there can be need to couple fluid to solid interaction (FSI) phenomenon to investigate dynamic behavior in time domain. Up to my knowledge beside Ansys there is another option like coupling Code Saturne to code Aster (Salome Meca, EDF) and I am not sure to which extent since literature on that is very scarce. There is also some development on that matter from NVIDIA company implementing various coupling approaches for FEM/Hydromechanics on their GPUs. Any further information regarding that matter would be very appreciated.

Demanding environment at conducting such analysis are leading to necessary simplifications and perhaps complex phenomenon interpretations, which shift resources from engaging with nature of researched problem to engagement with software/hardware equipment/tools behaviour.

Analysis program availability and suitability for very large models. I believe for many academic researchers access to public domain or open-source state of the art analysis programs is essential. According to my experience, conducting complex analyses often with very large models, requiring large computational power, when using commercial software, is nearly impossible, since combined costs for licenses and hardware in academic/educational domain are usually unacceptable, so is accessibility difficult.

Another topic may be efficient handling of plant-scale models in various simulation software and their capability of handling 1e6 DOF and above.

Importance of parallel computation. In today's world interconnections of various devices with constantly increasing computing power are abundant and very common. However parallel computations for large FEM applications are more less tied to larger institutions with excellent IT support capable of maintaining computing clusters, HPC?s and dedicated software. In my opinion, if there exists possibility to simplify parallelisation of computing and efficiency by simplified use of various network interconnected devices or simultaneous use of CPU+GPU, it could greatly reduce the computation efforts.

Analyses as a design tool in iterative design process. Design process may become tedious when FEM analyses are required and the design updates/corrections and analysis results are repeatedly exchanged, usually, between analysis and design departments. Fast Virtual prototyping has been known for several decades and evolved together with increasing CAD implementation for engineering purposes.

Using Machine learning (ML) to predict design features of devices when implementing non-linear dynamic analyses at devices investigations is becoming (may become) increasingly popular. ML integration may also enable further options for mathematical model migrations between different FEM codes (e.g. Code Aster to Real-ESSI). Any elaboration of research or knowledge on that topic could be very beneficial.

5.2 Participant No 2

1. Issues related to NL static and dynamic analysis I would suggest to add explicitly the Verification & Validation (V&V) procedure which are highly developed in aerospace engineering or fluid mechanics but unfortunately poorly developed in civil engineering. Specific indicators or tools should be developed in order to estimate when possible the applicability space of a given NL model or part of the model (constitutive law for instance); this material is of primary importance when assessing a safety demonstration based upon only numerical analysis, especially nonlinear ones.

2. Tools to be implemented in commercial softwares

    - As it is the case for basic structural elements in some commercial softwares (reference cross sections, reference assembly CAD model, type of beams, etc.), it could be very interesting to get reference CAD models for buildings which compose a nuclear island. Indeed, reading drawing and starting modeling from them is highly time consuming. Local specificities related to the most used nuclear reactors types may be included. In order to leave the possibility to affect the material properties each user want (coming from various considerations, expert assessment, etc,..), providing reference CAD models could be an idea.
    - It is generally needed to perform sensitivity analysis in order to assess the model robustness against variation of input data. Therefore, the fact of having a specific and dedicated environment in string connection with the software used may be helpful.

5.3 Participant No 3

Analysis program developer point of view.

- Availability:
  - commercial, open-source, public domain: importance of quality
  - control of the source code and the executable, hence
  - open-source and public domain source codes are not desirable, see T-experiments papers!
- Pre-processing tools and approaches:
  - Model development based on physics, close to professional engineering expertise
  - Model conversion between different programs
  - Model description, documentation, readable input language
  - Model control using domain specific language (DSL), that is a DSL for modeling of earthquakes, soil, structure and their interaction
- Post-processing tools and approaches
  - Visualization to gain understanding of model response
  - Visualization of full 3D response to gain understanding of ESSI system response
  - Visualization of a number/all of engineering quantities to gain understanding of ESSI response
  - Visualization of time histories of specific engineering quantities
- Modeling features: NEED ALL material models, elements, loads, loading stages, to realistically model elastic and inelastic behavior of soils and structures during static and dynamic loads, including realistic earthquake loads, hydrodynamic loads, etc.
- \- Simulation features:
  - Sequential HPC programs
  - Parallel HPC programs,

- Explicit, no equilibrium requirement
- Implicit, equilibrium satisfaction within tolerance
- Operating system: MS Windows, MacOS, Unix/Linux...

- Computers:
  - personal PCs,
  - workstations,
  - servers,
  - local-clusters,
  - supercomputers
- - Quality assurance:
  - Verification procedures,
  - Verification examples
  - Validation examples,
  - Development procedures,
  - Source code maintenance procedures
- - Documentation: Completeness, theory,
- - Examples, input files, need to cover:
  - many/all available models,
  - many/all available algorithms,
  - variety of simple, educational examples
  - variety of real world examples
- - Training and education:
  - In person
  - Live-online

  - Recorded-online
  - Certification of attendance and success
  - Just in time training

- - Acceptance and management of:
  - user feedback,
  - user suggestions and
  - user requests

Analysis program user point of view.

- Available education and training material, in person and online courses
- NL program availability, on local PCs, in the cloud, etc.,
- Modeling features that are close to engineers understanding of physics/mechanics, for example direct modeling of nonlinear behavior of soil, concrete and steel with direct definition of shear strength, compressive strength and tensile strength,

General Comment/Observation After Workshop.

In the USA, regulatory and energy agencies are not ready, do not have expertise, nor interest in quality assured programs for modeling nonlinear, inelastic nuclear installation/facilities SSI problems.

Moreover, nuclear installations/facilities analysis standards (ASCE-4,...) are showing very little interest in developing standards for nonlinear analysis. Such lack of work on standardizing nonlinear analysis seems to be mostly influenced by professional practice. Professional practice is reluctant to learn new analysis methods and loose comfortable position where 40+ years old methods and programs (SASSI,...) are used. Those old methods and programs rely on linear elastic material behavior assumption. It is known that modeling proper physics/mechanics of nuclear installations/facilities has to be done using nonlinear models, since realistic behavior of materials: soil, concrete, steel, rock, is nonlinear. Unfortunately, there is a significant reluctance, almost fear, to move forward with nonlinear analysis...

5.4 Participant No 4

- Research challenges:
  - Large-scale V&V: There is currently no experimental data at medium to large scales or at field scale for validating NLSSI models for larger soil strains and stronger EQs where nonlinearity becomes more important.
  - Modeling foundation-soil interfaces: This is a challenging numerical problem, especially given the lack of experimental data. It is more challenging when impact between the soil and the foundation is involved at high intensity shaking.
  - Uncertainty quantification: the complexity of NLSSI analyses in terms of simulation time as well as number of input parameters makes uncertainty quantification incredibly challenging. We need better software-agnostic guidance in performing UQ with NLSSI analysis. Some important points here are determining the distributions of soil parameters and foundation-soil interface parameters. Other UQ techniques (such as using stochastic FEM that Boris is already developing) are also very valuable.
  - Damping formulations: NLSSI analyses with traditional damping formulations (such as Rayleigh damping) can result in high-frequency response that can be problematic in nuclear systems. With the absence of experimental data, it is difficult to really understand if this response is real, and this response will be sensitive to damping formulations.
  - PSHA: Current practice in seismic hazard characterization is limited to vertically propagating shear waves and the complexity of the wave field itself is not well accounted for. NLSSI analysis will be impacted significantly by the nature of the 3D (or 6D including rotational GMs) wave-field and we need more advancements in PSHA to characterize the wave-field better.
- Challenges in implementation in practice:
  - Verification and validation (V&V): We need more software-agnostic guidance on the V&V and more specifically, commercial grade dedication of NLSSI software. There is a recent DOE-funded project led by SC solutions that addresses this topic, but I am

not sure if their report is public yet. And there are Real-ESSI manuals that provide a lot of V&V test cases.

- Determining GM input for NLSSI and compatibility with PSHA: Current PSHA methods typically provide ground motion at the surface that needs to be de-convolved to determine the ground motion input for NLSSI analysis. There is currently a lack of consensus on the best practices for performing deconvolution, especially for ground motions that elicit nonlinearity. Common practice is performing frequency-domain deconvolution, but this may not be appropriate for stronger ground motions.
- Training: We need more software-specific training to help practitioners understand the fundamental concepts of NLSSI and perform NLSSI in the software of their choice (which, currently is very few commercial software).
- Cost-benefits of NLSSI: This is, in my opinion, arguably the biggest impediment in implementing NLSSI. It is currently not always clear when the cost increases in performing NLSSI analysis can be justified by the cost benefits to the overall project. The answer varies from one project to another, but some insights from experienced practitioners on in what cases NLSSI can reduce costs and improve safety, would be valuable.

- Comments on software:

  Here are some important modeling features, in my opinion. I am indicating, in parentheses, the software I have used in the past that have the corresponding features.

  - Nonlinear soil and structure modeling
  - Absorbing boundaries
  - Ability to input complex 3D wave fields, i.e., domain reduction method
  - Ability to model contact between structure and the soil during conditions of sliding, gaping and uplift

5.5 Participant No 5

- Nonlinear Dynamic Soil-Structure Interaction
  - Determination of foundation uplift ratios under earthquake action (effect of embedement, presence of ground-water and buoyancy, consideration of P-delta effect, consideration of nonlinear soil behavior)
  - Nonlinear transient analyses of global stability (sliding, uplifting, effect of buoyancy, embedement)
  - Use of nonlinear macro-elements for foundation and/or structural elements
  - Foundation impedance calculations and hybrid methods for nonlinear SSI calculations in time domain (Fourier domain-Time domain / Laplace domain-Time domain)
  - Direct SSI calculations: techniques for definition of boundary conditions
  - Consideration of kinematic interaction for embedded structures: rotational component and nonlinear effects at the lateral interfaces
  - Generation of surface waves on sedimentary basins and incidence on large infrastructure
  - Modeling of soil liquefaction and effect of liquefaction for site-response analyses
- Nonlinear Constitutive modeling
  - Nonlinear constitutive modeling of reinforced concrete structures
  - Modeling of creep and cracking in concrete structures
  - Validation of global models for planar concrete structures (under impact or under in-plane actions)
- Non-seismic actions
  - Modeling of prestressing and coupling with nonlinear concrete response
  - Modeling of thermal actions at concrete-liner interfaces
  - Modeling of impact and explosions: Rapid Dynamics calculations for accidental impact and explosions (explicit nonlinear dynamics) are increasingly used in a nuclear context (e.g. internal explosions within underground structures for storage of radioactive nuclear waste)

  - Use of Limit Analysis methods for soil and concrete structures (e.g. strut-and-tie models for calculations of reinforcement in regions with geometric or load singularities

- Normative issues

  - Preparation of normative texts (RCC-CW) and definition of prescriptions that can be anticipated for implementing nonlinear analyses in a nuclear context

- Software

  - Finite Element Analysis practice in Nuclear Engineering as conditioned by issues of Quality Assurance and validation of software tools is promoted by the main actor/company,
  - The importance of documentation and example models is paramount
  - Since analyses procedures (even for nonlinear analyses) are becoming more and more standardized, an increasing emphasis is also given on pre- and post-processing tools (model validation, mesh quality, validation of mesh with respect to real structure etc., post-processing procedures for concrete, steel, soil)

5.6 Participant No 6

- Benefits for Research: Better understanding of local nonlinearities effects. Research studies should be encouraged since they are eye's opener for the industry practitioners.
- Benefits for Design: A sophisticated nonlinear time-domain SSI analysis should be useful for some particular modeling aspects. Unfortunately, nonlinear SSI analysis needs much more input parameters for calibrating the nonlinear models that will explode the field and lab test costs, well-above the costs of linear or equivalent-linear SSI analysis. Nonlinear models are often both numerically sensitive and computationally intensive, also often including highly uncertain nonlinear model parameters which may introduce a significant overall uncertainty in the final seismic analysis results.
- The significant increasing in complexity for nonlinear SSI analysis will add significant costs and risks to the design process and its review.
- I believe that a careful, experience-based good engineering using well-calibrated models and conservative approaches is key for maintaining the US nuclear industry business competitive. Simpler, iterative equivalent-linear SSI analyses to capture nonlinear structure behaviors, is the affordable practical solution that is also fully consistent with the current regulatory requirements.
- Benefits for Safety: Not obvious, due to added complexity in modeling and input preparation. Seismic ISRS and structural forces computed using nonlinear SSI analysis will be often much lower than those computed using linear SSI analysis. This could substantially reduce the design safety margins of NPP SSCs well below the existing safety margins of the current designs.
- As a simple example, nonlinear SSI analysis may indicate that the NPP building sliding under a severe earthquake reduces by few times the design ISRS peak amplitudes. Is such result a safer for a design? What happens if the numerically predicted building sliding under the severe earthquake does not occur in during a real earthquake since some theoretical assumptions do not hold?
- I believe that it should be understood by any responsible design engineer that an overly

sophisticated nonlinear seismic analysis is still a crude approximation of reality, not the reality, maybe still far from reality.

- Benefits to Risk Predictions in PRA Reviews: The probabilistic modeling based on the simplified current lognormal format used for computing fragility curves will become less applicable to highly nonlinear system behaviors. A more refined probabilistic modeling will be needed to ensure risks prediction accuracy for highly nonlinear systems.

- PRACTICALITY AT THIS TIME: Nonlinear seismic SSI analysis is less practical and affordable for industry projects since negatively impact on schedule and costs, since it is time consuming, needs more lab & field studies to define input parameters, numerically sensitive or less robust, and large uncertainties for input parameters and their statistical dependences, plus its results are difficult to check. This introduce additional complexity and risks for industry business that is risk adverse. Also, it requires much higher expertise reviewers who had an in-depth understanding of nonlinear SSI dynamics and uncertainty modeling and propagation assuming non-Gaussian variations due to various nonlinearities.

- TRAINING: Software training provides only very limited information that does not replace lack of engineering background and practical experience to avoid risks for industry projects using nonlinear analyses.

- EDUCATION: Many university courses show the trend toward a high sophistication of nonlinear modeling and analysis that goes well beyond the needs and practicality of the nuclear industry business.

- QA Activities: Most important QA aspect is to ensure the professional competence and individual responsibility, including sufficient engineering experience and adequate theoretical knowledge. Having experienced competent engineers leading the seismic projects shall be the highest priority to ensure real quality of the projects and NPP designs.

- In addition, the QA activity should initially focus on creating realistic project schedules and planned resources. Project schedule including QA activities is of key significance for industry business, since it should allow engineers to carefully reviews of the structure models, inputs and results, to avoid potential risks due to human omissions.

- Sometimes, there is a business tendency in practice to underestimates the overall effort and compress the project schedule so that the project proposal to management and financiers, and then, press the engineers to deliver under a highly compressed schedule. This could impact drastically on project quality and business.
- Using consulting experts for performing independent or per reviews is of essence for the project quality and to avoid pitfalls with major downstream unplanned costs.

5.7 Participant No 7

I would comment that validation and quality assurance of nonlinear tools aimed at regulatory acceptance is crucial. The principal barrier to the utilization of nonlinear analysis is a regulatory / standards environment that is not fully ready to provide guidance and employ nonlinear methods and this allows those that are dismissive of nonlinear advancements to be dismissive. There should be a careful development of validation requirements, that if rigorously met, would then allow the use of qualified nonlinear methods. The NRC is just not going to do this, the inertia against transformative change is too great in my view. DOE might be able to do this ...

5.8 Participant No 8

There are many points that need to be understood and digested by the community to use the nonlinear tools for design of nuclear structures. As you know for seismic design of the commercial nuclear power plants, the structures are required to remain effectively elastic. So the nonlinearity is focused on soil behavior and for cases where assessment of the response for beyond design events is needed. For Department of Energy nuclear facilities, consideration of nonlinearity is permitted for design level since DOE accepts the multiple levels of ASCE-43 seismic design category and limit state behavior.

For modeling soil behavior with nonlinear models, correlation with field performance data becomes very important. This is mainly due to inability of sampling actual foundation soil data in the field and performing tests suitable to develop the soil modeling parameters. Correlation with linear and equivalent linear analysis to the range applicable to each becomes method becomes important. Sensitivity of nonlinear results to the range of petameters at higher end of loading becomes very important. This by itself indicates the process must be step by step to show the benefits and challenges facing nonlinear modeling and analysis.

Simple and obvious cases need to be considered and the advantage of nonlinear modeling need to be demonstrated with the data that community cannot challenge the basis. The sensitivity of analysis results to the variation of input parameters need to be captured.

So in general and for the effort of applying nonlinear analysis for design purposes, a great deal of hand-holding, correlation with field performance data and, step by step development need to take place for the community to adopt it and for the regulatory agencies to rely on it.

I hope these remarks are not too negative but this reflects the trend as I have observed over the years.

5.9 Participant No 9

1. Lack of an efficient licensing pathway for the use of nonlinear seismic analysis

   This not a purely technical issue, but it is probably a major obstacle nowadays. We have now advanced tools and people trained to use them, but we avoid using them in new developments because the licensing path is uncertain and could take much more time. This is nonsense, because our designs could be better (more efficient and less expensive) if those tools were used.

   The US nuclear industry is aware of this difficulty and is pushing the US-NRC in this respect. I attended a public meeting with the NRC in November last year and my feeling is that the NRC is receptive but there is still a long way to go.

   During the meeting, NRC staff acknowledged that the use of non-linear seismic analyses is not precluded by the US Federal Law, but current NRC guidance and review plans are based on the use of linear or equivalent-linear analyses. This means that any attempt to licensing based on non-linear analyses needs to be reviewed on a case-by-case basis and this can take significant time and effort when compared with the use of "regular" (business-as-usual) analyses.

   Remember that the US-NRC is a model regulator for many regulatory authorities in the World, who will follow the steps of the NRC in this respect.

   During the public meeting, some NRC staff pointed out that seismic non-linear analysis is such a broad topic that it would need to be broken-up in a number of topics, in order to develop practical licensing guidance. Perhaps, during the SMiRT workshop, we could discuss about which non-linear applications would help us in making our designs more efficient and have a more general domain of application worldwide: Seismic isolation? Soil-structure interaction?

   The dialog between the US industry and the NRC will be kept open, and my understanding is that the US industry intends to produce a white paper on this issue, to be discussed with the NRC during a future workshop. The outcome of the SMiRT workshop could be a source of information for that white paper.

2. Non-linear analysis needs for the development of advanced reactors

There are now under development a number of small modular reactors (SMRs) which are not light water reactors. In those reactors, "new", inherently non-linear phenomena, have to be considered. Examples are molten salt or liquid metal reactors, with dense coolants (salt, lead), thinner reactor vessels (no internal pressure), and very high temperatures, which can reach 1000 C in accident conditions.

Do we have adequate, validated and understood tools, for instance, to assess the sloshing of molten lead within the reactor during severe shaking and the hydrodynamic pressures being generated?

High operating or accident temperatures mean closing of gaps and, potentially, severe cracking of structural concrete, even in normal operating conditions. How do we (efficiently) assess the safety of a severely cracked massive concrete structure?

How do we assess evolution of temperature fields in our structures? Heat transfer via radiation (no linear) could be very significant at high temperature.

These are some questions, but SMiRT participants involved in the design of advanced reactors may have many other questions and already experienced needs to assess non-linear behavior.

3. Role of non-linear analysis in safety assessment for beyond design basis external events

   In the post-Fukushima IAEA design requirements (IAEA SSR-2/1 Rev. 1) it is required that an "adequate" margin is introduced in the design for the design basis external events (earthquake, aircraft crash, flood, wind, etc.). In practice, this is achieved by the definition of a beyond design basis external event (sometimes called 'design extension event'), for which a safety assessment needs to be carried out.

   Beyond design basis events are substantially more severe than the design events. Assessing safety against them using linear analysis could result in uneconomical designs. A potential topic for discussion at the SMiRT workshop would be to review what we are actually doing in this respect for each type of external hazard (earthquake, aircraft crash, flood, wind, etc.), and see how our approaches could be improved (or not) by the use of non-linear analyses.

4. Safety assessment for existing nuclear installations

This topic relates to the previous one, but it is not exactly the same. Periodic safety reviews of existing installations may reveal that some design basis external events could have been underestimated. This is typical for the seismic, flood, or wind (hurricane) hazard. It has happened at many facilities.

In those cases, the licensee needs to show the safety of the installation for the new hazard assessments. Recourse is made to non-linear analysis techniques, in order to "squeeze" the margins provided by the original design to show safety for the new hazard conditions. The perceived needs in this respect may also be discussed at the SMiRT workshop.

5.10 Participant No 10

Need for more education!

5.11 Participant No 11

I am very interested in your topic regarding nonlinear SSI analysis.

This topic is one of the most important issues in Nuclear society.

But unfortunately, I did not perform any SSI related researches these days so I can not present my thought but I can participate in an audience.

5.12 Participant No 12

- What are modeling best practices and common pitfalls for probabilistic site response and explicit SSI response analysis?
- What are consistent and/or acceptably efficient approximate methodologies for distinguishing epistemic and aleatory variabilities in the response analysis output?
- How to distinguish spatial variability from epistemic uncertainty in measured soil profile properties, and how to model it in 3D soil models vs. in effectively 1D soil column models?
- How to constrain nonlinear response localization of 1D soil columns near impedance discontinuities?
- What input to use for soil constitutive modeling at large strains and how to "measure" its parameters in the lab?
- How to realistically model liftoff-impact of foundations with underlying media and resulting "shock" waves propagation within structure?
- What are best practices for modeling complex-geometried soil strata starting from site characterization?
- How to efficiently and consistently model inclined seismic waves and the response to them, especially for buried structures?
- How to avoid "measuring with a yardstick and cutting with a laser beam", i.e., the illusion and folly of using increasingly fancy and complex numerical models with opaque parameters and more-rule-of-thumb-than-measured input quantities?

5.13 Participant No 13

I would of course be very interested in participating in this technical exchange.

We are to review . . .

The calculations are with detailed overall models (structure, soil around foundation, NSSS incl. reactor core internals) and nonlinear effects are supposed to be considered. We will see what these effects are. In any case, for me a very important fragility failure mode is structural pounding, i.e. we will see which soil strains are to be expected around the foundation and whether nonlinear effects like (partial) foundation uplift are not to be expected there further.

5.14 Participant No 14

Principal use of non-linear analyses:

Static Material behaviour: damage, creep, plasticity (e.g. nuclear graphite, concrete, welding)

Static: Large deformation/displacement/rotations.

Static and Dynamic: Contact

Dynamic: Seismic response of nuclear reactor core

Identify important points and issues, communicate to organizers for posting online Analysis user community, designers, consultants, owners, regulators, energy agencies: participants are asked to prepare a list of important issues related to nonlinear static and dynamic analysis in their line of work, suggested strategies for implementation and use of nonlinear analysis.

- - Benefits of and problems with nonlinear static and dynamic analysis for soils, structures and SSI: Limited experience in SSI at the R&D center, recommend contact our colleagues in our other centers
- Practicality of analysis approaches, availability of different levels of sophistication:

  It is important to be able to perform studies at the appropriate level of sophistication for the desired problem. The simpler the model can be (e.g. linear elastic, 1D models or hand calculations), the better. It is often the case that more complex models are required to gain margins and reduce conservatism, but the trade off is high computational costs and advanced skills required.
- Universality, that is, many features versus specialty numerical tools:

  For wider use in the industry, standardization is key, therefore universality of the methods is a preferred option. Effort should be made to ensure that specialty numerical tools can be used in a user friendly way (e.g. using a simple GUI and customized tools to quickly set up studies, avoid error setting up the models and facilitating the skills transfer). Ultimately, integration in widely used commercial and open source software is the best way forward for maintenance perspectives.

- Availability and importance of documentation, training, education and example models:

  Highly desirable to enable repeatability of the studies and grow the community of users. This is to some extend a requirement for good quality assurance process (see section below)

- Importance of quality assurance procedures:

  Critical aspect often neglected in the R&D space (Universities). Quality assurance, via thorough validation and verification, test cases and version management are of primary importance for the acceptability of the method, its standardizing, use in the industry and its long-term development. EDF has a very stringent QA procedure, likely top-of-the-class in the open-source community, partly due to the tools being used for nuclear safety studies.

- Importance of analysis program management procedures:

  Not sure what is meant by this.

- Analysis program availability: commercial, public domain, open-source, etc.:

  . . . There is however a strong benefit of benchmarking with other commercial and open-source software to assess and push both the performance and the quality of the results.

- Any other related topic that you consider important:

  None

Analysis program developer community: participants are asked to develop a list of available analysis program modeling and simulation features for static and dynamic nonlinear analysis of soils and structures and their interaction for nuclear installations.

- Availability: commercial, open-source, public domain:

  . . .

- Pre- and Post- processing tools and approaches

  . . .

- Modeling features: material models, elements, loads, staging, ...

  . . .

- Simulation features: sequential/parallel-HPC, explicit/implicit-equilibrium, operating system, ...

  . . .

- Quality assurance, verification/validation, development and maintenance procedures

  . . .

- Documentation and examples:

  . . .

- Training and education:

  . . .

- Acceptance of user feedback, suggestions and requests:

  User feedback is welcome. From an open-source perspective, reporting bugs is useful but the most beneficial is actually the integration of new features developed by others!

- Any other related topic that you consider important:

  None.

5.15 Participant No 15

Unfortunately, we have not been able to set a document ready to share. Following our discussions at the end of January, we had created an internal task force (with several of our experienced engineers and experts) and conducted two working meetings, but so far we have only been able to identify the topics we would like to address. Our teams are very busy at the moment and my absence these weeks has not helped to progress on this issue.

The first three points listed in the workshop flyer are those that interest us the most, that is:

- Benefits of and problems with nonlinear static and dynamic analysis for soils, structures and SSI
- Practicality of analysis approaches, availability of different levels of sophistication
- Universality, that is, many features versus specialty numerical tools

In relation with these three points our idea was to prepare a 3 to 4 pages document detailing our point of view and experience on several topics related to nonlinear analyses, static and dynamic (not only open questions). In the following, you will find the different points we identified and wanted to explain more in detail:

- Static non-linear soil-structure interaction analyses

  In most cases, it is not necessary to use full 3D nonlinear calculations. The study of general rafts under static loading (a case often encountered in the nuclear field) can be limited to the use of linearized models and the appropriate choice of the soil modulus.

  Similarly, it is generally not necessary to take into account the phasing in the calculation except in the presence of deferred phenomena.

  From the "engineer's point of view", the calculation of foundations under static loading can be addressed according to three levels (depending on the complexity, characteristics and importance of the structure being studied):

  Level 1: calculation on fixed base (i.e., of no interest in the case of general rafts);

  Level 2: linearization of the problem and use of equivalent linear elastic models with the appropriate choice of the soil modulus (i.e., monotonic loads);

Level 3: use of nonlinear constitutive laws in soil and full non-linear 3D FEM models (or equivalent).

- Dynamic non-linear soil-structure interaction analyses

  Our point of view with respect to this topic is that it is necessary, from the "engineer's point of view", to use intermediate calculation tools/approaches in addition to full direct analyses involving high complexity numerical models. This strategy allows, in our opinion and based on our feedback, to control in a more direct way certain phenomena controlling the response of the system (i.e., nonlinear interaction at the soil-foundation interface).

  – Macro-element approach

    The main interest of this approach is that it allows to control directly the overall behavior of the foundation (i.e., evolution of overall stiffness, nonlinear mechanisms at the soil-foundation interface and bearing capacity by means of pre-established closed-form solutions). Also, it guarantees the continuity with classical substructuring approaches familiar to engineers in design offices.

    How the radiative damping is handled in the presence of strong nonlinearities is still an open question today. An "engineer's" solution may be to temporarily cancel the radiative damping term during the time intervals corresponding to strong nonlinearities taking place in the system. This is expected to be a conservative approach.

  – Global (direct) approach

    The main drawback is that damping cannot be controlled when a full nonlinear model is used (radiative damping and also hysteretic damping generated by constitutive laws).

    There is no longer continuity between the substructuring approach and the global one. This implies a change of paradigm in the design and verification of foundations and structures and the need to reorganize the way a given study is conducted, the interactions between different engineering teams, etc.

—

Since we have not attended this conference in the past, we have several questions regarding the organization of the conference and the workshop. We understand that in order to participate in the workshop it would be necessary to register to the full conference? Also, what possibilities would there be to present an article related to this topic during the conference? I understand that the official submission deadlines are long overdue but is there still a possibility to submit a paper for a special session?

Chapter 6

Participant Slides

Many participants made presentations about their work and their views on nonlinear analysis of for nuclear installations. Some of them were kind enough to share their slides. Those slides are provided on the following pages.

6.1 Steve McDauffie,

U.S. Department of Energy,

Office of Environmental Management

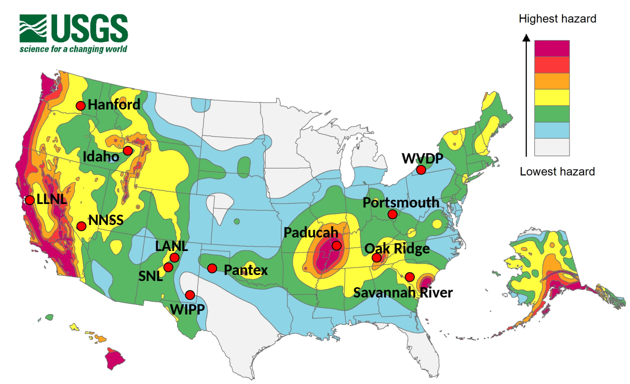
USA

The U.S. Department of Energy supports advancement in Nonlinear SSI.

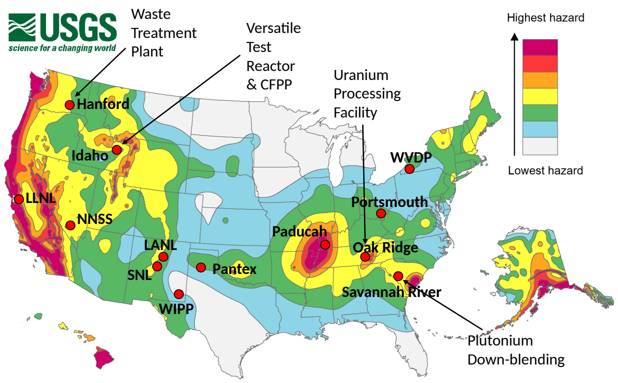
Why??

Steve McDuffie, U.S. Department of Energy, Office of Environmental Management

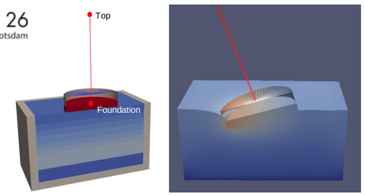
USGS 2018 National Seismic Hazard Map, peak ground acceleration with 2% probability of exceedance in 50 years (approximately 2500 year return period)



Future facilities, under construction and planned



6.2 Peter Rangelow, Basler & Hofmann AG Consulting Engineers, and Tadeusz Szczesiak, Swiss Federal Nuclear Safety Inspectorate, ENSI, Switzerland



Nonlinear SSI Analysis from a Regulatory Perspective

Workshop: Nonlinear SSI Analysis (Th.4.J)

Peter Rangelow[1],Tadeusz Szczesiak[2]

[1] Basler & Hofmann AG Consulting Engineers, Switzerland

[2] Swiss Federal Nuclear Safety Inspectorate ENSI, Switzerland

SMiRT 26 - Berlin/Potsdam, Germany | 10 - 15 July 2022 | NL-SSI Workshop | P. Rangelow & T. Szczesiak

Basler & Hofmann

Contents of the Presentation:

Nonlinear SSI Analysis from a Regulatory Perspective

- Background, Motivation and Objective
- Typical Sources of Nonlinear Behavior in the SSI
- When and How to Perform Nonlinear SSI Analysis
- Practical Questions Related to Nonlinear SSI
- Performed Nonlinear-Interface SSI with Real-ESSI
- RCC-CW – 2018 : DA 6500 “Validation of Linear Modelling of Uplift Effect”
- Nonlinear SSI Analysis
- Summary and Conclusions
- Next Steps

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Basler & Hofmann

Background, Motivation and Objective

- **Background**
  - In Switzerland regulatory activities are restricted to the four existing plants.
  - After the post-Fukushima external hazard reviews, new buildings (housing emergency systems) were designed and built at some sites, however, most of the ENSI regulatory activities focus on reevaluation of existing SSCs.
  - After a PSR update the seismic hazard of Swiss NPP sites significantly increased: “ENSI 2015” → operators are obliged to update seismic safety assessments
  - Because of the significantly increased “ENSI-2015” seismic hazard, the stress utilization of SSCs at SSE level is expected to be closer to the limit of elastic behavior.
  - In consideration of DEC 4a events (without core damage) we expect to deal with inelastic response in the whole soil-structure system.

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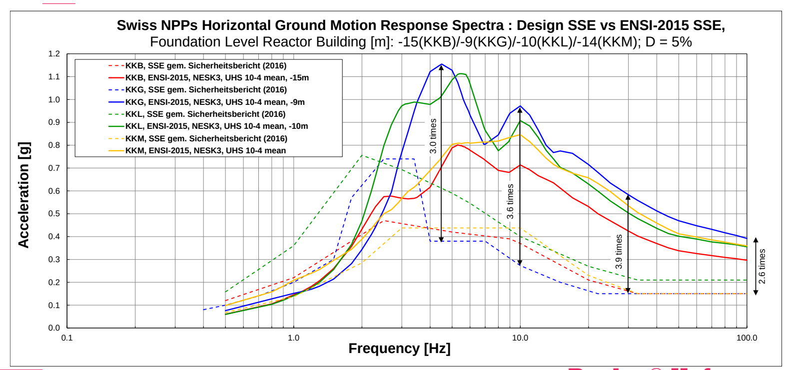
Background, Motivation and Objective



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Basler & Hofmann

Background, Motivation and Objective

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Federal Nuclear Safety Inspectorate ENSI

Nonlinear SSI Analysis from the Swiss Regulatory Perspective:

- **Motivation and Objective**
  - The Swiss Federal Nuclear Safety Inspectorate (ENSI) needs quality-assured, reliable and independent state-of-the-art analysis tools to deal with nonlinear SSI problems
  - Typically specific issues arise in the daily regulatory practice that need to be addressed adequately and resolved with limited resources in short time.
  - Hence, the need for user friendly and quality assured, robust analysis tools.
  - Evaluated analysis tool : Real-ESSI
    → assess its suitability for performing nonlinear SSI analyses
    in accordance with the ENSI requirements.

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Typical Sources of Nonlinear Behavior in the SSI

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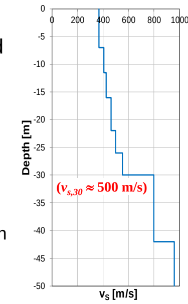
Swiss Federal Nuclear Safety Inspectorate ENSI

Nonlinear SSI Analysis from the Swiss Regulatory Perspective:

- Safety-related nuclear structures are generally stiff, massive and embedded structures for which SSI effects are important.
- Typical sources of nonlinear behavior in the SSI system are:
  - <u>primary nonlinearity</u>: nonlinear material behavior induced in the soil by the wave propagation in the soil medium under the free-field condition (typically determined from an iterative equivalent-linear analysis).
  - <u>secondary nonlinearity</u>: nonlinear material behavior induced in the soil by the structural response in the region immediately adjacent to the foundation (typically considered only for calculation of seismic soil pressure).
  - <u>interface nonlinearity</u>, i.e. loss of contact (uplift) and/or sliding between soil and structural foundation (→ RCC-CW, NRC SRP).
  - <u>nonlinear material behavior</u> in structural members of building (incl. basemat).



Typical V_s Profile

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When and How to Perform Nonlinear SSI Analysis

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Swiss Federal Nuclear Safety Inspectorate ENSI

Nonlinear SSI Analysis from the Swiss Regulatory Perspective:

- Nonlinear SSI analysis is not recommended as the primary analysis method for new design (SSE) but for the analysis of design extension events (DEC) or fragility analysis for different failure modes: e.g. loss of soil bearing capacity, extensive differential settlement (control rods), extensive cracking of the basemat (leaktighness), pounding…
- However, exceptions may apply for specific cases including geotechnical ULS (large contact stress under the foundation or along embedded walls), sliding and basemat uplift analysis in case linear methods are not validated (→ e.g. RCC-CW).
- Nonlinear SSI may be used to evaluate internal forces and deformations for design check of structural members, in-structure response spectra (ISRS) or foundation input motions for analysis performed with substructure methods.
- In nonlinear SSI analyses not all elements need to be modelled with a nonlinear constitutive law (i.e. prioritize and soil and/or structure, soil-structure interface)
- Normative guidance on nonlinear SSI: ASCE 4-16/Appendix B; IAEA TECDOC-1990; RCC-CW 2022/DA 3340 (to be published)

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Practical Questions Related to Nonlinear SSI

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Swiss Federal Nuclear Safety Inspectorate ENSI

Nonlinear SSI Analysis from the Swiss Regulatory Perspective:

- Here are some practical questions related to nonlinear SSI analysis:
  - Application limits for SSI analysis based on equivalent-linear soil model (primary nonlinearity) (e.g. RCC-CW – 2018, Ch. DA 3223: effective distortion in each layer $\gamma_{eff} < 0.1\%$)
  - Can higher γ_{eff} values be accepted (e.g. in case of design extension events) ? (Nonlinear analysis with adequate constitutive relation for soil can provide the answer.)
  - Can the strain-compatible soil material properties derived for primary soil nonlinearity be accepted for secondary soil nonlinearity along deep embedded basement walls?
  - How significant are the effects of foundation uplift and the sliding on the relative displacement of the building to the free-field (seismic demand on ducts, channels and piping) and to adjacent buildings (seismic demand on piping; structural pounding) and on the ISRS (i.e. seismic demand for equipment) ? How to adequately model the soil-foundation interface?
  - Earthquake-induced damage of the bank area near the water intake by excess pore water pressure (liquefaction).

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Lateral Sliding – NRC NUREG-0800 Sec. 3.8.5

4. Design and Analysis Procedures

…

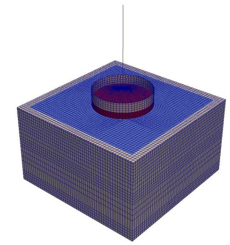
In addition to the above, the design and analysis procedures for the following details are reviewed on a case-by-case basis:

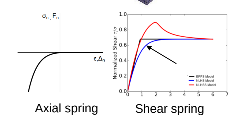
A. …

B. Adequacy of the sliding analysis method and the analysis results to account for **potential mat foundation liftoff effects**.
The staff should also review the calculation of the factor of safety against sliding. If **sliding resistance** is the sum of shear friction along the basemat and contribution of soil lateral pressure up to the full passive pressure capacity induced by embedment effects, the adequacy of the analysis to consider these effects is addressed using a consistent lateral displacement criterion. This involves the use of static versus dynamic coefficient of friction consistent with the use of partial versus full passive pressure.
The **reviewer should also consider** whether the **selection of the coefficient of friction** used in the sliding stability analysis **considers** the **various sliding interfaces** (e.g., **soil shear failure**, **concrete to soil**, **waterproofing to soil**, **concrete basemat to concrete mudmat**).

Performed Nonlinear-Interface SSI with Real-ESSI

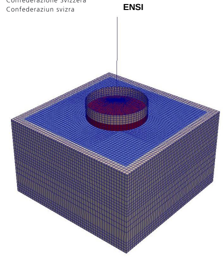
- Comparison of ISRS generated with Real-ESSI at foundation level and top of the concrete containment for a model with a nonlinear (soft or stiff) or a “welded” soil-basemat interface
- Simplified reactor building MDoF-model:
  - Concrete containment and all internal structures (realistic mass and center of gravity)
  - Surface foundation (4.5 m thickness) diameter: 42 m

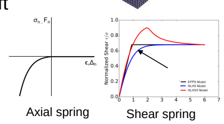




Performed Nonlinear-Interface SSI with Real-ESSI

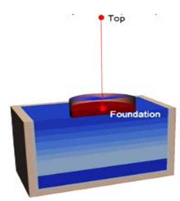
- Soil model:
  - 7 layers (t_{tot} = 42 m) on bedrock, 84 × 84 m in width
- Preliminary material properties of contact elements at interface (zero-length):
  - Modelling slippage in horizontal directions (nonlinear hardening shear model) and uplift (penalty function for compression and zero stiffness for tension)
  - Initial stiffness of stiff interface = 6 × initial stiffness of soft interface
  - Friction coefficient:
    - stiff interface μ = 0.80 (plateau)
    - soft interface μ = 0.35 (plateau)

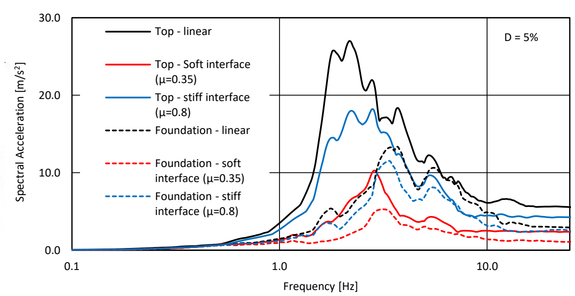




Performed Nonlinear-Interface SSI with Real-ESSI

Comparison of results accounting only for the **horizontal** component:





RCC-CW – 2018 : PART D DESIGN

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DA 6500 VALIDATION OF LINEAR MODELLING OF UPLIFT EFFECT

The following cases shall be addressed for the validation of linear modelling of soil-structure interface:

1) If the **uplift area of tensile springs** between the structure and the supporting fixed points is **less than 10%**, the **linear model** representing the **soil-structure interface** is **validated** and it **can be used** for the calculation of **steel reinforcement** and **floor spectra in the structure**.
2) If the **uplift area of tensile springs** between the structure and the supporting fixed points is **larger than 10% but smaller than 30%**, the **linear model** representing the soil-structure interface is **validated** as in case 1. The resulting dynamic loads can be used for the static justification of the structures. If needed, step 3) may be used to obtain less conservative loads.
3) If the **uplift area of tensile springs** between the structure and the supporting fixed points is **larger than 30%**, an **energy-based** approach, a **non-linear time history analysis** or other **alternative justified approach** can be used to **demonstrate** that **70% of the total interface area remains in contact**: if one of these alternative methods is **successful**, the **linear model is validated** and the methodology of case 2 shall be followed
4) **If no alternative method can be found to demonstrate a contact area larger than 70%, then the model shall be non-linear.**

Summary and Conclusions

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- Nonlinearities in the soil-basemat interface (horizontal slippage in both horizontal directions and foundation uplift) are investigated:
  - Significant reduction of resulting ISRS with a simultaneous increase in relative displacements obtained in the preliminary analysis.
  - Consideration of horizontal slippage is crucial for the assessment of realistic foundation uplift. However, the modelling of interface friction is associated with great uncertainties, which have to be treated in sensitivity analyses.
  - Interface nonlinearities play a decisive role in realistic SSI analysis of nuclear structures and determining the seismic demand on equipment. The selection of key modelling parameters of the interface is found to affect the SSI response to a high degree.

Next Steps

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- Further parametric studies on interface nonlinearities, with a focus on the validity of the elastic design and FRS in relation to foundation uplift.
- Consideration of nonlinear material properties of soil and structure.

Acknowledgement

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- The authors would like to thank Prof. Boris Jeremić and his Real-ESSI development team at UC Davis for the fruitful technical discussions and valuable support and help throughout the course of the present work.


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Swiss Federal Nuclear Safety Inspectorate ENSI
Peter Rangelow1,Tadeusz Szczesiak2
1 Basler & Hofmann AG Consulting Engineers, Switzerland
2 Swiss Federal Nuclear Safety Inspectorate ENSI, Switzerland
Thank you!
Basler & Hofmann – ENSI
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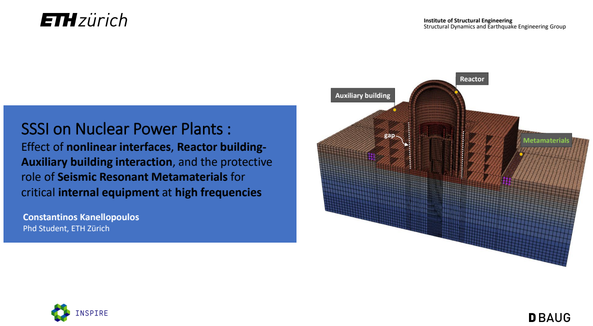
SMiRT 26 - Berlin/Potsdam, Germany | 10 - 15 July 2022 | NL-SSI Workshop | P. Rangelow & T. Szczesiak
Basler & Hofmann

Ongoing work, at at Basler & Hofmann AG Consulting Engineers, Switzerland, and Swiss Federal Nuclear Safety Inspectorate, ENSI, Switzerland, High fidelity models of Swiss NPPs:

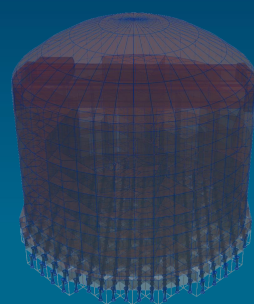


6.3 Aleš Buršič, GEN energija, d.o.o., Slovenia

Workshop: Nonlinear SSI Analysis

SMiRT 26
50 Anniversary Berlin/Potsdam

- Implicit non-linear dynamic analyses Multiphysics and CFD coupling
- Analysis software availability and suitability for very large models
- Importance of parallel computation
- Analyses as a design tool in iterative design process



Implicit non-linear dynamic analyses Multiphysics and CFD coupling

For more specific cases like assessing seismic dissipation devices, the use of non-linear dynamic analyses is inevitable. At such examples often more complex contact problems are involved and integrated in models.

In case of (implicit) non-linear dynamic analyses with contact problem beside solid to solid interaction there can be need to establish efficient fluid to solid interaction (FSI) phenomenon to efficiently investigate dynamic behaviour in time domain, on top of adjacent nonlinear (e.g. implicit contact) problems.

Some options like:

- coupling Codes (Code Saturne to code Aster, Salome Meca, EDF…) ,
- distribute characteristics of specific mass tothe nodes of the interface fluid-structure of the face upstream without adding degrees of freedom apart from the structure.

There is also some development on that matter from NVIDIA company implementing various coupling approaches for FEM/Hydromechanics on their GPUs. Any further information regarding that matter would be very appreciated.

Demanding environment at conducting such analysis are leading to necessary simplifications and perhaps complex phenomenon interpretations, which shift resources from engaging with nature of researched problem to engagement with software/hardware equipment/tools behaviour.

Analysis program availability and suitability for very large models

Conducting complex analyses often with very large models, requiring large computational power, when using commercial software, is nearly impossible, since combined costs for licenses and hardware in academic/educational domain are usually unacceptable, so is accessibility difficult.

Another topic may be efficient handling of plant-scale models in various simulation software and their capability of handling 1e6 DOF and above.

Importance of parallel computation

In today's world interconnections of various devices with constantly increasing computing power are abundant and very common. However parallel computations for large FEM applications are more less tied to larger institutions with excellent IT support capable of maintaining computing clusters, HPC's and dedicated software. In my opinion, if there exists possibility to simplify parallelisation of computing and efficiency by simplified use of various network interconnected devices or simultaneous use of CPU+GPU, it could greatly reduce the computation efforts.

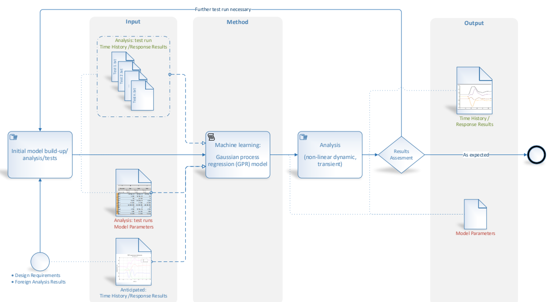
There may be need on MPI solving approaches handling efficiently nonlinear problems (e.g. implicit contact…)

Analyses as a design tool in iterative design process

Design process may become tedious when FEM analyses are required and the design updates/corrections and analysis results are repeatedly exchanged, usually, between analysis and design departments. Fast Virtual prototyping has been known for several decades and evolved together with increasing CAD implementation for engineering purposes.

Using Machine learning (ML) to predict design features of devices when implementing non-linear dynamic analyses at devices investigations is becoming (may become) increasingly popular. ML integration may also enable further options for mathematical model migrations between different FEM codes (e.g. Code Aster to Real-ESSI).

Any elaboration of research or knowledge on that topic could be very beneficial.



6.4 Francisco Beltrán, BELGAR Ingenieros Consultores, Spain

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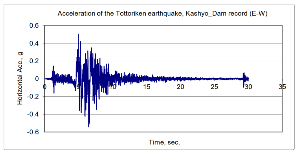

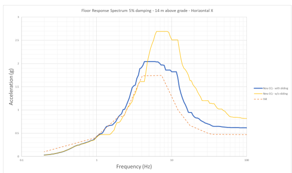

SMiRT 26
Berlin/Postdam, July 10-15, 2022
Workshop, Nonlinear SSI Analysis

Reducing Floor Spectra by Introduction of Nonlinearity at the Soil-Structure Interface

Francisco Beltrán
BELGAR Ingenieros Consultores

Belgar
Engineering Consultants

Outline

1. Background
2. Pilot analytical study
   - Sample building
   - Sliding and uplift allowed at the soil-structure interface
3. Results
   - Comparison of floor spectra
4. Concluding remarks
   - Points for discussion

2

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Engineering Consultants

Introduction
Background

- Plant designed and built in the 1980s
  - Westinghouse PWR, Bechtel-type design
  - SSE based on RG 1.60 spectra, anchored to a PGA obtained deterministically from historical earthquakes
  - Seismic analysis and design according to US-NRC Standard Review Plan at that time
- After the European Stress tests (2015), the regulator asks for a new seismic hazard analysis using modern practice (PSHA following the SSHAC Level 3 protocol)
  - Geological structures active during the Plio-Quaternary (about 5 million years) need to be identified and characterized
  - A fault with some activity in the Plio-Quaternary is identified in the site near region
  - Geologists characterize the fault as able to produce magnitude M 6+ earthquakes with a recurrence period of 30000-50000 years
  - Design earthquake (GMRS) derived from the new hazard curves is significantly larger than the SSE

3

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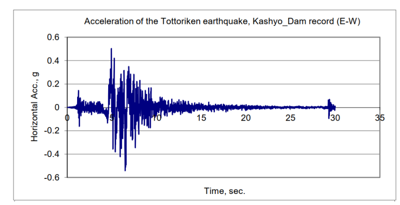
Introduction
Background

- Site seismic hazard becomes dominated by "near field" earthquakes
- Near field earthquakes are characterized as causing short duration (shock-type) acceleration time-histories, with a marked directionality
  - For engineered structures, they are less damaging than "regular" earthquakes with the same response spectrum
  - Structures respond with a small level of non-recoverable deformation (i.e. non-linear), which results in negligible damage
  - The same can be said for small sliding or uplift at the foundation slabs



M_w 6.6 earthquake, Epicentral distance of 3 km

IAEA TecDoc 1655 – Non-linear Response to a Type of Seismic Input Motion (2011)

4

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Introduction
Background

- A realistic treatment of "near field" earthquakes requires that we introduce a small amount of non-linear response in our computational models
  - Structural response
  - Soil-Structure dynamic interaction
- If not, our results will probably be very conservative
  - But <u>we cannot afford too much conservatism</u> when assessing seismic safety of existing plants

5

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Pilot analytical study
Main ideas

- Take a representative plant building and compute the response for the new near field earthquakes assuming that sliding and uplift is possible at the foundation slab
  - Regular, frequency domain, procedures cannot be used
  - Switch to time domain and "direct method" of SSI (vs. regular substructuring methods)
- For the direct method, rigorous treatment of boundaries is available (Domain Reduction Method, DRM) but commercial software implementing those methods is less known…
  - The contractor eventually opted for a "brute force" approach, setting the vertical boundaries very far away from the structure
  - Huge model, which needed to be processed by an explicit integration code.
- Even if possible, no other non-linearities were introduced
  - Geological materials were considered "equivalent" linear
  - Structural materials were considered linear elastic

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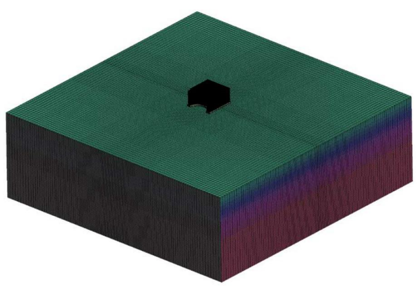
Pilot analytical study
Model

Computational model



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Pilot analytical study
Results

- In general, the analytical approach follows the guidelines in ASCE 4-16
  - Representation of mass
  - Representation of stiffness
  - Number of earthquakes
  - Consideration of uncertainties in soil properties
  - Soil-Structure interaction
  - … … … …
- A range of possible friction coefficients at the soil-structure interface was considered
  - A range between 0.5 and 0.9

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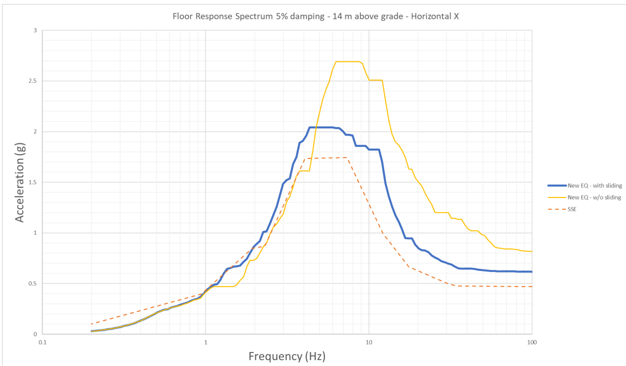
Pilot analytical study
Representative results



Envelope of broadened mean spectra

(3 soil columns
x3 friction coefficients
x7 earthquakes)

9

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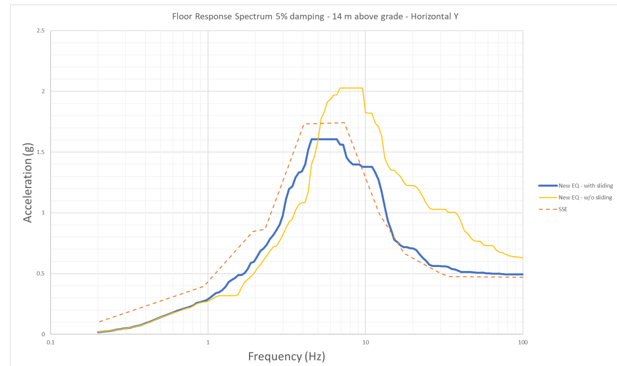
Pilot analytical study
Representative results



Envelope of broadened mean spectra

(3 soil columns
x3 friction coefficients
x7 earthquakes)

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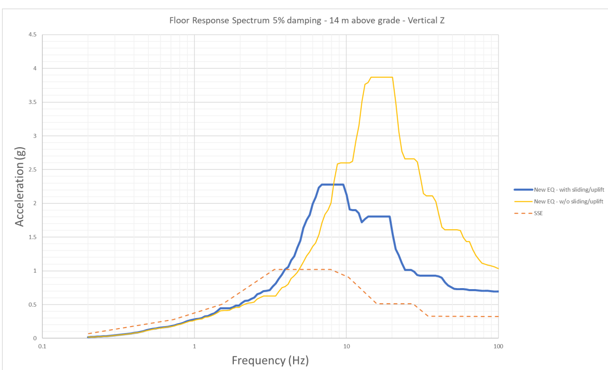
Pilot analytical study
Representative results



Envelope of broadened mean spectra

(3 soil columns
x3 friction coefficients
x7 earthquakes)

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Final remarks

Points for discussion

- ✓ Can we afford ignoring non-linear effects ?

  We can discuss about which technique or approach is better to consider non-linearities…

  … but in many cases we cannot afford ignoring them.

  This is especially true when assessing existing installations against the (ever) increasing seismic hazard at the site

- ✓ Do we have adequate tools in our toolbox ?

  It is not just the tools, we need qualified/trained people.

- ✓ What about licensing the analyses with the regulatory authority ?

  Too much uncertainty in the licensing process ?

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Discussion ?

www.toonsup.com/hsbcartoon

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The End

(Thank you !!)

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6.5 Charisis Chatzigogos, Géodynamique & Structure, France

SMiRT 26

26th International Conference on Structural Mechanics in Reactor Technology

WORKSHOP ON Nonlinear SSI Analysis

Charisis T. CHATZIGOGOS

Géodynamique & Structure, FRANCE

Presentation of Géodynamique & Structure (GDS)

- **Geodynamique & Structure (GDS) is a consulting firm specializing in the analysis of the behavior of soils, structures, equipment and their interactions under cyclic, dynamic and thermomechanical actions with more than 40 years of experience, and with clients throughout the world**
- **Since its foundation in the early 80's, GDS has been particularly active on seismic studies of nuclear facilities and other critical industrial infrastructure, mainly in France**
- **The company is located at Montrouge, France**
- www.geodynamique.com

Nonlinear Dynamic Soil-Structure Interaction

- **Nonlinear transient analyses of global stability and uplift ratio** (sliding, uplifting, presence of groundwater and buoyancy, embedment, P-δ effect, consideration of nonlinear soil behavior)
- **Use of nonlinear macroelements** for foundation and/or structural elements
- **Foundation impedance calculations and hybrid methods for nonlinear SSI calculations in time domain** (Fourier domain-Time domain / Laplace domain-Time domain)
- **Direct SSI calculations:** techniques for definition of boundary conditions
- **Kinematic interaction for embedded structures:** nonlinear effects at the lateral interfaces
- **Generation of surface waves** on sedimentary basins and incidence on large infrastructure
- **Modeling of soil liquefaction** and effect of liquefaction for site-response analyses
- **Use of Limit Analysis Methods** for concrete and soil structures
- **Seismic Isolation**

Software, Normative Issues, Implementations

- **Possibilities for NLSSI analyses in Design** (Design Basis / Design Extension)
- **Quality Assurance and validation of software tools is paramount →** the development of in-house tools needs to be accompanied by extensive qualification procedures
- **Standardized methodologies for calibration of nonlinear constitutive laws** (soil, reinforced concrete)
- **Standardization in algorithmic implementations** (numerical damping, time steps and mesh sizes, dynamic integration schemes…)
- **Hierarchical implementation of nonlinear modeling →** for understanding the successive "refinements" obtained in passing from linear to fully nonlinear
- **Definition of "structural failure" in relation to "numerical convergence" :** definitions and control of convergence criteria
- **Qualification of engineers performing the analyses** (peer reviewing / independent verifications)
- **Consideration of uncertainty/randomness within nonlinear analyses → computational resources**
- **3D versus 2D analyses** (for stability and geotechnical problems…)

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