# SOME INSIGHTS ON FREQUENCY VS. TIME-DOMAIN APPROACHES FOR SEISMIC SSI ANALYSIS OF NPP STRUCTURES

## A PERSONAL PERSPECTIVE TECHNICAL NOTE

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## ARE TIME-DOMAIN APPROACHES TAKING OVER SOON?

From a pure mathematical modeling point of view, the nonlinear approaches in time domain are clearly superior to the equivalent linear aproaches in frequency domain. However, from a practical design point of view time domain approaches are much less attractive especially due to their large sensitivity to various numerical modeling aspects involved in the seismic SSI analysis. It is known by practitioners that the nonlinear time-domain analysis results (using DYNAFLOW, LS-DYNA, etc.) are numerically sensitive to the constitutive soil material models and their parameters, and to the soil-foundation interface modeling. Most often, the analyst has to put a lot of extrawork to adjust and tune the soil-foundation interface parameters, or the soil model parameters, to avoid getting ridiculous, unplausible SSI dynamic results.

When dealing with nonlinear systems and incremental step-by-step solutions in time domain, numerical errors are committed due to lack of exact determination of the time at which transition in material properties occur. The overshooting and backtracking effects due to the lack of perfect determination of the times at which changes in the stiffness occurs can introduce erroneous noisy, high-frequency components. Equilibrum corrections are sometimes applied when the system goes from linear-elastic to plastic, but it must be remembered that the correction is not exact. When a reversal occurs and the system which was in plastic state again becomes elastic, no correction is usually applied. These sudden changes in properties introduce fictitious noisy, high-frequency spurious components into the system response. To avoid these noisy spurious components, is typical to incorporate in the model some viscous damping and reduce the time step as much as possible. However, the artificial incorporation of viscous damping in the model to improve the solution can filter excessively the high-frequency components, and the reduction of the time step increases severely the computational analysis effort.

Time integration implicit methods, as implemented in various FEA codes, as ANSYS, GT STRUDL, SAP, etc. are unconditionally stable, but their stability is achieved by introducting fictitious damping, as in the popular Wilson theta and Newmark integration methods. As the result of this numerical damping, the computed seismic SSI results may be dangerously unconservative, especially for higher frequencies.

The time integration explicit methods, as implemented in ANSYS and LS-DYNA, instead requires a very small time step for stability as by this require unreasonably large computational efforts.

# SOIL AND SSI MODELING ASPECTS

It should be noted that the second large source of uncertainity in seismic SSI analysis, after seismic input uncertainty, is related to the determination of the soil properties to be used in the dynamic analysis. This involves measuring soil properties in the laboratory and relating them to the properties in-situ, determining the variation of these properties with level of strain, and choosing the mathematical model to reproduce the nonlinear soil behavior. Sophisticated soil models have a large number of parameters that need to be accurately measured in the laboratory and then, extrapolated correctly in the soil field. There are large uncertainties related to the correct determination of the soil material and soil-foundation interface modeling parameters for the SSI dynamic analysis.

The soil modeling uncertainties that impact heavily on SSI analysis results make nonlinear SSI analyses less attractive to experienced structural designers. More important for designers than the soil modeling sophistication is to capture variability aspects. A structural design analyst looks for performing many, various sensitivity analyses using numerically efficient SSI models that can help him understand the structure SSI dynamic behaviour under different possible inputs and alternate modeling scenarious, rather than an ultrasophisticated analysis, difficult to check in detail, and computationally too intensive to be repeated for a number of times for considering the input and modeling uncertainties.

It should be noted that in the past, the equivalent linear soil models rather than the sophisticated nonlinear plasticity soil models have been often preferred by practitioners, since they are simple to handle and computationally fast. Equivalent linear model captures well the global nonlinear soil behavior as function of the strain amplitude with minimum sophistication. However, for a given particular soil analysis case, the equivalent linear model may not be as accurate as a sophisticated Prevost's multiyield plasticity cap model with twelve parameters. But for these types of sophisticated plasticity models, their parameters are hard to obtain and calibrate for the field in practice. It is obvious that the uncertainties in the soil parameters and the extrapolation of laboratory results to the soil field behavior always exist, and these uncertainities may offset any increase in accuracy of the mathematical model in the time domain.

The most important modeling limitations of the frequency domain approaches are related to the local nonlinear aspects at soil-foundation interface. The effects of uplift and soil separation cannot be captured in the frequency domain approaches that assume linearized SSI sytems. The equivalent linearization approach is a simplified approach that is theoretically applicable up to moderate levels of nonlinear material behaviors.

In the recent NUREG/CR-6896 is written: "For the case of strong ground motions, the non-linear effect is expected to have a strong impact on the SSI response calculations. For deeply embedded structures, the issue arises in the aspects of the interface modeling and soil material modeling, and the SSI response calculation could be sensitive to the modeling assumptions made for the soil/structure interface and application of a particular material model for the soil. These modeling assumptions can only be validated through correlations with field or laboratory measured seismic response data, which unfortunately are scarce, especially for moderate to strong earthquake events."

Related to the linear SSI approaches in time and frequency domains, the above mentioned NUREG report indicates that "The linear SSI methodologies (i.e. both in frequency and time domain) including both simplified and detailed approaches can be extended to deeply embedded structures and produce acceptable SSI response calculations, provided that the SSI response induced by the ground motion is very much within the linear regime or the non-linear effect is not anticipated to control the SSI response parameters." Further it is written, "Since there are as yet no general criteria that enable an analyst to predict a priori when nonlinear effects will become significant for a particular problem, it is recommended that the results of the linear calculations be examined in enough detail to evaluate the potential for such effects. For example, peak stresses and stress ratios (shear/pressure) at critical locations along the building wall-soil interface can be determined from the linear calculation to estimate if separation and/or shear sliding may potentially occur. Similarly, stresses under the toe of the foundation slabs can be examined to estimate if stress ratios are high enough to potentially lead to local failure levels."

In ACS SASSI it is implemented, as an additional capability option, Option A, an efficient frequency-time hybrid approach obtained by coupling ACS SASSI with ANSYS in a two step procedure. This hybrid approach includes a global linearized SSI dynamic analysis using ACS SASSI in the first step, and then, a linear or nonlinear structural equivalent-static analysis, or a set of analyses using ANSYS in the second step. The ANSYS structural analysis inputs are the boundary conditions from the seismic SSI analysis done in the first step. The ANSYS analysis can include the effects of the foundation uplift and separation from side soil. The hybrid approach limitation is in its lack of applicability to extreme earthquakes, when the foundation uplift and separation from soil become very large, so that these nonlinear interface effects start affecting significantly the overall SSI response of the structure.

It should be noted that for large earthquakes, the concrete structures may also behave strongly nonlinear, well outside of the validity range of the linearized material behavior. I believe that the current engineering code requirements on the concrete cracking modeling for seismic SSI analysis are overly simplistic for large earthquake situations. However, a rational, practical design solution to the concrete cracking modeling is not obvious at the present state of engineering practice. In contrast to the code simplistic modeling at this time, the "academic" idea to assess all the large nonlinear effects that could occur in the concrete structure, surrounding soil and soil-foundation interface using a single, huge, sophisticated nonlinear SSI dynamic analysis is both engineering naive and dangerous. Such a purely "academic" alternative should not be viewed as the present time as a potential, viable design practice for NPP structures.

The extreme situations produced by large earthquakes, that produce seismic demands that are well above the design-basis demands, should be investigated on a case-by-case basis, using on a careful expert engineering judgement. For these situations, various computational tools capaable of handling highly nonlinear structure and soil behaviours should be used in addition to design-basis analysis tools. Such case-by-case nonlinear SSI analyses done for seismic safety margin assessment will need to involve the "best" experts on concrete cracking, soil material behaviour and dynamic SSI.

A variety of nonlinear analysis tools should be used to compare their results since each of these tools could be highly unreliable, without spending lots of effort and time for the model parameter tunning. Such a case-by-case, sophisticated nonlinear 3D SSI analysis it is expected to cost tens, or even hundreds of times more than a design-basis SSI analysis based on the frequency domain substructuring approach. The affordability of such overly costly nonlinear time-domain analyses is also a serious drawback that most-likely will limit their use in nuclear industry practice for the present and the next 10-15 years.

## HYSTERETIC SYSTEM DAMPING MODELING ASPECTS

The selection of an appropriate damping matrix is a serious problem in time-domain, since both structure and soil material hysteretic damping must be reproduced. Soil damping is generally different for various layers and is of a hysteretic nature (i.e. frequency independent). Forming a damping matrix that maintains these properties is not possible in time domain. Assembling the (internal) damping matrix from individual damping matrices for each finite element of Rayleigh type may note produce the desired effects for the complete SSI system.

The Rayleigh damping that is frequently used in conjunction with the direct time integration approach in many FEA codes, such ANSYS, GT STRUDL, SAP, etc. assumes that the damping matrix is a linear combination of stiffness and mass matrices. This assumption produces a frequency variation of the damping with frequency that is not compatible with the hysteretic systems for which the damping ratio should be constant with frequency. Thus, low and high frequency responses are overdamped, and the intermediate frequency responses are slightly underdamped.

## COMPUTATIONAL ANALYSIS ASPECTS: TRANSMITTING BOUNDARIES AND SUBSTRUCTURING

The main drawback of time approaches is still the lack of sufficiently accurate and numerically efficient transmitting boundaries which can be placed directly at the foundation edge. The most recent and sophisticated absorbant boundaries in time-domain, as PMM and PML, are not yet fully proven for complex SSI problems, and are still not sufficiently efficient for practical industry applications. The simple linear or parabolic attenuation functions selected for simple, 1D or 2D demonstrative wave problems might not work correctly for more complex 3D wave patterns. In addition to some accuracy problems, the time-domain transmitting boundaries require at least 5-12 layers of FE elements surrounding the foundation that makes the SSI model size much larger than the structure model size. This is highly undesirable for the analyst since produces much larger analysis runtimes.

In contrast to the time-domain absorbant boundaries, the frequency-domain consistent boundaries for the 3D wave transmission in the infinite soil media provide an "exact" solution within the accuracy of FE solution. The consistent boundaries correspond to a solution where equal columns of finite elements of differential widths extend all the way to infinity. It should be noted that the consistent boundaries can be placed directly at the foundation edge. This is ideal from a computational point of view, since all the FE model degrees of freedom can be used to model the structure in more detail without wasting a lot of FE mesh for the soil deposit modeling.

The frequency domain permits the application of substructuring for linearized SSI problems. Substructuring implies that all FE model degrees of freedom are used for the structural modeling. Using substructuring, only the structure is modeled by finite elements, while the soil is modeled by local lumped parameters at the foundation-soil interface. Thus, substructuring creates an ideal situation from the analyst point of view that is interested in detailed modeling of the structure. The surrounding soil medium is modeled by lumped frequency-dependent complex impedances (i.e. simple complex spring-dashpot elements) placed at foundation-soil interface nodes. Subtructuring is not possible in time-domain, since frequency-dependent soil dynamic behaviour cannot be correctly modeled in time-domain. An additional advantage of substructuring is that the FE mesh needed to reproduce the dynamic response of the structure is not as refined as that needed to determine stresses/strains in soil accurately, if the soil is included in the FE modeling.

Very importantly, the combination of the frequency-domain consistent boundaries with innovative substructing approaches, such as in the flexible volume method implementated in the original SASSI code, produces extremely fast and accurate analysis solution for linearized SSI systems with shallow or deep embedment. The SASSI methodology exploits at maximum the numerical efficiency of consistent boundaries implemented within an extremely ingenious substructuring approach that makes the soil impedance calculation totally trivial. In the SASSI flexible volume method only the free-field soil impedances and the free-field motions that are ease to determine are needed for computing the seismic forces on the foundation. The soil impedance evaluation problem is solved extremely efficiently using simple, fast free-field solutions that take full advantage of consistent boundaries. Thus, instead of performing the SSI analysis for the structure coupled with the surrounding, unbounded soil deposit, the SSI analysis is performed for the structure coupled with the excavated soil (the soil removed to create the embedment). Thus, the *external source* problem with the force excitation defined at the far-distant external boundaries of the SSI system is reduced to an *internal source* problem with the force excitation defined inside the excavated soil system. The internal source problem size is much smaller than the external source problem size. The flexible volume method as implemented in SASSI is an unique SSI substructuring approach that provides fast and accurate solutions for linearized SSI systems. Unfortunately, these days there are not many SSI “experts” that realize the real merit of the flexible volume substructuring methodology.

The slow computational speed of the university SASSI is not due to limitation of the flexible volume substructuring, but due to an inefficient IO programing and an old solution algorithm. In the recent ACS SASSI versions, the flexible volume substructuring solution algorithm was completely reprogrammed using new, efficient matrix storage and parallel solution algorithms, and by this, the SSI analysis runtime was cut up to tens of times, or even hundreds of times for the larger-size SSI models. A 80,000 node FE structural model (about 300,000 dofs without soil) was run with ACS SASSI up to 70 Hz cut-off frequency in only several hours using regular 16 GB RAM PCs! The runtime was about 250 times faster than the standard SASSI algorithm runtime on the same PCs. If LS-DYNA or ANSYS are to be used in the time domain for the same SSI model (about 300,000 dofs without soil), probably, it will need at least a week for a linear transient SSI analysis, and possibly, a couple of months of runtime for a nonlinear transient SSI analysis *on the same PCs.*

It should be noted that, in contrast to the time-domain step-by-step integration approaches, for which the dynamic response at any time-step depends on the response at the previous steps, the frequency-domain approaches use independent solutions computed for the set of selected SSI frequencies (responses are then interpolated at all Fourier frequencies). Thus, frequency-domain solutions provide an ideal HPC implementation scalability since frequency domain calculations at each frequency could be independently performed on separate cluster nodes with no MPI intercommunication overhead. Parallel FEA could be implemented at SMP level, as done in ACS SASSI fast-solver option for multiple core processors PCs. This is the most efficient HPC implementation of SSI solution from a scalability point of view.

## ENGINEERING INTERPRETATION OF SSI RESULTS

For nuclear-safety structures, the aspects related to the validation of the SSI model and verification of the SSI results using engineering expert judgement are of paramount importance. From the SSI result verification point of view, the frequency-domain approaches offer much more information than the time-integration approaches. Using frequency domain, various intermediate SSI results, such as structural transfer functions of accelerations and forces, which can be reviewed to indentify FE modeling problems, numerical issues, and gross SSI input mistakes. In the frequency domain, it is easier to identify key features of the SSI response and the key parameters contributionss to the observed behavior. It is also easier to understand the effects of different input uncertainties. The time approaches could hide SSI input or modeling problems.

It should be noted that at the present time of the use of time-integration approaches for performing 3D nonlinear SSI analyses is very limited, to only few, sparse case studies done mainly in national labs, or top universities for pure research purposes, as the ESSI simulator program. There is no well-established, accummulated engineering expertise in nuclear industry on performing 3D nonlinear SSI analysis. Thus, there is an additional, quite imminent risk associated to the use time-integration approaches for design purposes in the next future.

# CONCLUSIONS

1) For the present and next 10-15 years, I believe that the frequency-domain approaches are the best fitted approaches for design-basis SSI analyses for nuclear structures. They are fast, practical and capture the overall SSI effects up to moderate levels of soil nonlinear behavior. A structural design expert should look for performing various sensitivity analyses using numerically efficient SSI models that can help him understand the structure SSI dynamic behavior under possible inputs and alternate modeling scenarious, rather than a single, huge, ultrasophisticated analysis, difficult to check and computationally too intensive to be repeated for a number of times for considering the input and modeling uncertainties. The frequency-domain approaches are ideal from practical point of view since they can be used to perform expedient, practical background sensitivity studies on various SSI input and modeling uncertainties.

2) The hybrid approaches, such as the ACS SASSI-ANSYS integration capability, could be efficiently used to explore the effects of local nonlinearities in the structure and at the foundation-soil interface. Using the hybrid approaches the effects of the foundation uplift and separation from soil could be evaluated up to severe levels of nonlinearities.

3) The lack of field proven reliable nonlinear soil material and foundation-soil interface models, the large analysis runtime costs and the existence of a large number of uncertainties involved in seismic SSI analyses, make the nonlinear, or even linear, time-domain approaches too expensive and hard to justify for design purposes. The time-domain approaches are also less informative for understanding and validating the SSI system dynamic behavior than the frequency approaches.

4) In the present and next 10-15 years, I believe that the nonlinear time-domain approaches could be useful for performing background research studies, especially for large earthquake situations. Time-domain approaches should be used as companion reseach tools to help the engineers to understand the effects of highly nonlinear aspects of the SSI problem. These nonlinear aspects should include the foundation uplift and foundation-soil separation, but also address the complexity of the cracked concrete structural behaviour. The concrete cracking aspect remains an important, open modeling issue that is intensively discussed these days in various engineering meetings, with loud voices, but still not reflected sufficiently well at this time in the engineering codes and regulatory documents.