ENGINEERING ANALYSIS TOOLBOX, THE REAL-ESSI SIMULATOR SYSTEM

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ABSTRACT

Presented here is a number of numerical analysis challenges for analysis of nonlinear behavior of Earthquake-Soil-Structure Interacting (ESSI) Nuclear Installation (NI) systems, during static an dynamic loading. Presented is also a a summary of education, training and quality assurance activities that are necessary to develop high quality numerical analysis of NI ESSI systems response for static and dynamic loads.

INTRODUCTION

Engineering design and assessment of soil-structure systems behavior requires knowledge about, competence in and capability to analyze behavior of soils, structures and their interaction (SSI) for static and dynamic loads. This is particularly true for nuclear installations, large, important objects for which safety and economy dominates all phases of design and assessment. Engineering design and assessment of SSI systems for static and dynamic loads requires use of efficient, sophisticated, quality assured, numerical analysis tools. Practicing engineers, knowledgeable in statics and dynamics of soils and structures, need versatile, efficient, sophisticated numerical analysis tools to explore different design options and to assess state of existing objects for service and hazard loads. Analysis tools need to be capable to analyze SSI models of different levels of sophistication, and to offer engineers capability to model all necessary components of the SSI system. A number of analysis challenges need to be addressed for numerical analysis to develop high quality results that are then used for design and assessment.

ANALYSIS CHALLENGES

Numerical analysis of earthquake soil structure interaction (ESSI) aims to develop understanding of the realistic behavior of the ESSI systems for static and dynamic loads. Static loads are present before the main dynamic, earthquake loading is applied. Static analysis is very important as most nonlinear, inelastic materials, soils, and structures, do have memory, that is, their nonlinear behavior will be influenced very much by their prior, static and dynamic loading history. In a sense, when we discuss ESSI analysis, static loading history prior to the main dynamic, earthquake loading is also as important, and so the ESSI analysis encompasses both static and dynamic analysis.

A number of analysis challenges, that need to be addressed with certain level of sophistication, are present. Analysis challenges are comprised of both modeling challenges, challenges that have to deal with proper modeling of loads and material behavior, as well as algorithmic challenges that deal with space and time discretization and use of proper numerical algorithms in order to properly solve numerical analysis models.

MODELING ANALYSIS CHALLENGES

A number of modeling analysis challenges that need to be addressed exist. Modeling analysis challenges are listed below:

- Modeling of realistic seismic motions that feature all three components icluding three translations and three rotations (3C/6C). Simplifying assumption of using only one components (1C) motions needs to be verified against using full 3C/6C components of motions.
- Modeling of realistic behavior of soil and rock materials that show nonlinear, inelastic, elastic-plastic behavior and can be dry and/or partially or fully saturated.
- Modeling of realistic behavior of interfaces, joints, and contacts that show nonlinear, inelastic, elastic plastic behavior.
- Modeling of realistic behavior of structure, systems and components (SSCs), beams, walls, plates, shell made of steel and reinforced concrete, base isolators and dissipators, systems that feature nonlinear, inelastic, elastic-damage-plastic behavior.
- Interaction of soil/rock – structure systems with fluids (water, air,etc.): (a) internal, within structure or in pores of porous materials (soil, rock, concrete) and (b) external fluids in reservoirs, pools.
- Modeling of the complete SSI system with all realistic loads, realistic material behavior and realistic interactions.
- Modeling of parametric uncertainty, aleatory uncertainty in material behavior and in loads.

Modeling analysis challenges need to be addressed with reqired level of sophistication as they add to the modeling, epistemic uncertainty of developed results. Some simplification in modeling sophistication might be made, however it is the task of responsible engineer to demonstrate that such simplifications are adequate for the purpose of performed analysis.

ALGORITHMIC ANALYSIS CHALLENGES

In addition to the modeling analysis challenges, numerical analysis brings in a number of challenges related to discretization process and numerical algorithms that are used to solve underlying static and dynamic modeling equations. Algorithmic analysis challenges are listed below:

- Challenges of proper spatial discretization of the continuum soil-structure systems into finite elements for analysis of
    - Elastic-plastic analysis with possible localization of deformation, for example for plastic hinges in beams and plastic zones in plates, walls and shells, plastic shear zones in solids and interfaces,
    - Propagation of seismic waves, motions of required frequency through the finite element mesh, with elastic or elastic-plastic material behavior,
- Challenge of proper time discretization for linear and nonlinear ESSI systems, into finite time steps at which ESSI systems response is analyzed.
- Challenge for high performance computing methods including parallel computations.

EXPERT ENGINEER, EDUCATION AND TRAINING

Expert engineer, analyst working on nonlinear analysis of nuclear installations needs to be properly educated, trained and experienced. Education and training can be done through university courses, professional practice short courses on nonlinear analysis. Expert engineers can also gain significant knowledge through self study as a significant amount of learning material as well as a significant number of educational example are available online. It is really important to note that education and training for capable nonlinear analysis requires time! With proper education and training, competent, expert engineers can handle with ease all the challenges noted above. Current experience show that some guidance from available, just in time (JIT) education and training material, and occasional consultations with nonlinear ESSI analysis experts might be required sometimes.

ANALYSIS QUALITY ASSURANCE

The main of this paper is on focus is on numerical analysis, that is overwhelmingly used nowadays for design of new and assessment of existing nuclear installations SSI system response to static and dynamic loads. In numerical analsys there always exists a numerical discretization error, an error that is omnipresent due to space and time discretization process in numerical analysis. Numerical discretization error needs to be thoroughly analyzed, understood and documented through a detailed verification process. Detailed verification of all the components of the numerical analysis tool, program is essential for quality assurance of results. In addition, validation, using hight quality experiments is also an essential part of quality assurance of results [13, 10, 12, 11, 5] It is noted that verification, that has to do with mathematics and computer science is usually developed in more details. On the other hand, validation, that to do with mechanics, is requiring high quality experiments of components, subsystems and complete system, is currently not as available, and will require further development in the future.

ENGINEERING ANALYSIS SYSTEM

Engineering analysis challenges noted above were used as inspiration for the development of the Real-ESSI Simulator system. The Real-ESSI Simulator (Realistic Modeling and Simulation of Earthquakes, and/or Soils, and/or Structures and their Interaction [4]) is a numerical analysis system for high performance, sequential or parallel, time domain, linear or nonlinear, elastic and inelastic, deterministic or probabilistic, engineering analysis of ESSI problems. The system is developed to address all the modeling and simulation challenges noted above. The system is also developed and used to provide engineers with analysis tools to investigate design options and to develop high quality assessment for static and dynamic behavior of nuclear installations ESSI systems [9, 14, 3, 2, 6, 7, 8, 21, 20, 23, 22, 25, 24, 15, 17, 16, 18, 19, 1, 5]. The Real-ESSI system features models, methods, and algorithms to address all of the above challenges. In addition, the Real-ESSI system features extensive quality assurance effort and documentation [5]. The Real-ESSI system web site `http://real-essi.us` provides an up to date list of models, methods and features. Moreover, number of detailed manuals and documents, and a large number of examples, as well as access to the program is available for local install, on MS Windows or Linux systems, or for use on cloud computers, for example on Amazon Web Services.

CONCLUSION

Realistic behavior of nuclear installation ESSI systems for static and dynamic loads can be successfully analyzed, provided that analysis challenges, noted above, are addressed. Realistic nonlinear, inelastic behavior of all components and of a complete nuclear installation ESSI system has to be adequately modeled using capable and quality assured nonlinear analysis programs, by competent and trained engineers, analysts. Significant benefits in safety and economy from such realistic modeling can be gainded and should are used to promote and encourage nonlinear analysis of nuclear installations. The Real-ESSI Simulator system is one example of a nonlinear analysis program that has all the necessary models and algorithms for high fidelity nonlinear analysis if nuclear installation ESSI systems. The Real-ESSI Simulator system features a significant documentation and examples library Capable, competent expert engineer, can use the Real-ESSI Simulator systems to improve economy of, and to assess safety for design basis and beyond design basis loads for nuclear installations ESSI systems.

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REFERENCES

[1] Feng, Y., Zamani, K., Yang, H., Wang, H., Wang, F., and Jeremić, B. (2019). "Procedures to build trust in nonlinear elastoplastic integration algorithm: solution and code verification." *Engineering with Computers*, 1–14.

[2] Guidio, B., Jeremić, B., Guidio, L., and Jeonga, C. (2022). "Full-waveform inversion of sh-wave input motions in a domain truncated by wave-absorbing boundary conditions." *Structural Dynamics and Earthquake Engineering* in print.

[3] Jeremić, B. (2020). "Report to the US-DOE for project: A modern computational framework for the nonlinear seismic analysis of nuclear facilities and systems; the Real-ESSI Simulator system development and analysis of nuclear facilities and systems, 2015-2020." *Report No. UCD-CompMech-Oct2020*, UCDavis (October).

[4] Jeremić, B., Jie, G., Cheng, Z., Tafazzoli, N., Tasiopoulou, P., Pisanò, F., Abell, J. A., Watanabe, K., Feng, Y., Sinha, S. K., Behbehani, F., Yang, H., and Wang, H. (1988-2023a). *The Real-ESSI Simulator System*. University of California, Davis. `http://real-essi.us/`.

[5] Jeremić, B., Yang, Z., Cheng, Z., Jie, G., Tafazzoli, N., Preisig, M., Tasiopoulou, P., Pisanò, F., Abell, J., Watanabe, K., Feng, Y., Sinha, S. K., Behbehani, F., Yang, H., and Wang, H. (1989-2023b). *Nonlinear Finite Elements: Modeling and Simulation of Earthquakes, Soils, Structures and their Interaction*. Self-Published-Online, University of California, Davis, CA, USA URL: `http://sokocalo.engr.ucdavis.edu/~jeremic/LectureNotes/`.

[6] Kanellopoulos, C., Jeremić, B., Anastasopoulos, I., and Stojadinović, B. (2020). "Use of the domain reduction method to simulate the seismic response of an existing structure protected by resonating unit cell metamaterials.." *Proceedings of the EURODYN 2020, XI International Conference on Structural Dynamics,*, M. Papadrakakis, M. Fragiadakis, and C. Papadimitriou, eds., Athens, Greece, EASD Procedia, 2926–2938 (November).

[7] Kanellopoulos, C., Psycharis, N., Yang, H., Jeremić, B., Anastasopoulos, I., and Stojadinović, B. (2022). "Seismic resonant metamaterials for the protection of an elastic-plastic sdof system against vertically propagating seismic shear waves (SH) in nonlinear soil." *Soil Dynamics and Earthquake Engineering*, 162, 107366.

[8] Kanellopoulos, C., Rangelow, P., Jeremić, B., Anastasopoulos, I., and Stojadinović, B. (2023). "Linear

and nonlinear dynamic structure-soil-structure interaction for nuclear power plants." *Soil Dynamics and Earthquake Engineering*, in Review.

[9] Lizundia, B., Crouse, C., Harris, S., Jeremić, B., Stewart, J. P., and Valley, M. (2020). "A practical guide to soil-structure interaction, FEMA P-2091." *Report No. FEMA P-2091*, Applied Technology Council, Redwood City, CA, USA.

[10] Oberkampf, W. L., Pilch, M. M., and Trucano, T. G. (2007). "Predictive capability maturity model for computational modeling and simulation.." *OSTI*, (SAND2007-5948, TRN: US201009

[11] Oberkampf, W. L. and Roy, C. J. (2010). *Verification and Validation in Scientific Computing*. Cambridge University Press.

[12] Oberkampf, W. L. and Trucano, T. G. (2007). "Verification and validation benchmarks." *Report No. SAN2007-0853*, Sandia National Laboratory, Albuquerque, New Mexico 87185 and Livermore, California 94550 (February).

[13] Oberkampf, W. L., Trucano, T. G., and Hirsch, C. (2002). "Verification, validation and predictive capability in computational engineering and physics." *Proceedings of the Foundations for Verification and Validation on the 21st Century Workshop*, Johns Hopkins University / Applied Physics Laboratory, Laurel, Maryland, 1–74 (October 22-23).

[14] Pecker, A., Johnson, J. J., and Jeremić, B. (2022). *Methodologies for Seismic Soil-Structure Interaction Analysis in the Design and Assessment of Nuclear Installations*. Number IAEA-TECDOC-1990. United Nations, International Atomic Energy Agency, UN-IAEA, External Events Safety Section, IAEA, VIC, PO Box 100, 1400 Vienna, Austria (February) IAEAL 21-01471.

[15] Wang, F., Wang, H., Yang, H., Feng, Y., and Jeremić, B. (2020a). "A modular methodology for time-domain intrusive stochastic seismic wave propagation." *Computers and Geotechnics*, (139).

[16] Wang, H., Wang, F., Bayless, J., Yang, H., Baglio, M., Abrahamson, N. A., and Jeremić, B. (2020b). "Time domain intrusive stochastic seismic risk analysis using ground motion prediction equations of fourier amplitude spectra." *Soil Dynamics and Earthquake Engineering*, in Review.

[17] Wang, H., Wang, F., Yang, H., Feng, Y., Bayless, J., Abrahamson, N. A., and Jeremić, B. (2020c). "Time domain intrusive probabilistic seismic risk analysis of nonlinear shear frame structure." *Soil Dynamics and Earthquake Engineering*, 136, 106201.

[18] Wang, H., Wang, F., Yang, H., Feng, Y., Bayless, J., Abrahamson, N. A., and Jeremić, B. (2020d). "Time domain intrusive probabilistic seismic risk analysis of nonlinear shear frame structure." *Soil Dynamics and Earthquake Engineering*, 136, 106201.

[19] Wang, H., Yang, H., Feng, Y., and Jeremić, B. (2021). "Modeling and simulation of earthquake soil structure interaction excited by inclined seismic waves." *Soil Dynamics and Earthquake Engineering*, 146, 106720.

[20] Yang, H., Feng, Y., Wang, H., and Jeremić, B. (2019a). "Energy dissipation analysis for inelastic reinforced concrete and steel beam-columns." *Engineering Structures*, 197, 109431.

[21] Yang, H., Sinha, S. K., Feng, Y., McCallen, D. B., and Jeremić, B. (2018). "Energy dissipation analysis of elastic-plastic materials." *Computer Methods in Applied Mechanics and Engineering*, 331, 309–326.

[22] Yang, H., Wang, H., Feng, Y., and Jeremić, B. (2019b). "Plastic energy dissipation in pressure-dependent materials." *ASCE Journal of Engineering Mechanics* In Print.

[23] Yang, H., Wang, H., Feng, Y., Wang, F., and Jeremić, B. (2019c). "Energy dissipation in solids due to material inelasticity, viscous coupling, and algorithmic damping." *ASCE Journal of Engineering Mechanics*, 145(9).

[24] Yang, H., Wang, H., and Jeremić, B. (2021). "Numerical modeling and validation of earthquake soil structure interaction: A 12-story building in Ventura, California." *Engineering Structures* In Review.

[25] Yang, H., Wang, H., and Jeremić, B. (2022). "An energy-based analysis framework for soil structure interaction systems." *Computers & Structures* In Print.