3D SSI Analysis of Nuclear Islands Including Foundation Uplift Effects Based on JEAC 4601-2015 Recommendations. Part 1: Uplift SSI Analysis Procedure for 3DFEM SSI Models Subjected to Simultaneous Horizontal Seismic Inputs

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Uplift SSI 3DFEM

1. INTRODUCTION

The JEAC 4601 standard recommends two nonlinear uplift approaches applicable to SR models and Pseudo3DFEM (2D FE structural models) based on the base uplift severity: 1) A simplified nonlinear uplift approach based on a nonlinear seismic analysis considering uplift nonlinearity of soil spring, applicable if the base surface contact ratio is in the 65%-75% range, and 2) A refined nonlinear uplift approach based on nonlinear seismic analysis considering vertical motion induced by rocking motion, applicable if the surface contact ratio is in the 50%-65% range. For contact ratios above 75%, the linear SSI analysis results are considered reasonable accurate.

The JEAC 4601 App. 3.6 foundation uplift approaches were implemented in the ACS SASSI software by combining the equivalent-linearization of the overall SSI analysis in complex frequency with the JEAC 4601 nonlinear time-domain uplift analysis occurring at the foundation-soil interface. The new ACS SASSI uplift SSI analysis implementation permits use of refined fully 3DFEM structural models which can be subjected to single or simultaneous X and Y seismic inputs for the uplift SSI analysis.

2. ACS SASSI UPLIFT 3D SSI ANALYSIS PROCEDURE

A two-step SSI analysis procedure is required: 1) An initial 3D SSI analysis, before considering the nonlinear uplift effects, and 2) A final 3D SSI analysis, after considering the nonlinear uplift effects by adjusting the bottom-soil rocking impedances per the JEAC 4601 recommendations.

Figure 1 visually illustrates the key nine computational steps implemented in ACS SASSI for performing the uplift SSI analysis for embedded structures. To make the 3DFEM uplift SSI analysis highly efficient for embedded foundations, the condensed and global excavated soil impedances are computed and used. The SSI analyses include foundation flexibility effects.

The nine computational steps can be executed *automatically* by the user after he prepares the 3DFEM models for structure and excavated soil.

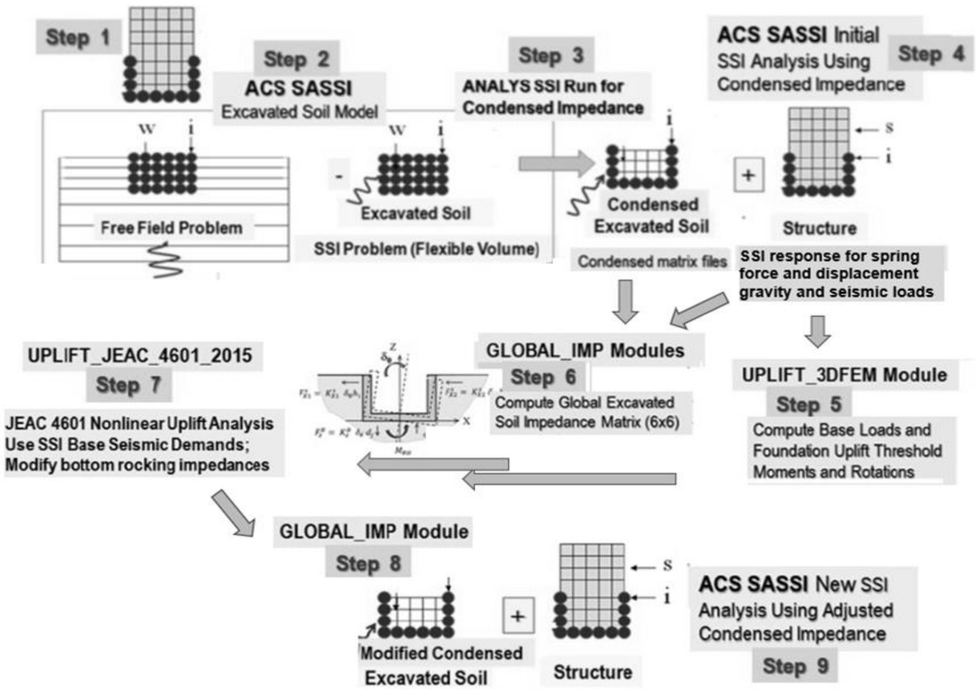

Figure 1 ACS SASSI Option UPLIFT SSI Analysis Implementation per JEAC 4601-2015

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These nine computational steps are described in detail below:

1) Build ACS SASSI Structure model with stiff springs at foundation-soil interface. The stiff springs should connect the basement structural nodes with the interaction nodes defined at the soil layering interfaces for the bottom and lateral surfaces of the excavated soil model.

2) Build ACS SASSI Excavated Soil model mesh-compatible with Structure model.

3) Run the Excavated Soil model SSI analysis using the ANALYS “Condensed Impedance” option to produce the condensed soil impedance matrix.

4) Perform the linear ACS SASSI SSI restart analysis using the condensed soil impedance matrix for X, Y and Z directions, and post-process SSI response for spring force and foundation displacement. The static analysis under the gravity loads should be also post-processed using the Z-direction solution. The acceleration transfer functions at few selected nodes should also be reviewed at this time to identify the dominant SSI frequency for the global rocking modes in the X and Y directions. From this dominant SSI frequency, a subset of frequencies is selected around the dominant SSI frequency to be used for the uplift SSI analysis.

5) Run the UPLIFT_3DFEM module to compute the seismic global time-varying loads and the uplift threshold values of the basemat moments and the rotations based on the foundation bottom spring forces and node vertical displacements. These quantities are computed separately for each of the two horizontal seismic directions, X and Y.

6) Run the GLOBAL_IMP module to compute the global soil impedances for the soil under the foundation basemat (the global soil impedances are split in bottom soil and side soil contributions) for a reduced frequency subset including dominant SSI rocking frequencies identified by analyst in Step 4.

7) Run the UPLIFT_JEAC_4601_2 015 module to compute the foundation contact area and the base motions (translations and rocking motions) including the base uplift vertical displacement effects per the JEAC 4601 Appendix 3.6 recommendations. The end results of this module are the equivalent-linear values for the bottom-soil impedances for the foundation rocking motions in the X and Y directions.

8) Run the GLOBAL_IMP module for the reduced frequency subset used to adjust the distributed soil impedances of the foundation bottom nodes in the Z-direction based on the computed equivalent-linearized values of the bottom-soil global rocking impedances in Step 7. The GLOBAL_IMP module should be run separately for X and Y inputs since the rocking soil impedance modification might be different for the two directions.

9) Perform the final linear ACS SASSI SSI restart analysis for the selected frequency range for the X and Y directions using the newly modified condensed soil impedance matrix to compute and then post-process the SSI responses of interest. There is no need to redo the vertical SSI analysis, since rocking motions are produced by horizontal inputs.

3. 3DFEM vs. SR MODELS

It should be noted that per JEAC 4601 App. 3.6 for SR models the uplift threshold base moments and rocking angle are calculated using simple formula that depend building weight widths and the soil pressure distribution. However, for 3DFEM SSI models there is no direct requirement. Therefore, for 3DFEM in ACS SASSI, the uplift threshold moments for X and Y directions are computed using the no-tension force criterion for the foundation bottom springs for the structure subjected simultaneously to both the gravity loads and the seismic loads.

To be consistent with the JEAC 4601-2015 requirements, the no-tension force criterion is applied separately for each direction, X and Y. Uplift occurs when in the critical bottom spring, seismic tension force is larger than gravity compression force.

The foundation rocking rotation for each principal direction is then obtained by the linear regression of the seismic vertical SSI displacements of the foundation bottom nodes. The uplift threshold rocking rotation corresponds to the uplift threshold moment for each direction.

A case study for an uplift 3D SSI analysis for a nuclear island is shown in Part 2.

4. CONLUDING REMARKS

The JEAC 4601-2015 Section 3.5.5.4 and Appendix 3.6 requirements were implemented using the ACS SASSI 3D SSI methodology applicable to complex 3DFEM models, with or without embedment, including the effects of foundation flexibility and simultaneous horizontal inputs. If the Stick or SR model option is used, then, the threshold moments and rotations are computed based on the JEAC 4601-2015 App.3.6 equations.

5. REFERENCES

1) Nuclear Standard Committee of Japan Electric Association (2016), Technical Code for Aseismic Design of Nuclear Power Plants, Japan Electric Association Code (JEAC 4016-2015)

2) Ghiocel Predictive Technologies, Inc. (2020). ACS SASSI Version 4.1 User Manual for Option UPLIFT, Revision 0, May 31, Rochester, New York, USA

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3D SSI Analysis of Nuclear Islands Including Foundation Uplift Effects Based on JEAC 4601-2015 Recommendations. Part 2: Uplift SSI Analysis Case Study for RB Complex Subjected to Simultaneous Horizontal Seismic Inputs

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Uplift SSI 3DFEM

1. INTRODUCTION

The new ACS SASSI uplift SSI analysis implementation permits use of refined 3DFEM structural models subjected either to single or simultaneous X and Y seismic inputs. The uplift SSI analysis procedure was described in Part 1.

2. NUCLEAR ISLAND CASE STUDY

2.1 3DFEM BASESLAB LOADS AND DEFORMATION

This Part 2 shows the application of the ACS SASSI uplift SSI analysis to a typical RB complex building modeled using a complex 3DFEM with about 40,000 nodes sitting on a uniform deep soil site with Vs = 1,500 fps. For seismic input, the RG1.60 spectrum anchored to a maximum ground acceleration of 1.4g was used. The foundation sizes are 225 ft and 300 ft.

A two-step SSI analysis procedure is applied as described in detail in Part 1, including: 1) An initial 3D SSI analysis, before considering the nonlinear uplift effects, and 2) A final 3D SSI analysis, using adjusted bottom-soil rocking impedances per JEAC 4601 recommendations to include the base uplift effects.

The uplift threshold moments are defined based on the criterion of no-tension force in the foundation bottom springs under gravity and seismic global base loads for each direction as shown in Figure 1. Base flexibility is included. The base loads are computed using the spring forces in X, Y and Z directions

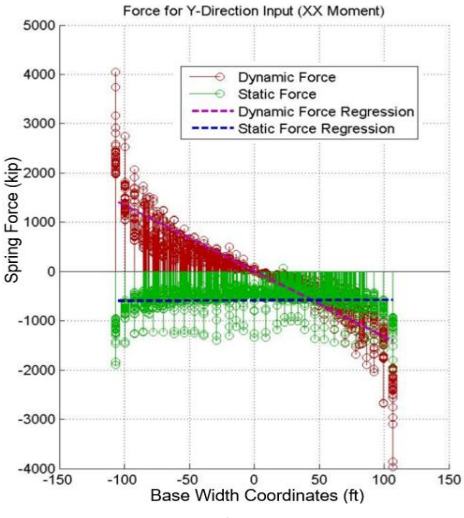

Figure 1. Base Spring Forces for Gravity and Seismic Loads

The rocking rotation is obtained by linear regression of the node vertical displacements. Figure 2 compares the base vertical displacements for the transverse direction versus the linear regression approximation. For each direction, the uplift threshold rocking rotation correspond to the threshold moment.

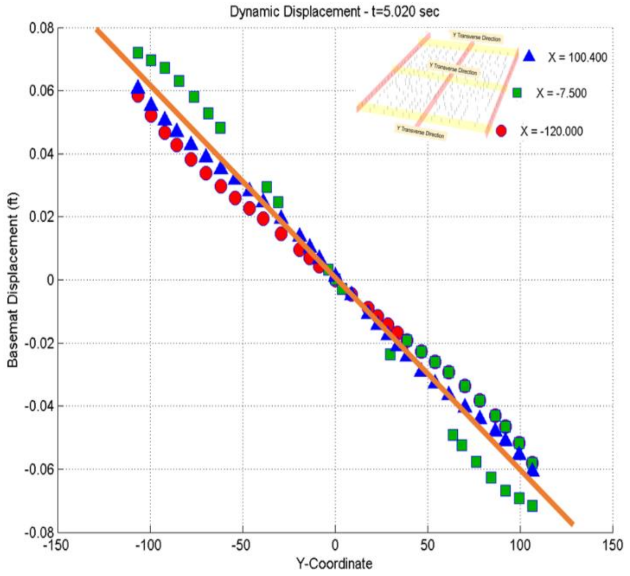

Figure 2. Base Displacements vs. Linear Regression Estimate

2.2 NONLINEAR UPLIFT ANALYSIS PER JEAC 4601

Based on the computed uplift threshold base moments and rotations for each direction, and the seismic base loads computed using the 3DFEM SSI model, the nonlinear uplift analysis is performed in accordance with the JEAC 4601 App. 3.6 requirements. The differential equations of motion of the base are solved using an adaptive time integration scheme.

The seismic motion can be defined either separately for each principal direction or simultaneous for both directions. The consideration of simultaneous seismic inputs for both base principal directions represents an option beyond the current JEAC 4601 requirements. It is assumed that the two principal direction base uplift responses are not coupled, except that the vertical response of the base center is common for both directions at each time step. The soil global impedances for the bottom soil are used in compliance to JEAC 4601 guidelines.

Usually, the base uplift is not directional only, but can be oblique, especially if the difference between the base sizes in the two directions is not too large, as shown in Figure 3 for the investigated RB complex. Figure 4 shows the time-variation of the based contact surface computed separately for each direction and for simultaneous loss of contact. The 7.30 sec. time uplift event is marked by the vertical red line. It can be seen that due to the simultaneous loss of contact in both directions, the overall contact surface value by about 30% smaller, below than 0.40 (that is below the 0.50 accepted by the JEAC 4601-2015).

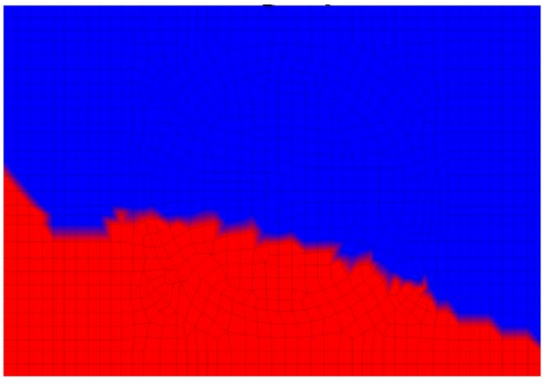

Figure 3 Oblique Base Uplift Area at 7.30 Sec. Time (Red)

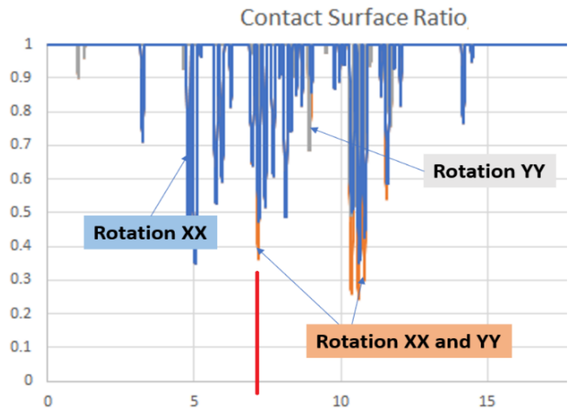

Figure 4 Contact Surface for Each Direction and Simultaneous

The nonlinear base moment-rotation hysteretic curve for the base rocking for transverse direction is shown in Figure 5 (orange). The hysteretic loops indicate significant high nonlinear base rocking behavior. For comparison purposes in the same figure is shown the linear SSI moment-rotation loops (blue) computed for no uplift for the same seismic base loads.

2.3 EQUIVALENT-LINEAR 3D SSI ANALYSIS

Based on the obtained nonlinear moment-rotation hysteretic curves, an equivalent-linear bottom soil rocking stiffness is automatically computed, as shown in Figure 6 (blue). The computed equivalent-linear global rocking stiffness and damping is then backward transmitted to adjust the distributed soil impedance matrix associated to the 3DFEM SSI model.

Figure 7 shows the in-structure response spectra (ISRS) at a high elevation within the RB complex computed for the initial linear SSI (red) analysis and the equivalent-linear SSI analysis including uplift effects (blue). The rocking mode amplification is significant since the base uplift is very large and as a result of this, the bottom soil stiffness and damping are reduced by about 25%. This suggests a seismic load increase, and, therefore, a new uplift SSI analysis is necessary for this increased base load.

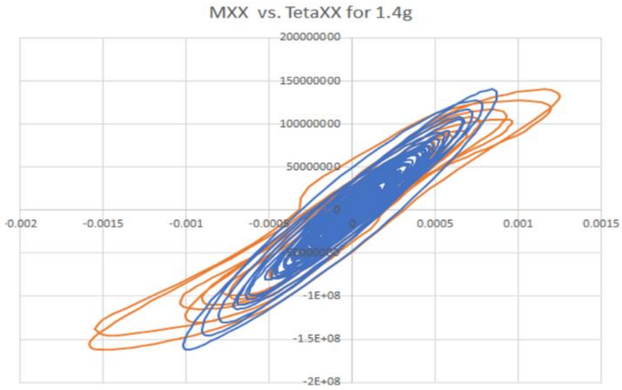

Figure 5 Initial Linear vs. Nonlinear Hysteretic SSI Results

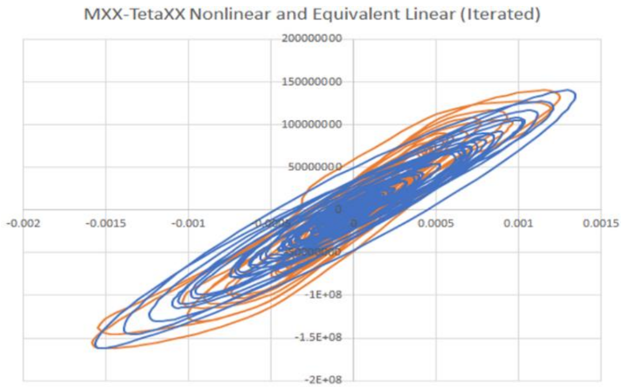

Figure 6 Equivalent-Linear vs. Nonlinear Hysteretic Results

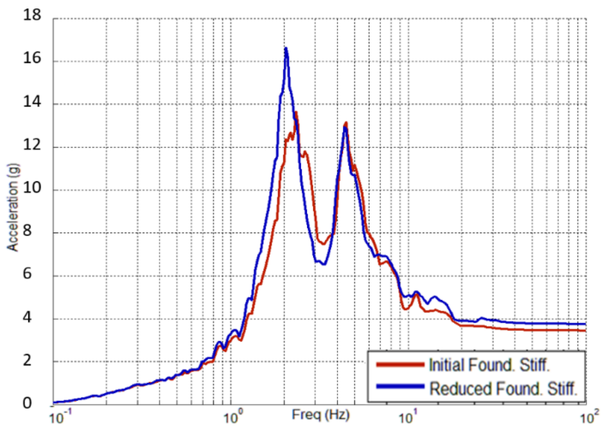

Figure 7 ISRS Computed for Initial and Final SSI Analysis

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