ACS SASSI Version 3.0

MS Windows Software for Linear and Nonlinear 3D Seismic Soil-Structure Interaction Analysis for Coherent and Incoherent Motions

ACS SASSI is a state-of-the-art, highly specialized finite element computer code for performing *3D nonlinear soil-structure interaction (SSI) analyses* for shallow, embedded, deeply embedded and buried structures under coherent and incoherent earthquake ground motions. The ACS SASSI software is an user-friendly, modern engineering software under MS Windows with an unique suite of SSI engineering capabilities. ACS SASSI uses an automatic management of all data resources, files, directories, and interconnections between different software modules. ACS SASSI can be run interactively for a single SSI model or batch for single and multiple SSI models. ACS SASSI uses an automatic management of all data resources, files, directories, and interfaces between different software modules. ACS SASSI is equipped with two translators for converting inputs of structural finite element models from ANSYS (CBD file) (ANSYS is a trademark of ANSYS Inc.) or original SASSI or SASSI2000 (fixed format input files) to ACS SASSI, and also from ACS SASSI to ANSYS (APDL input file format). The recently developed ACS SASSI parallel fast-solver is tens to hundreds of times faster than the university SASSI2000 standard solver based on the skyline per block algorithm.

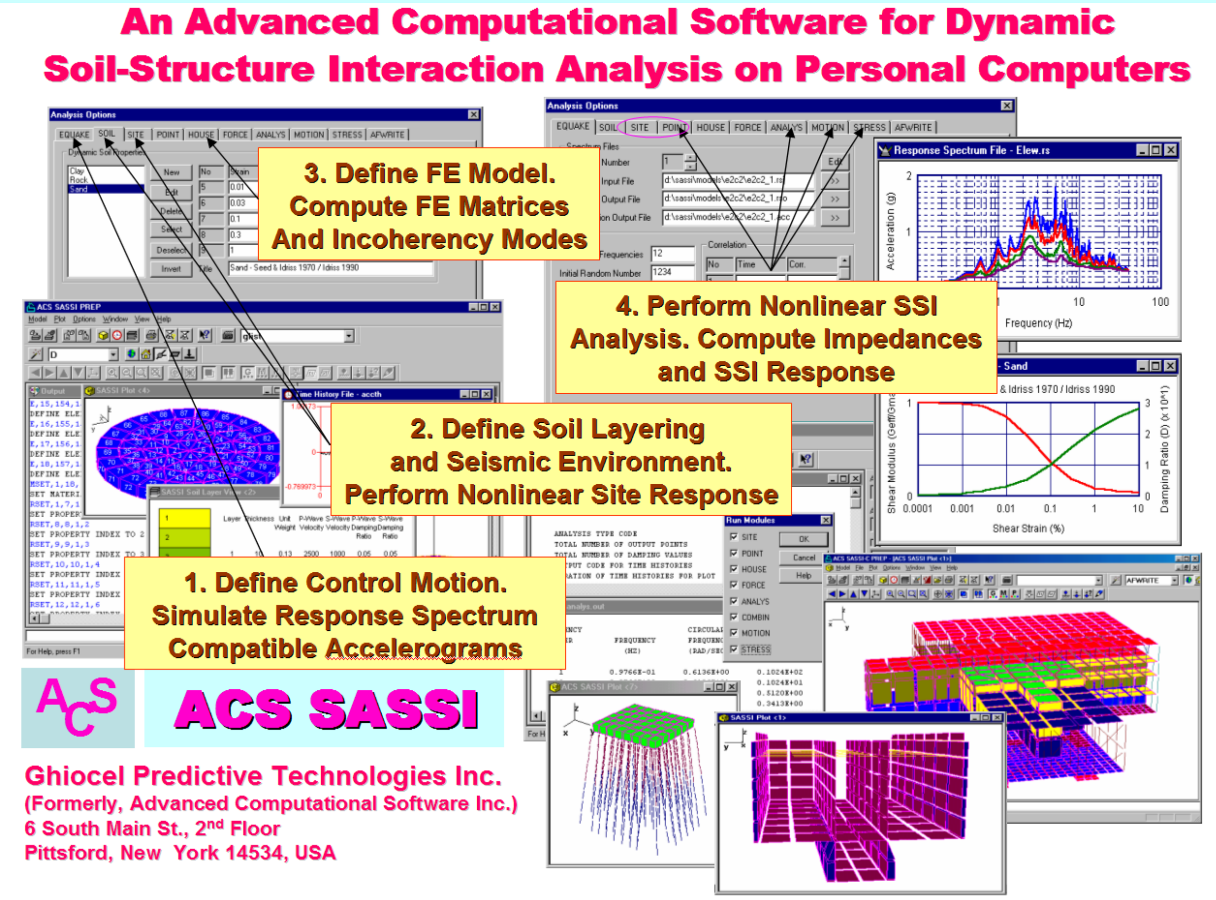

Figure 1 ACS SASSI Graphical User Interface Layout

In ACS SASSI Version 3.0, the size of the SSI problems can be up to a FE model size with 100,000 nodes. The ACS SASSI Version 3.0 has two solution implementations with very different computational speeds. These two “solvers” are: i) the standard solver and ii) the newer, parallel fast-solver. The fast-solver is tens to hundreds of times faster than the standard solver also used by the university SASSI2000 code. The *standard solver* code was tested for complex 3D SSI models with sizes up to 25,000 nodes and up to 5,000 interaction nodes on 16 GB RAM workstations. The *fast-solver* that is much faster was tested for much larger size 3D SSI models with up to 100,000 nodes and 35,000 interaction nodes on 192 GB RAM workstations running under MS Windows 7 or 8.

The ACS SASSI Version 3.0 fast-solver released in July, 2014 is about 3 times faster than the current ACS SASSI Version 2.3.0 fast-solver code for coherent SSI analysis. It does not need any SSI restart analysis for the three-directional seismic input components, since it solves the X, Y and Z input cases in memory without the need of writing and reading the large restart files. The lack of restart analyses for performing SSI analysis for multiple seismic inputs implies that for the incoherent SSI analysis using the stochastic simulation approach, the computational speed is increased by 3 times in comparison with the current version, since the incoherent SSI analyses are solved in a single restart run per incoherent sample for the three input directions, instead of 3 restart runs, one restart run for each input direction. For external forces, the new version can run 9 load cases in a single run with no restarts required. Because of this, the new version is at least 3 times faster for external force cases than the current version. It should be noted that for the moment fast-solver is not applicable to 2D SSI models and symmetric models, but only to 3D SSI models with arbitrary geometries.

It should be noted that the new version includes up to 200 soil layers for SSI modeling. It also extends nonlinear soil behavior idealized by the iterative equivalent-linearization procedure to nonlinear structure behavior based on shear stress-shear strain constitutive models defined by analyst. This nonlinear analysis capability based on equivalent-linearization is applicable at this time only to the solid element groups selected by the user that are defined as nonlinear groups with their appropriate material curves. This new nonlinear structure SSI capability could be used to investigate the seismic SSI effects for the nuclear structures that use highly shear-deformable rubber materials for the seismic isolation.

The ACS SASSI Version 3.0 code includes a number of specialized toolboxes that complement the basic software. These toolboxes are made available to our users in three consecutive releases, in July 2014 April 2015 and July 2015. These toolboxes include a new powerful ACS SASSI- ANSYS interfacing capability to run SSI analysis using directly the ANSYS structural models with no need for conversion to ACS SASSI (Option AA in July), a more efficient parallel fast-solver capability (new Option FS in July) and new probabilistic SSI (Option Pro, in April 2015), RVT-based SSI (Option RVT, in April 2015) and nonlinear structural analysis capability (Option Non, in July 2015). The software will be also upgraded to include Section Cuts capability (April, 2015). All these new capabilities have separate, specific software documentations in addition to the general software documentation including the user manual. Some of these new ACS SASSI Version 3.0 capabilities are related to the ASCE 04--2015 standard and include i) probabilistic SSI analysis (Option Pro), ii) Random Vibration Theory based SSI analysis for deterministic and probabilistic predictions (Option RVT), and iii) an integrated two-step SSI analysis that uses directly the

ANSYS FE structural models in the 1st step for the overall SSI analysis (Option AA), and is also capable of considering basement flexibility, local nonlinear structural behavior and the foundation uplift and sliding in the 2nd step using refined ANSYS FEA stress models (Option A).

The ACS SASSI-ANSYS interfacing capability covers an area that was uncovered up to now for practical engineering applications. This capability provides an advanced two-step SSI approach that can include more refined FEA structural models in the second step, including some local nonlinear material and/or nonlinear geometric effects in the structure or at foundation interface with the soil. There are two ACS SASSI-ANSYS interfacing options: i) Option A or ANSYS, and ii) Option AA or Advanced ANSYS, to be introduced in July, 2014. Demo problems are provided to help users understand how to best use the ACS SASSI-ANSYS interface using Options A and AA. For more information on Options A and AA, please see pages 8-10 of this brochure.

OPTION ANSYS or A: The Option A ACS SASSI-ANSYS interfacing capability is based on an integrated two-step SSI approach in which the 1st step is the overall SSI or SSSI analysis using the ACS SASSI model and the 2nd step is the detailed structural stress analysis using the ANSYS model with the input boundary conditions defined by the SSI responses. The 2nd step can have two distinct functionalities: i) perform structural stress analysis using refined ANSYS FE structural models with detailed meshes, eventually including enhanced element types, non-linear material and plasticity effects, contact and gap elements, and ii) compute seismic soil pressure on basement walls and slabs including soil material plasticity, foundation soil separation and sliding using refined ANSYS FE soil deposit models.

OPTION Advanced ANSYS or AA: The Option AA ACS SASSI-ANSYS integration capability consists of using directly an ANSYS structural model for SSI analysis without the need for converting the structural model to ACS SASSI. The ANSYS structural stiffness, mass and damping matrices are used directly by ACS SASSI for the seismic SSI analysis. Relative displacements, absolute accelerations and response spectra can be fully computed in ACS SASSI. For computing structural stresses, the Option A should be used to transfer the SSI response motions at all time steps or selected critical steps as boundary conditions for ANSYS superstructure model. Automatic commands are used to transfer the data from the ACS SASSI result database to the ANSYS input files.

OPTION Fast-Solver or FS: The *fast-solver* capability includes new SSI modules for the HOUSE and ANALYS modules that replace the baseline software HOUSE and ANALYS modules. The current fast-solver is tens or even hundreds of times faster than the university SASSI2000 standard solver based on the skyline per block algorithm. The fast-solver option is highly recommended for larger size SSI models with up to 100,000 nodes and more than 2,000 interaction nodes. For very small size SSI models, the standard solver competes in speed with the fast-solver. For more information on Option FS, please see pages 10-12 of this brochure.

OPTION Probabilistic or Pro (April, 2015): Probabilistic site response and SSI analysis capabilities were developed in accordance with the recommendations of the new ASCE 04-2015 standard. Both probabilistic site response and probabilistic SSI analysis are based on efficient Latin Hypercube Sampling (LHS) simulation algorithms. Probabilistic SSI analyses are run efficiently in batch mode using new auxiliary modules to generate the input files for probabilistic simulations. For more information on Options Pro, please see pages 12-13 of this brochure.

OPTION Random Vibration Theory or RVT (April, 2015): The RVT-based SSI analysis capability was implemented in accordance with the new ASCE 04-2014 standard recommendations. Option RVT includes several RVT methods. For more information on Option RVT, please see page 13 of this brochure.

OPTION Nonlinear or Non (July, 2015): The nonlinear structural analysis capability is based on the equivalent linearization of the hysteretic material behavior in the complex frequency domain. Both frequency-independent and frequency dependent linearized hysteretic models will be implemented. The new nonlinear structure analysis capability will be limited for the moment to the low-rise concrete shearwall structures (in accordance with the ASCE 43 and 41 recommendations). The complex frequency domain implementation is more robust and hundreds of times faster than traditional nonlinear time-history analysis by direct integration. For more information on Option Non, please see page 13 of this brochure.

Comparing with the standard SASSI methodology as implemented in the university SASSI2000 code, the ACS SASSI incorporates many additional SSI capabilities and specialized features, in addition to its much faster computational speed:

(i) Generation of three-component input acceleration time histories compatible with a given design ground response spectrum with or without time-varying correlation between the components. The user has also the option to generate acceleration histories using the complex Fourier phasing of selected acceleration records (called "seed records" in the ASCE 04-2015 Standard). The software provides baseline correction and computes PSD and peak ground accelerations, velocities and displacements to be used by the analyst to check the US NRC SRP 3.7.1 requirements for the simulated accelerations.

(ii) Evaluation of the seismic motion incoherency and wave passage effects. ACS SASSI Version 3.0 includes state-of-the-art modeling including both isotropic (radial) and anisotropic (directional) incoherency models. Both stochastic and deterministic incoherent SSI approaches could be employed for simple stick models with rigid basemats. These incoherent SSI approaches were validated by EPRI (Short et. Al, 2006, 2007) for stick models with rigid basemats, and accepted by US NRC (ISG-01, May 2008) for application to the new NPP seismic analyses. ACS SASSI includes six incoherent SSI approaches, namely, two simplified deterministic approaches that are the AS and SRSS approaches benchmarked by EPRI (Short et al., 2007), three other alternate deterministic approaches, and a rigorous stochastic simulation approach that is called "Simulation Mean" approach included in the 2006-2007 EPRI validation studies. There are also six plane-wave incoherency models incorporated into the code: the Luco-Wong model, 1986 (theoretical, unvalidated model), and five Abrahamson models (empirical, isotropic or anisotropic, based on the statistical dense array records). The Abrahamson models include the coherency models published in 1993, 2005 (all sites, surface foundations), 2006 (all sites, embedded foundations), 2007a (rock sites, all foundations) and 2007b (soil sites, surface foundations).

The new version includes directional or anisotropic Abrahamson coherency models in addition to the currently implemented isotropic or radial Abrahamson coherency models. Also, it includes user-defined coherence functions that can be different in two orthogonal, principal horizontal directions. The user-defined plane-wave coherency models could be useful for particular sites for which more detailed seismological information is available, or for sensitivity studies.

For the SSI applications with elastic foundation FE models, only the stochastic simulation approach should be used. The AS and SRSS deterministic approaches are simplified incoherent SSI approaches that have only a limited application to rigid basemat SSI models, as validated by EPRI. Thus, the deterministic approaches are not directly applicable to elastic foundation models. The SRSS approach requires a SSI restart analysis for each incoherent mode. The SRSS approach is also difficult to apply since it has no convergence criteria for the required number of the incoherent spatial modes. For flexible foundations, the number of required incoherent spatial modes could be very large, in order of several tens or even hundreds on a case-by-case basis that could make SRSS impractical for elastic foundation problems. The SRSS approaches were implemented in ACS SASSI for benchmarking purposes, since this approach was validated by EPRI for stick models, rather than for their practicality. It should be noted that the SRSS approach could provide incoherent responses that are overly conservative in the mid-frequency range, sometime even much higher than coherent responses, and unconservative in the high-frequency range.

(iii) Nonlinear hysteretic soil behavior is included in seismic SSI analysis using the Seed-Idriss iterative equivalent linear procedure for both the global (due to wave propagation in free-field) and the local soil nonlinearity (due to SSI effects). The local soil nonlinear behavior could be included using near-field soil elements. For the SSI iterations, the ACS SASSI code uses a fast SSI reanalysis (or restart) solution that uses the already computed far-field soil impedance matrix available from the SSI initiation run. This reduces the run time per SSI iteration by a factor of 5 to 20 times depending of the foundation embedment size.

(iv) Fast computation of global, "*unconstrained"* soil foundation impedances for arbitrary shaped shallow, embedded or buried foundations, i.e. computing the global frequency dependent soil foundation lumped parameters, stiffness and damping (including both the hysteretic and radiation energy loss). These global impedances are "unconstrained" impedances, so that do not include the effects of foundation stiffness, but only soil stiffness. For surface foundations under vertically propagating waves, these "unconstrained" impedances are identical with the rigid foundation impedances. Lumped, global foundation complex soil impedance function matrix (for rigid body motion) with 6x6 size, including all coupling terms, could be extracted for a selected foundation reference point. It should be understood that these global lumped, "unconstrained" impedances cannot be used directly in a 2nd step analysis for the FE models with elastic foundations. Rather than the global, lumped soil impedances, the distributed soil impedances that can be extracted from output data files for each frequency of interest, can be used to generate the spring-dashpot elements distributed under the elastic foundations.

(v) The nonuniform or multiple seismic input motion option includes the capability to consider variable amplitude seismic input motions. The nonuniform motion input is applicable to continuous foundations assuming that the free-field motion complex amplitude varies in the horizontal plane after specific frequency dependent spectral patterns. These patterns are described by user by complex amplification factors at different borehole soil column locations computed with respect to the reference amplitude motion. The nonuniform motion assumption could be combined with motion incoherency and wave passage to create more realistic seismic environments. The multiple support excitation option assume the existence of discrete, isolated foundations, such as bridge piers or multiple neighboring building foundations in a nuclear facility. In the new version, the differences between multiple input motions can be completely defined by nodal input complex amplitude transfer function rather than by a simple real amplitude scale factor as in the current version.

(vi) A new interpolation scheme for the complex responses was implemented. The new interpolation scheme that uses bicubic splines is recommended for complex FE models under incoherent seismic inputs. The bicubic spline interpolation should be applied only if the number of SSI frequencies is sufficiently large, so that spectral peaks are not clipped by the smooth spline interpolation. For such cases, when number of frequencies is sufficiently large, the bicubic spline interpolation provides most accurate results for incoherent analysis since does not create any spurious peaks or valleys.

Thus, the new ACS SASSI Version 3.0 includes seven options for the interpolation schemes, 0 to 6, that are implemented available for computing accurate nodal acceleration and element stress complex transfer function (TF) solutions. These interpolation schemes were implemented for both the structural motions and the stresses. Different interpolation techniques could perform differently on a case-by-case basis, especially for highly complex FE models with coupled responses. The various interpolation options that are available in the code provide to structural analyst a set of powerful tools for identifying and avoiding the occurrences of spurious spectral peaks in the computed transfer functions of structural motions and stresses. The first six options implemented include the original SASSI 1982 scheme that uses a non-overlapping moving window, the SASSI2000 scheme that uses a weighted average moving window, and four new interpolation schemes including two non-overlapping window schemes with different shifts and two average overlapping moving window schemes with different numbers of sliding windows. To check the interpolation accuracy, convenient comparative plots of the computed TFs versus the interpolated TFs can be easily obtained using the PREP module graphics.

(vii) The new Fast Flexible Volume (FFV) method provides accurate and numerically efficient SSI analysis solutions for deeply embedded structures (DES) such as small modular reactors (SMRs). The FFV method in addition to the interaction nodes defined at the outer surface of excavation volume includes interaction nodes defined by internal node layers within excavation volume. The user can automatically generate the interaction nodes for the FFV method. The FFV method speeds up the SSI analysis of deeply embedded structures by tens of times faster than the traditional, reference FM method.

(vii) Automatic selection of additional SSI calculation frequencies that are required to improve the accuracy of interpolated TF that is applicable to both node acceleration/displacement TFs and element stress TFs. This is an important practical capability, especially for larger size FE model applications. We believe that this capability saves a lot of labor effort and also ensures a better quality of SSI analysis.

(viii) Visualization of complex TF variation patterns within the entire structural model for selected, SSI calculation frequencies (Figure 2). The complex TF patterns are visualized on the structure using colored *vector plot* animations including all three-directional components (red for X, green for Y and blue for Z). The TF amplitude is given by vector length, and the TF phase is given by vector orientation. This capability is extremely useful for checking the correctness of the FE modeling and understanding the structural dynamic behavior.

(ix) Computation and visualization of the amplitude TF or spectral accelerations for a selected damping value at a given SSI calculation frequency for the entire SSI model using either structural deformed shape or *bubble plots* (Figure 3). The deformed shape plots are animated structural plots with a controlled movie frame speed, so that they can be also viewed as static plots. For selected resonant frequencies, the spectral amplitudes or the ZPA values could be plotted as a deformed shape plot.

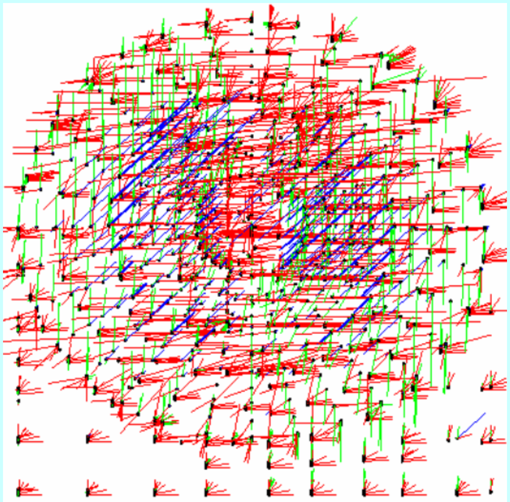

Figure 2: TF Vector Plots at Given Frequency

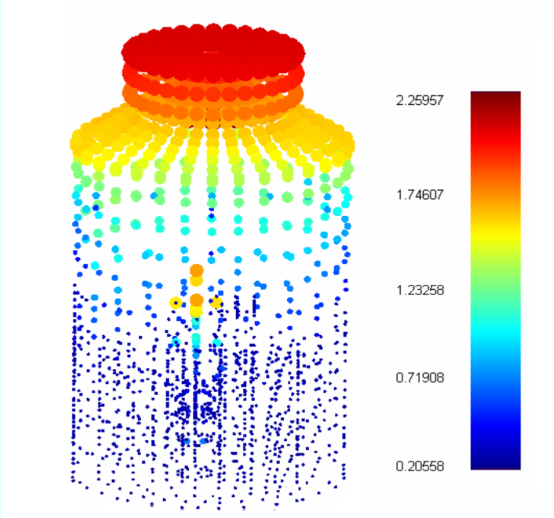

Figure 3: Spectral Acceleration at Given Frequency

(x) Computation and visualization of structural acceleration and relative displacement time histories using *structural deformed shape plots* (Figure 4). The deformed shape plots can be static structural plots for selected times, or maximum values, or structural animations of the SSI response variation in time during the earthquake action.

(xi) Computation and *contour plotting of the average nodal seismic stresses* (for all six components in global coordinates) in the entire structure, or for selected parts of the structure based on the computed element center stresses for the SHELL and SOLID elements. Both maximum and time-varying values of nodal stresses are computed and available for plotting. The approximation is based on the assumption that element center and node stresses are equal (no shape function extrapolation is included). For sufficiently refined finite element models this approximation appears reasonable. Contour stress plotting can be either static maximum values or animated time-varying values at selected time frames (automatic frame selection is included). Maximum element center stresses values are also available in a convenient text file format.

(xii) Computation and *contour plotting of seismic soil pressure on foundation walls* using near-field SOLID elements. The nodal pressure is computed based on averaging of adjacent element center pressures. Both maximum and time-varying values of nodal seismic pressures are computed and available for plotting. The analyst can also automatically combine the seismic soil pressures with the static soil bearing pressures and then, plot the resultant soil pressure of foundation walls and mat. Contour seismic soil pressure plotting can be either static contour plots of maximum values (Figure 5) or animated contour plots of time-varying values at selected time frames (an automatic frame selection capability is included).

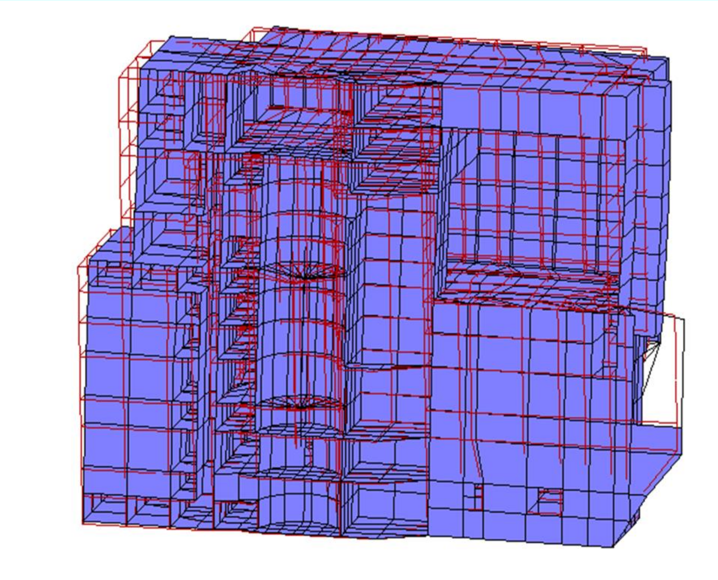

Figure 4: Relative Displacement Deformed Shape

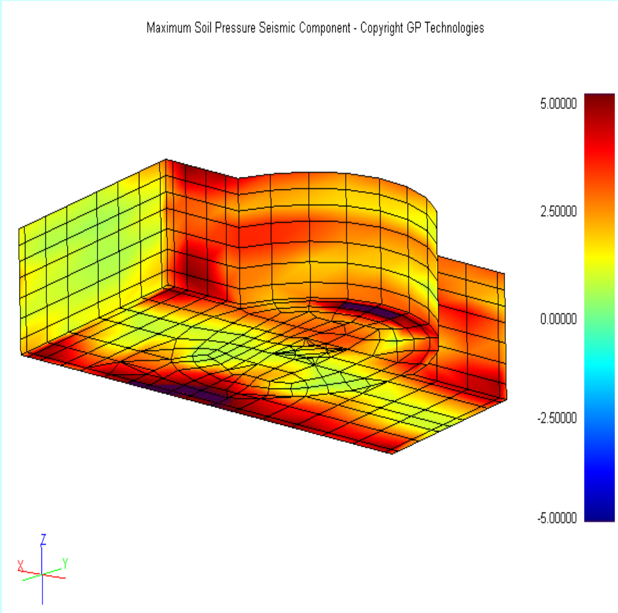

Figure 5: Maximum Seismic Soil Pressure for X-Input

(xiii) Post SSI run calculations for superposition of the co-directional SSI effects in terms of acceleration, displacement of stress time-histories and in-structure response spectra. For time histories both the algebraic summation and subtraction is available. For in-structure response spectra i) the weighted linear combination and ii) the square-root of sum of square (SRSS) combination are implemented. The analyst can also compute the average in-structure response spectra (ISRS) from multiple spectral curves. These post-processor calculations can be done interactive or batch.

(xiv) Post SSI calculations can be performed for the SRSS superposition of the co-directional effects from X, Y and Z input runs, for computing the in-structure response spectra (ISRS) maximum structural stresses, forces and moments, and/or the maximum seismic soil pressure on walls and mat with or without including the soil static bearing pressure component. These quick post SSI calculations can be done both interactive and batch.

ACS SASSI-ANSYS Integration Options A and AA:

The ACS SASSI-ANSYS SSI integration capabilities are additional options that cover an area that was uncovered up to now for SSI analysis. Using the Option A two-step approach, the user can do much more accurate SSI stress analyses using refined FE models (Figure 6) and compute seismic soil pressures on deeply embedded walls and basemats including nonlinear soil material and nonlinear geometric effects including foundation sliding and soil separation (Figure 7). Since the FE stress analysis model can be refined at the ANSYS level (for structure and soil submodels) by reducing mesh size, including sophisticated FE types, soil material plasticity, local gaps, the accuracy of computed structural stresses/forces and soil pressures is highly improved.

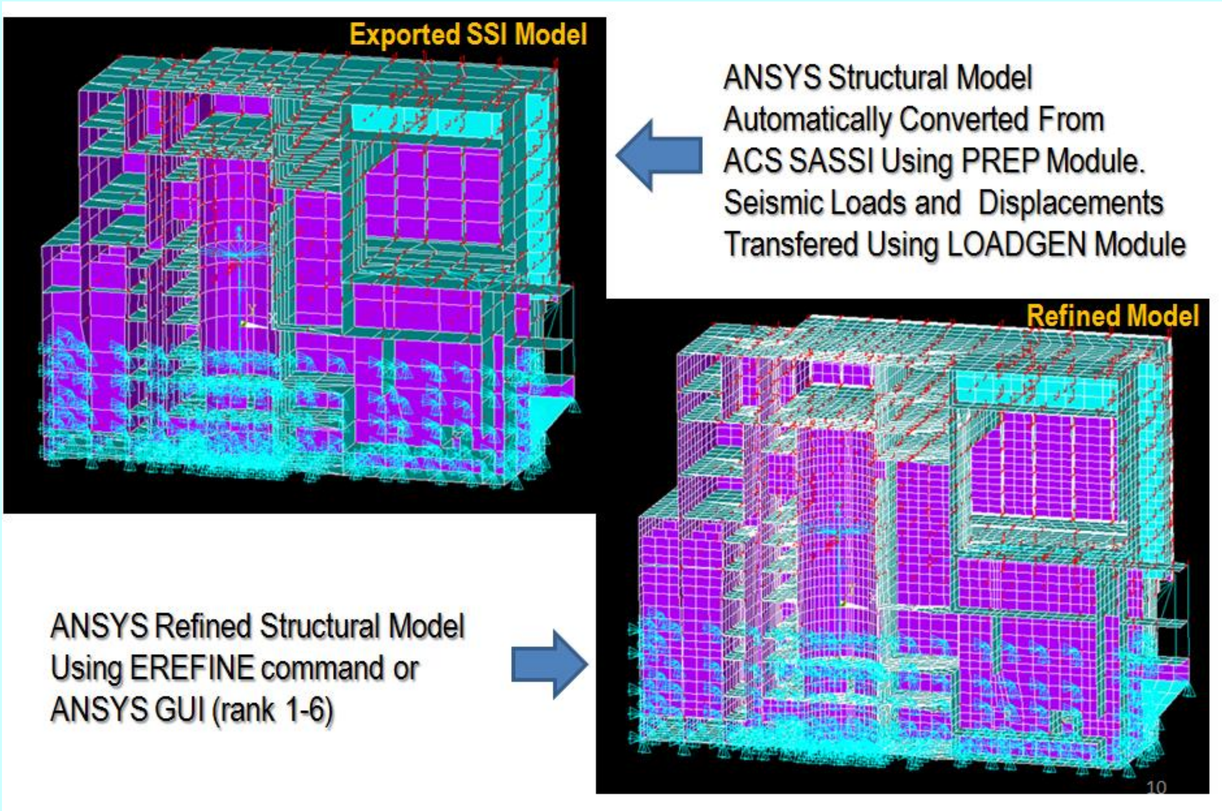

Figure 6 ACS SASSI SSI Model vs. ANSYS Refined Model (ANSYS is a trademark of ANSYS Inc.)

The Option A capabilities include two types of ANSYS analysis in the 2nd step: i) the equivalent static or quasi-static analysis and ii) the dynamic analysis using the time-integration based on the boundary conditions coming from the ACS SASSI SSI analysis in the 1st step.

It should be noted that the SSI equivalent-static stress analysis approaches implemented via integration with ANSYS are significantly more accurate than the traditional seismic stress analysis approach based on static seismic forces computed using the nodal masses and ZPA values. For high-frequency seismic inputs, the traditional static ZPA-based method becomes totally inconsistent since only the high-order structural models are significantly excited. For the user convenience, we also implemented the traditional ZPA-based approach.

The ACS SASSI-ANSYS interface is launched from the ACS SASSI MAIN module, and is fully automatic and very simple to use. It reduces enormously the analyst's labor effort for computing accurate structural stress/forces and soil pressures on foundation walls and mats. Using the ACS SASSI to ANSYS model converters, the analyst could perform quick ANSYS modal analysis of the automatically converted ACS SASSI structural model. These ANALYSIS modal analyses are always required to ensure that the cumulative modal mass contribution up to the SSI cut-off frequency is at least 90 percents.

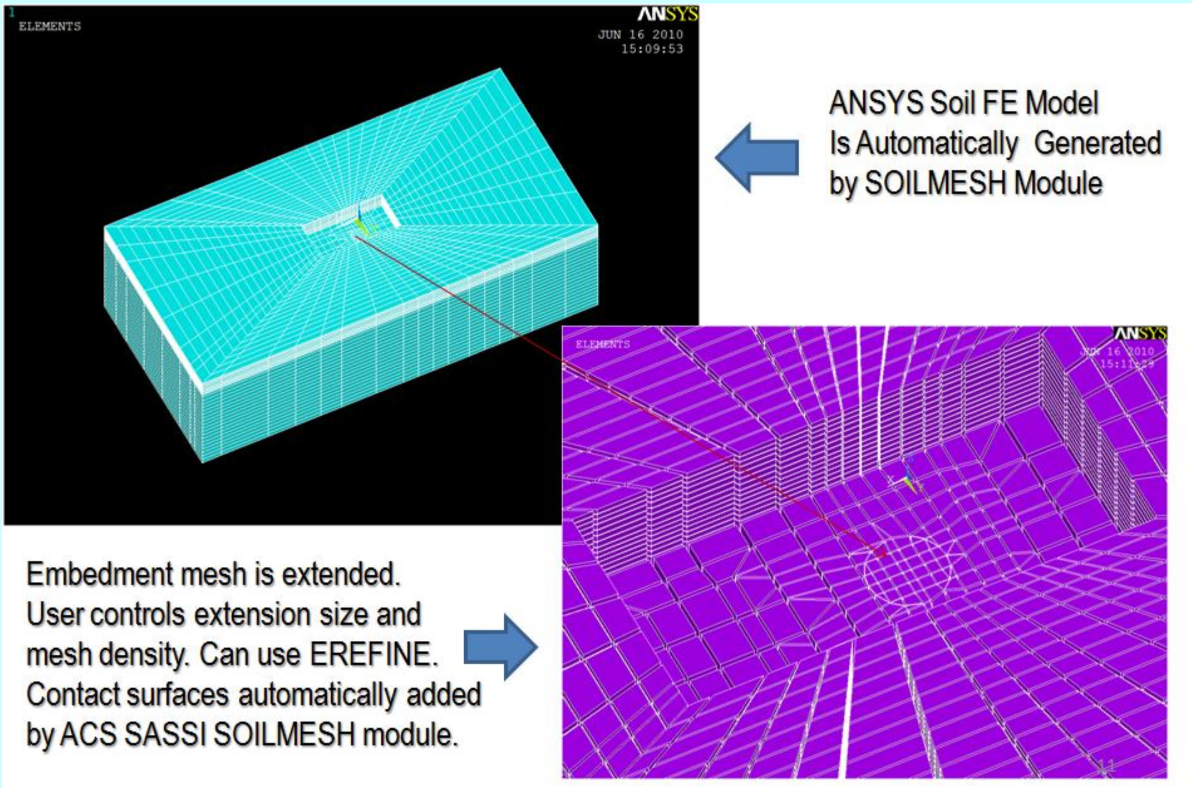

Figure 7 Surrounding Soil ANSYS Model Generated by ACS SASSI SOILMESH Module

The new Option AA SSI analysis capability consists of a new ACS SASSI-ANSYS interface that permits to use the ANSYS structural model directly for the SSI analysis without the need of converting the ANSYS structural model to the ACS SASSI model. This new capability uses directly the ANSYS structural model matrices, stiffness, mass and damping, for the SSI analysis. For Option AA new HOUSE module was developed that reads the ANSYS structure model matrices instead of forming the ACS SASSI model matrices. The Option AA ANSYS model could include the following element types: i) SOLID element types, ii) SOLID45, SOLID185, and SOILD186, iii) SHELL element types: SHELL63, SHELL181, v) BEAM element types: BEAM44, BEAM188, and BEAM189, v) PIPE element types: PIPE288, a, vi) COMBIN element types: COMBIN14, vii) Couple nodes, viii) Constrained equations and ix) Structural multipoint constraint element types: MPC184: Rigid Link and/or Rigid Beam.

Fast-Solver Option:

The fast-solver uses compact matrix storage formats and fast parallel numerical algorithms based on the ten years research experience on efficient parallel FEA solutions under DOD research projects. It provides much faster solutions that are tens and hundreds of times faster than the standard SASSI solver, being much faster for larger-size SSI problems that include hundreds of thousands of equations. The larger the SSI model is, the much faster the new fast-solver is in comparison with the standard SASSI solver based on the skyline per block algorithm. The required hard-drive storage by the fast-solver version for the SSI initiation runs is only a small fraction of that required by the standard SASSI code versions. For large-size SSI models, this reduction of the required hard-drive space could of hundreds of times.

In comparison with the current version fast-solver that includes parallel algorithms for the soil impedance and the SSI solution calculations, the new version fast-solver includes new parallel algorithms for the assembly of overall SSI system dynamic stiffness matrix. The parallelization speeded up about ten times for the overall SSI system assembly step. In addition, we reprogrammed the impedance calculations using a new matrix partitioning algorithm that save 30-40% of the impedance calculation runtime, and we also eliminate some writing and reading of files on the hard-drive for the restart analyses that saves another 40% of the SSI solution runtime. Thus, for a full SSI analysis for three input directions, X, Y and Z, the overall speed up factor for the new version fast-solver is about 3 times in comparison with the previous version fast-solver.

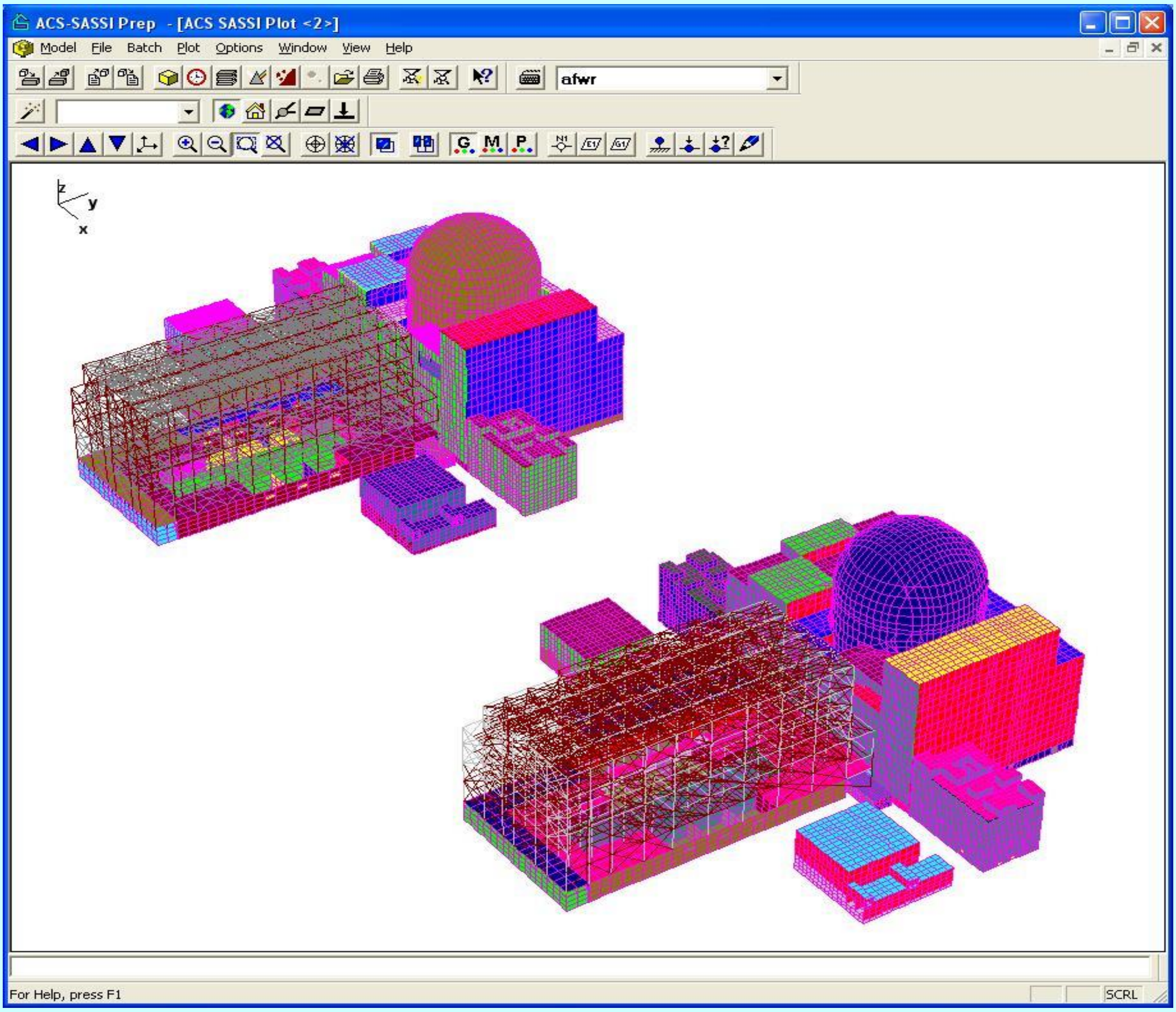

Figure 8 Generic Standard Plant SSSI Model Including 2 Units

The new ACS SASSI fast-solver has been validated for a good number of large size surface and embedded SSI models up to 100,000 nodes. In the validation tests we included complex SSI models such as a generic standard plant SSSI model with 2 units, as shown in Figure 8, including 12 nuclear building FE models, with a total of about 85,000 nodes and 8,000 SSI interaction nodes. This SSSI model was run using the "Fast-Solver Option" modules on a simple, regular Windows 7 PC with 16 GB RAM and IC-7 quad-processor in only 60 minutes/frequency for the initiation SSI run for X input and only 10 minutes/frequency for the restart SSI runs for Y and Z inputs. The same SSI problem is practically not runnable on the same PC, i.e. about 250-300 times slower, using the university SASSI2000 V1 code based on the standard skyline per block algorithm.

On MS Windows PCs with 16 GB RAM, SSI problems with sizes up to 100,000 nodes including up to 8,000 interaction nodes can be run efficiently with the fast-solver using the in-core SSI solution algorithm. For the SSI problems including larger-size models with more than 80,000 nodes and 10,000-20,000 interaction nodes, MS Windows PCs with RAM ranging from 64 GB up to 192 GB are recommended. For very large-size SSI problems with more than 25,000 interaction nodes, MS Windows 8 PCs with up to 512 GB RAM are recommended..

The ACS SASSI fast-solver option is currently applicable o 3D SSI models with no symmetry conditions. The coming soon upgrade (April, 2015) will make fast-solver applicable also to 2D models and quarter or half-models.

The ACS SASSI NQA fast-solver code version has some unique features for complex SSI model checking. The fast-solver code automatically checks the SSI solution based on the computed complex acceleration transfer functions (ATF) as follows:

Zero-Frequency Checking: For the 1st frequency (it should be the frequency number equal to unity), the fast-solver ANALYS module checks the ATF amplitudes for all the translation dofs in the principal direction. This SSI model checking is applied to coherent SSI analysis. If the computed ATF amplitudes vary more than 5% from unity, then a warning message is displayed and also printed in the ANALYS output. A list of the equations for which the ATF amplitude values deviate from 1.00 by more than 5% is provided. Node number dofs can be identified using the node-equation mapping scheme available in the HOUSE output. In these cases, the SSI model should be carefully revised by the user.

All Frequency Checking: For all the selected SSI frequencies, the fast-solver ANALYS module code checks the ATF amplitudes for abnormally large values. These are most likely due to inconsistent FE modeling, or SSI analysis input errors. Large ATF amplitudes for translation dofs could also occur if the SSI model is numerically overly sensitive, slightly unstable due to inconsistent FE modeling. If the ATF amplitudes for translation dofs exceed an abnormally high threshold, then the frequency is automatically deleted from the SSI results in FILE8. This ATF amplitude checking is applied to both coherent and incoherent SSI analyses.

Probabilistic SSI Analysis Option:

The new ACS SASSI probabilistic SSI analysis capability called Option Pro includes approaches recommended by the ASCE 04-2015 standard in Section 5.5 entitled “Probabilistic SSI Analysis”. The probabilistic SSI analysis shall be performed by a simulation approach, most efficiently using the Latin Hypercube Sampling (LHS). Parameters significant to the seismic response shall be treated as correlated random variables. These random parameters include the structure stiffness and damping, the soil/rock layering stiffness and damping, and the seismic input motion amplitude and spectral shape.

The ACS SASSI probabilistic SSI analysis uses the LHS simulation for simulating seismic inputs with spectral amplitude and shape random variations, soil profiles with spatially correlated random layer properties, and effective structural stiffness and damping with random variations that are conditional to the stress levels in structure. The effective structural stiffness and damping variable can be defined differently for various parts of the structure based on the stress levels achieved in those structure parts.

For seismic input probabilistic modeling, two options are available: i) Method 1: deterministic spectral amplitude shape multiplied by a random factor, or ii) Method 2: random spectral amplitude shape based on the soil site response spectral amplification statistics. For the soil profiles, the Vs and Damping profile simulations can include both the layer property spatial correlations with depth and the physical dependence between soil layer Vs and Damping values. For structure stiffness and damping variations, simulated values are defined per each element group including potential spatial correlation between these variables in different parts of the structure. The statistical functional dependence between the stiffness degradation and damping variables is considered either by a negative correlation coefficient, or more rigorously by a nonlinear statistical function defined based on experimental evidence.

Random Vibration Theory (RVT) SSI Analysis Option:

The Random Vibration Theory (RVT) SSI analysis called Option RVT uses the analytical relationship between the power spectral density functions (PSD) and the response spectra (RS). The advantage of RVT is its simplicity, since it does not need to use acceleration time histories. The RVT SSI analysis capability can be used for both deterministic and probabilistic SSI analyses. To compute RS from PSD, the maximum of the stochastic response is determined by solving the “first-passage problem” for Gaussian processes. The “first passage problem” consists of computing the maximum value of the stochastic response for a given motion duration, T. The motion duration T should correspond to the stationary, intense part of the motion that can be defined as the time for the accumulated energy of the input motion to increase from 5% to 75% of its total energy (Arias Intensity). Three different analytical formulations are used to solve the “first-passage” problem and compute SSI extreme response: i) *MK-UK Approach*: Uses Maharaj Kaul and Unruh-Kana formulations for computing SSI maximum response given the non-exceedance probability, *P*, *ii) AD Approach*: Uses Alan Davenport formulation (AD) for the maximum response statistical peak factors and *iii) AD-DK Approach:* Uses Alan Davenport formulation including Der Kiureghian’s correction for the signal frequency content for maximum response statistical peak factors.

Nonlinear Structure SSI Analysis Option:

The new Option Non capability is related to ASCE 43-2005 recommendations for seismic analyses beyond the design level earthquake. The nonlinear structure SSI analysis approach can be used to perform fast and accurate nonlinear SSI analyses, including sophisticated nonlinear hysteretic models, at a small fraction of the runtime of a time domain nonlinear SSI analysis. In addition, the complex frequency nonlinear SSI approach is much more stable and robust than the time domain nonlinear SSI approaches.

The Option Non capability extends the application of the equivalent-linear approach to the reinforced concrete cracking behavior for low-rise shearwall systems. The nonlinear concrete shearwall behavior is described by the Chen-Mertz hysteretic model that was used in a number of US DOE and ASCE 43-2005 standard background studies in the last 15 years.

NQA Version:

The ACS SASSI NQA Version 3.0 has been tested, verified, documented and released under the Ghiocel Predictive Technologies Nuclear Quality Assurance Program which is in compliance with the requirements of 10 CFR50 Appendix B, 10 CFR21, ASME NQA-1, ASME-NQA-1 Addenda Subpart 2.7. The ACS SASSI NQA version comes with a complete set of software documentations that were developed under the quality assurance requirements of the GP Technologies NQA-1 Level Program. The ACS SASSI NQA version documentation includes the user and verification manuals and the V&V computer files for a large set of various seismic V&V problems, including shallow, embedded and buried foundations, rigid and flexible foundations, piles, subjected to various different seismic environments, different surface and body seismic waves, motion incoherency and directional wave passage along a arbitrary horizontal direction, multiple support excitations for isolated foundations, linear or nonlinear SSI analysis.

The ACS SASSI NQA Version 3.0 includes a set of 44 seismic SSI verification problems, some of these including many subproblems. The Verification Manual has about 272 pages. In these V&V problems, the computed SSI results using ACS SASSI are compared against benchmark results based on published analytical solutions or computed using other validated with computer programs, including SHAKE91, SASSI2000 and ANSYS. Each SSI verification problem tests a different capability of the ACS SASSI NQA code. The total number of the V&V computer input files and output files for all the SSI verification problems of the ACS SASSI NQA version is about 5,000 files that require about 300 MB hard drive space.

If you have any question, please contact us at the TPOC's email address dan.ghiocel@ghiocel-tech.com.