# ACS SASSI Version 2.3.0

## 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 extremely 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 can be run interactively for a single SSI model or batch for single and multiple SSI models. 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 (ADPL file).

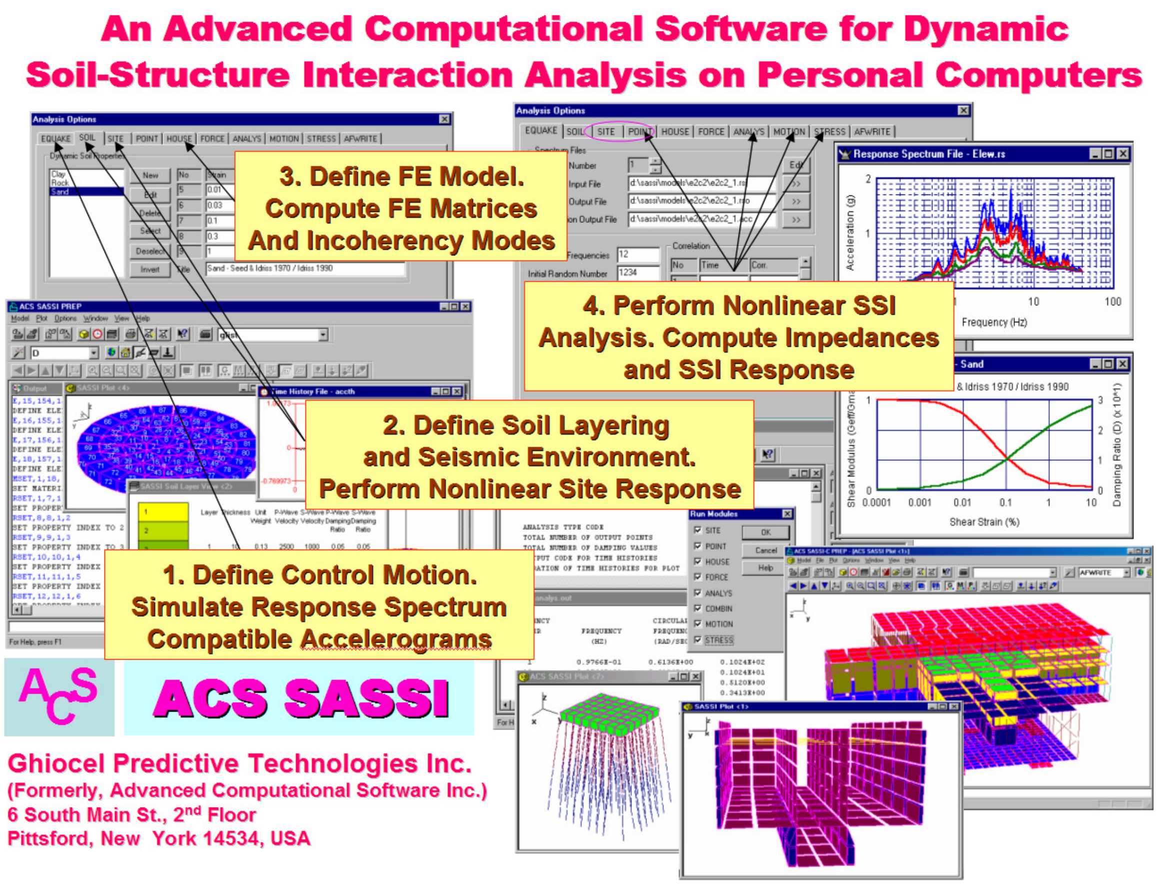



Figure 1 ACS SASSI Graphical User Interface Layout

The 2011 ACS SASSI Version 2.3.0 code also includes two additional capability options that are not included in the *baseline software* the Option ANSYS, or A, and the Option Fast-Solver, or FS. These two additional options can be used integrated with either the Standard version or the NQA version. The additional Option A includes the ACS SASSI-ANSYS integration capability. The ACS SASSI-ANSYS integration capability covers an area that was uncovered up to now for practical engineering applications. The ACS SASSI-ANSYS integration capability has two distinct functionalities: i) perform SSI 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. The ACS SASSI-ANSYS integration capability has a separate user manual. The additional Option FS is the fast-solver code capability. The *fast-solver software* includes new SSI modules that replace baseline software modules. These new modules speed up the SSI analysis by tens or hundreds of times comparing with the baseline software. The fast-solver option is highly recommended for larger SSI models with up to 100,000 nodes and more than 2,000 interaction nodes. The *baseline software* based on the skyline per block solution algorithm becomes inefficient for SSI models with more than 15,000 - 20,000 nodes, or even smaller if they have significant embedment with more than 2,000 interaction nodes. For more information on Options A and FS, please see pages 7-10 of this brochure.

The ACS SASSI code SSI capabilities incorporate many algorithms and specialized features that are not available in any other SSI code:

(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 04-2014 Standard).

(ii) Evaluation of seismic motion incoherency and directional wave passage effects. Both stochastic and deterministic incoherent SSI approaches could be employed. These incoherent SSI approaches were validated by EPRI (Short et. Al, 2006, 2007) and, then, endorsed by US NRC (ISG-01, May 2008) for application to the new NPP seismic analyses. The ACS SASSI code includes six incoherent SSI approaches, namely, two simplified deterministic approaches that are the AS and SRSS approaches benchmarked recently by EPRI (Short et al., 2007), three other deterministic approaches, and a rigorous stochastic simulation approach that is the Simulation Mean approach included in EPRI validation studies (Short et al., 2007). There are six plane-wave incoherency models incorporated in the code: the Luco-Wong model, 1986 (theoretical, anisotropic, but unvalidated model), and five Abrahamson models (empirical, isotropic, based on seismic dense array records), 1993, 2005 (all sites, surface foundations), 2006 (all sites, embedded foundations), 2007a (rock sites, all foundations) and 2007b (soil sites, surface foundations). For SSI applications, but especially for those applications with larger size, flexible foundation SSI models, we recommend the use of stochastic approach that is both accurate and numerically efficient, and also more informative for the analyst since includes the response statistical variation information.

The AS and SRSS deterministic approaches are simplified, approximate incoherent SSI approaches that have limited application. They are recommended only for SSI stick models with rigid or very stiff mat foundations. The AS approach is few times faster than the stochastic approach (the incoherent SSI run time using AS is about equal to the coherent SSI run time). The SRSS approach requires a SSI reanalysis for each incoherent mode. The SRSS approach is more difficult to apply since 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 hundreds that could make SRSS impractical for such problems. The SRSS approaches were implemented in ACS SASSI for benchmarking purposes, since this approach was validated by EPRI, rather than for its practicality.

(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 solution that does not recompute the far-field soil impedance matrix available from the initiation run. This reduces the run time per SSI iteration by a factor of 3 to 30 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.

(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 continuos foundations assuming that the free-field motion amplitude varies in the horizontal plane after specific frequency dependent spectral patterns. These patterns are described by user defined amplification factors computed with respect to the mean motion amplitude at different borehole soil column locations. 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.

(vi) Six interpolation schemes are implemented available for computing accurate nodal acceleration and element stress complex transfer function (TF) solutions. These six 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 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 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. Difficult situations could occur more often for complex SSI flexible foundation models, for coupling responses and incoherent seismic motions. Convenient comparative plotting of the computed TFs versus interpolated TFs can be easily obtained using PREP module.

(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, or all, 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.

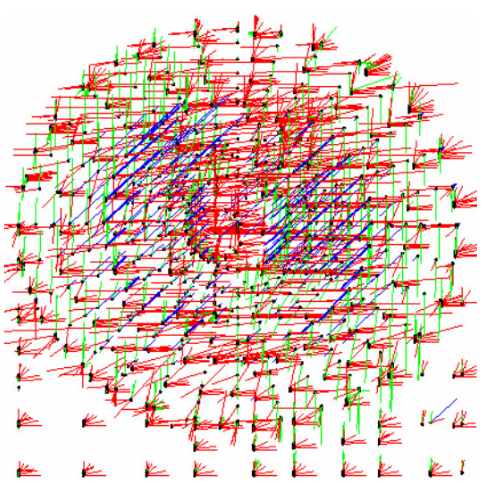


Figure 2: TF Vector Plots at Given Frequency

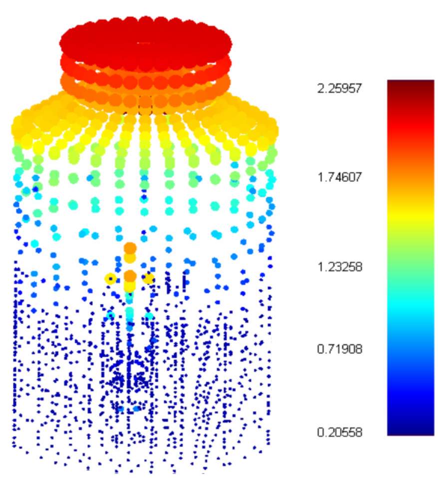


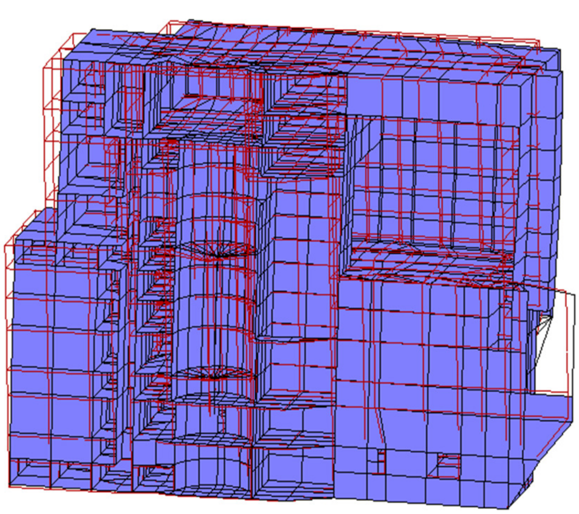

Figure 3: Spectral Acceleration at Given Frequency

(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.

(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 nearfield 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).



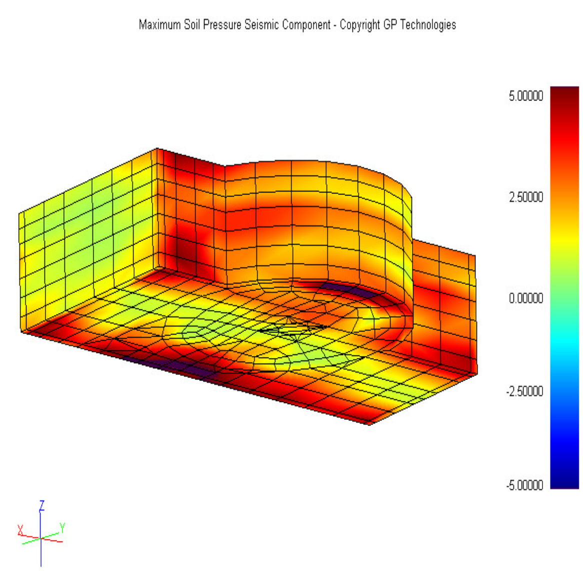


Figure 4: Relative Displacement Deformed Shape

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.

In ACS SASSI Version 2.3.0, the size of the SSI problem to be solved is limited to a FE model size of 100,000 nodes. The ACS SASSI Version 2.3.0 *baseline software* that was verified and validated under our company NAQ-1 program was extensively tested for various complex 3D SSI models with sizes up to 25,000 nodes and up to 5,000 nodes interaction nodes. It should be noted that the ACS SASSI code includes a node numbering optimization algorithm that can improve significantly the computational effort for large-size SSI models with significant embedments. The speed of the ACS SASSI baseline code is about the same with other SASSI-methodology codes, as SASSI2000, that uses the same SSI solution algorithm in the complex frequency domain based on the skyline per block out-of-core algorithm. We warn the users that larger size SSI model runs could consume large hard-drive storage resources up to hundreds of gigabytes for storing the restart database files that are needed for efficient use of the software. The sizes of the produced files depend largely on the mesh refinement of the embedment part, i.e. excavated soil mesh size, and on the number of SSI frequencies. For SSI models with more than 2,000 interaction nodes, we strongly recommend the use of the *fast-solver software* that is available for both Standard and NQA versions. The fast-solver capabilities are described in this brochure at pages 8-10.

The ACS SASSI NQA Version 2.3.0 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 includes a set of 37 seismic SSI verification problems, some of these including many subproblems. The Verification Manual has 235 pages and 235 figures. 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 5,800 files that require about 480 MB hard drive space.

***ACS SASSI-ANSYS Integration Option:***

In addition to the baseline code, we offer the ACS SASSI-ANSYS SSI integration capability that is a additional option of the code ("Option A") that covers an area that was uncovered up to now. 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.

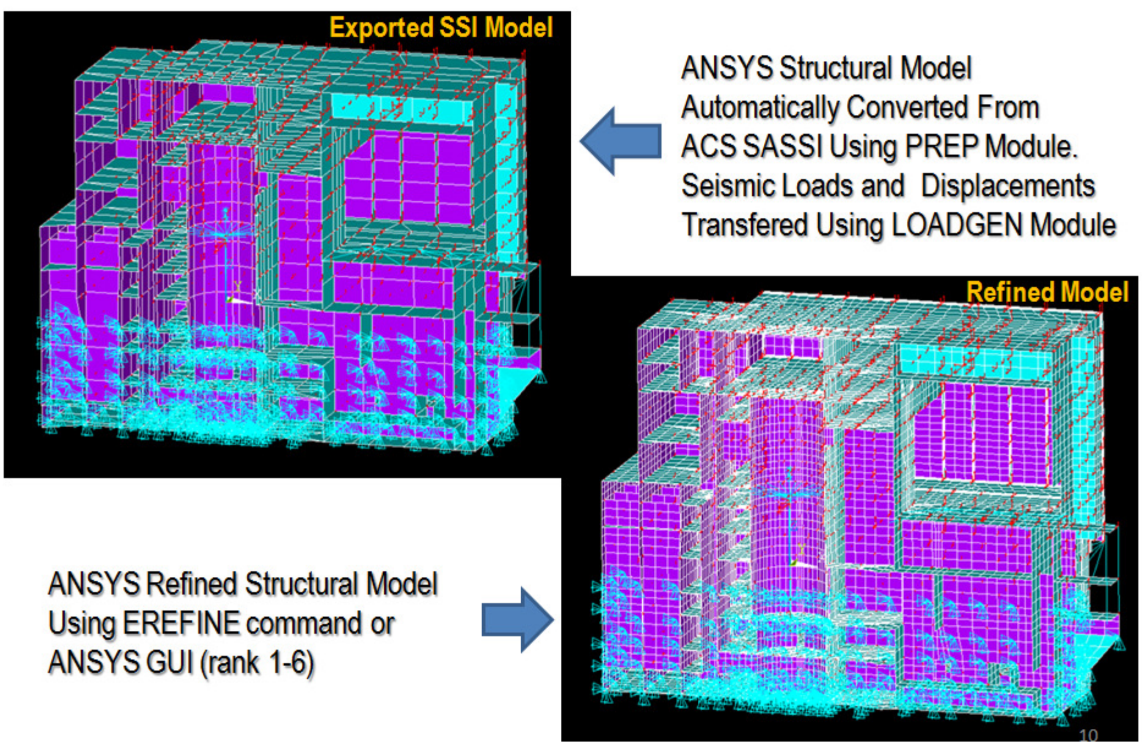



Figure 6 ACS SASSI SSI Model vs. ANSYS Refined Model (ANSYS is a trademark of ANSYS Inc.)

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 lauched 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 analysis are always required to ensure that the cumulative modal mass contribution up to the SSI cut-off frequency is at least 90 percents.

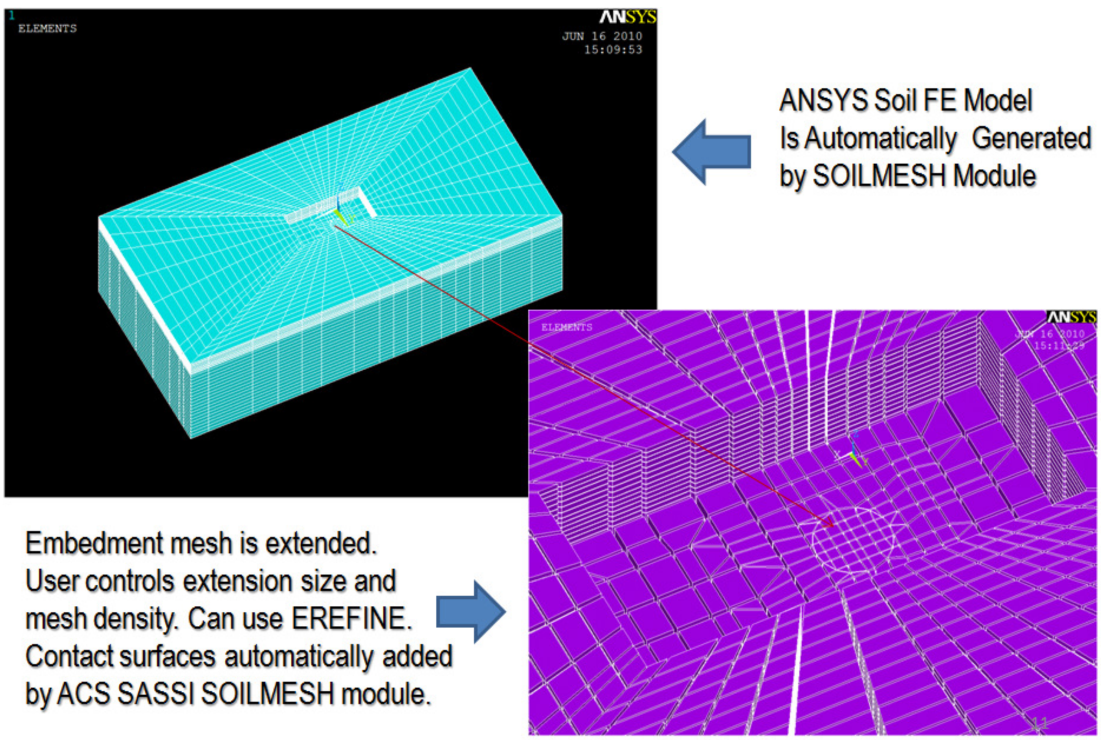



Figure 7 Surrounding Soil ANSYS Model Generated by ACS SASSI SOILMESH Module

The ACS SASSI-ANSYS integration option is included in *the baseline software*.

***Fast-Solver Option:*** The fast-solver code that takes advantage of the MS Windows 64-bit multicore-processor PC architectures. The fast-solver capability is called Option FS or Fast-Solver. 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 reseach projects. The fast-solver code runs under the current ACS SASSI GUI, so that it is perfectly transparent to the users. 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, up to 100,000 nodes or 600,000 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.

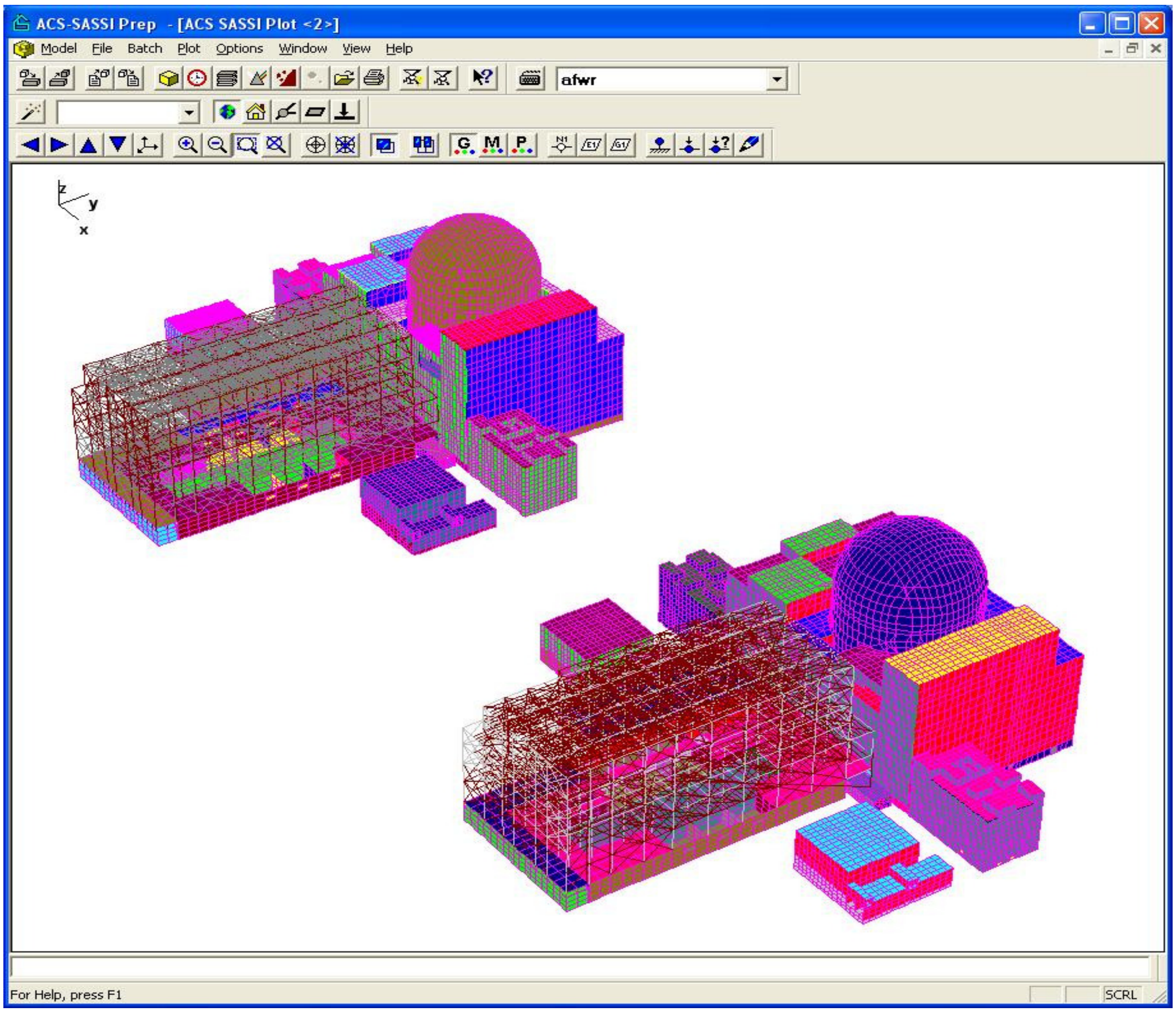



Figure 8 Generic Standard Plant SSSI Model Including 2 Units

We validated the new ACS SASSI solver for a good number of large size surface and embedded SSI models up to 100,000 nodes. The 100,000 node upper bound is imposed by the use of 5 digit fields to define the FEM node numbers. 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 80 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 standard SASSI-methodology solver based on the 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 algoritm. For the SSI problems including larger-size models with more than 80,000 nodes and more than 10,000 interaction nodes, MS Windows PCs with RAM ranging from 64 GB up to 192 GB are recommended. For large-size SSI problems with more than 18,000-22,000 interaction nodes, MS Windows 8 PCs with up to 512 GB RAM are recommended. The ACS SASSI Version 2.3.0 *fast-solver* code has been extensively verified, tested under our company NQA program for various seismic 3D SSI models up to 100,000 nodes including up to 35,000 interaction nodes on a 192 GB RAM PC Workstation running under the MS Windows 7 OS.

The ACS SASSI fast-solver option is currently applicable only to 3D SSI models with no symmetry conditions. Other SSI capabilities applicable to 3D SSI analysis remain the same including the restart analysis option for "new seismic environment" and "new structure" that can used for different seismic input directions and incoherent SSI simulations.

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. For example, when a nodal mass is applied to a free BEAM node with end release for the same degree of freedom, the ATF amplitude can be on the order of thousands instead of unity. 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.

The ACS SASSI "Fast-Solver Option" is offered in both the Standard and the NQA versions. If you have any question, please contact us at the TPOC's email address dan.ghiocel@ghiocel-tech.com.