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SEISMIC SSI ANALYSIS OF BUILDING FOUNDATION UPLIFT BASED ON JEAC 4601-2015 RECOMMENDATIONS

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ABSTRACT

The paper illustrates the nonlinear SSI uplift analysis of a building foundation under a severe earthquake motion. The paper describes the uplift SSI analysis methodology based on the Japan JEAC 4601-2015 standard recommendations (JEA, 2015). The JEAC 4601 standard recommends nonlinear uplift approaches applicable to SR (Sway-Rocking) models based on the base uplift severity.

The JEAC 4601 foundation uplift approaches were implemented in the ACS SASSI Option UPLIFT software (GP Technologies, 2021) by combining the equivalent-linearization for the overall SSI analysis in complex frequency with the nonlinear uplift time-domain analysis occurring at the foundation-soil interface. The multi-step analysis procedure applied for the uplift SSI analysis is described in this paper.

In order to check the applicability of the new Option UPLIFT function, a comparison analysis study was performed for the simple building foundation located on the uniform soil condition subject to various levels of input motion. The response obtained by the ACS SASSI 3D FEM model and Stick with basemat shell model were compared with those obtained by the program DYNA2E (CTC Itochu, 2019) which is the nonlinear uplift time-domain analysis program broadly used for the uplift SSI analysis of nuclear facilities in Japan. According to the comparison results, it was confirmed that the new Option UPLIFT function can provide good agreement with the seismic response results obtained by the conventional time-domain analysis program DYNA2E.

INTRODUCTION

When the foundation of a building is uplifted during an earthquake, geometrical nonlinearity due to the uplifting of the foundation must be considered. JEAC 4601−2015 recommends a procedure to evaluate the dynamic seismic response using the nonlinear time-domain analysis method that can take into account such uplift of the foundation based on the base uplift severity as shown in Figure 1.

contact ratio η ≧75%:	Linear seismic response analysis
contact ratio η ≧65%:	Non-linear seismic response analysis considering nonlinearity of uplift on soil rotational spring (See. Figure 2)
contact ratio η ≧50%:	Uplifting nonlinear seismic response analysis considering induced vertical motion (See. Figure 3)
contact ratio η <50%:	Special consideration is required.

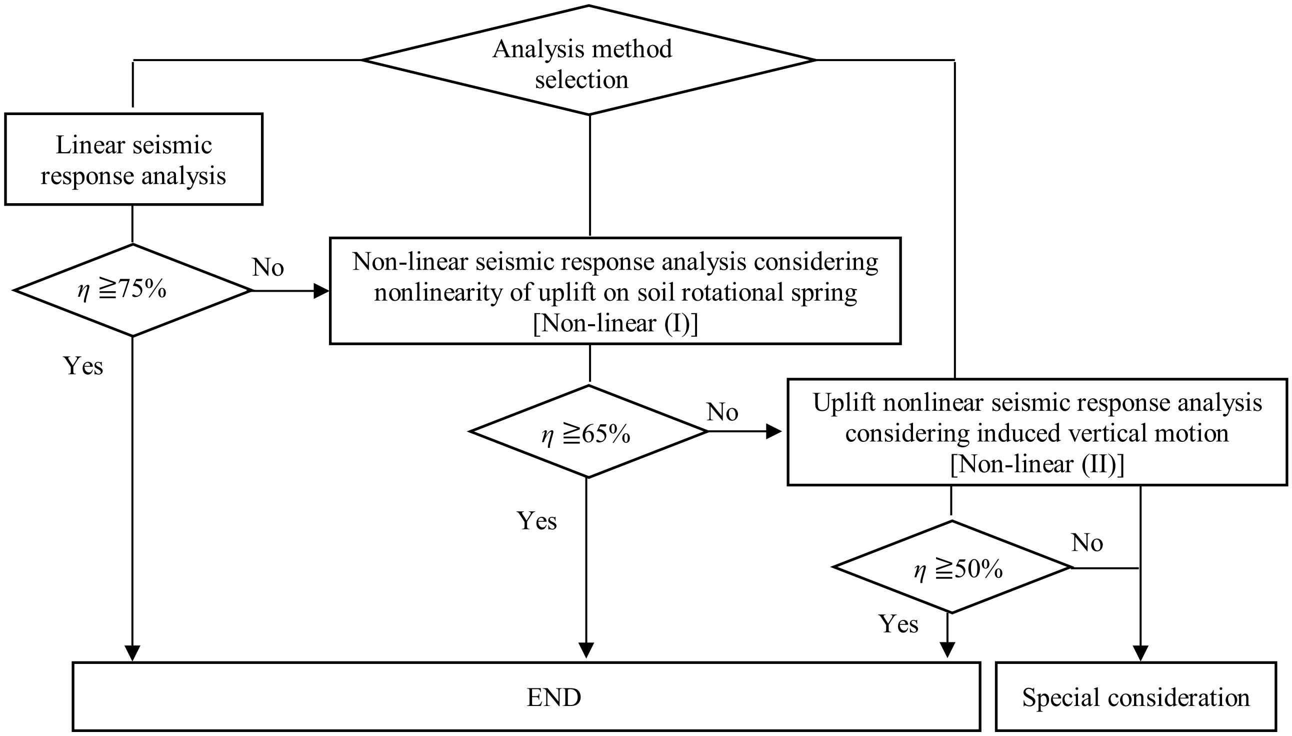
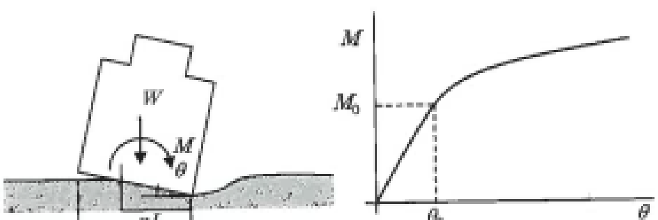


Figure 1. JEAC 4601 Sec 3.5.5.4 Contact Ratio Criteria for Performing Nonlinear Uplift Analysis

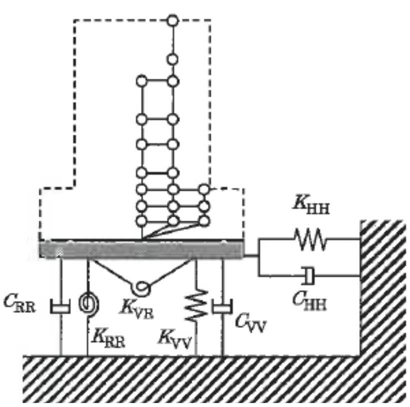


Skeleton curve of foundation rotational spring stiffness

$$\eta = \frac{2\alpha}{\alpha-2}\left(\frac{1}{2}-\frac{M_{\max}}{W\cdot L}\right) \qquad \frac{M}{M_0}=\frac{\alpha}{2}-\frac{\alpha-2}{2}\left(\frac{\theta_0}{\theta}\right)^{\frac{2}{\alpha-2}}$$

$M_{\max}$: Maximum overturning moment from seismic analysis
W: Total weight of buildings L: Basemat width
α: Value depending on the soil reaction force distribution (Triangular 6.0, Rigid plate 4.7)
M_0, θ_0: Uplift threshold moment and rotation

Figure 2 Conceptual Diagram of Foundation Uplifting and M-θ Skeleton Curve.



$$\begin{Bmatrix} P \\ N \\ M \end{Bmatrix} = \begin{bmatrix} K_{HH} & 0 & 0 \\ 0 & K_{VV} & K_{VR} \\ 0 & K_{VR} & K_{RR} \end{bmatrix} \begin{Bmatrix} u_0 \\ w_0 \\ \theta \end{Bmatrix} + \begin{bmatrix} C_{HH} & 0 & 0 \\ 0 & C_{VV} & 0 \\ 0 & 0 & C_{RR} \end{bmatrix} \begin{Bmatrix} \dot{u}_0 \\ \dot{w}_0 \\ \dot{\theta} \end{Bmatrix}$$

The evaluation formula for soil springs and dashpots at foundation-soil interface considering uplift effect is provided in JEAC 4601 App. 3.6.

Figure 3 Conceptual Diagram of SR Model considering Induced Vertical Motion.

This JEAC 4601 foundation uplift approaches were implemented in the ACS SASSI Option UPLIFT software (GP Technologies, 2021) by combining the equivalent-linearization for the overall SSI analysis in complex frequency with the nonlinear uplift time-domain analysis occurring at the foundation-soil interface. Figure 4 illustrates the flowchart for performing the uplift SSI analysis of an embedded structure by integrating the functionalities of the three UPLIFT modules.

An iterative multi-step SSI analysis procedure is applied: 1) An initial SSI analysis, before considering the nonlinear uplift effects, and 2) A final or iteratively converged SSI analysis, after considering the nonlinear uplift effects by adjusting the bottom-soil rocking impedances per the JEAC 4601 recommendations. Also, it should be noted that the foundation uplift effects affect only a very limited frequency range associated to the 3DFEM SSI model rocking mode. Therefore, the final SSI analysis is a fast restart analysis using the computed soil impedance matrix for only few frequencies of interest around the SSI dominant rocking mode frequency.

In order to verify the applicability of the new Option UPLIFT function, a comparison analysis study was performed for a test building foundation constructed on the uniform soil condition (Vs=720m/s) subject to various levels of input motion (NRC RG 1.60 spectrum) according to the following steps.

1) The three stories test building is employed for the 3DFEM model using ACS SASSI. Then the equivalent stick with basemat shell model is constructed. And a set of soil springs and dashpots for the stick-SR model is calculated according to the JEAC 4601-2015 Sec 3.5.5.2 using the dynamic ground compliance (DGC) theory.
2) Using the generated stick-SR model, the nonlinear uplift time-domain analysis is performed by the program DYNA2E, which is broadly used for the uplift SSI analysis of nuclear facilities in Japan.
3) Using the 3DFEM model (SASSI 3DFEM model) and the stick with rigid basemat shell model (SASSI Stick model), the SSI uplift analyses are performed by the ACS SASSI Option UPLIFT modules.
4) Both analysis results are compared for the soil impedance, natural frequency, foundation uplift moment and soil contact ratio and structure response spectra.

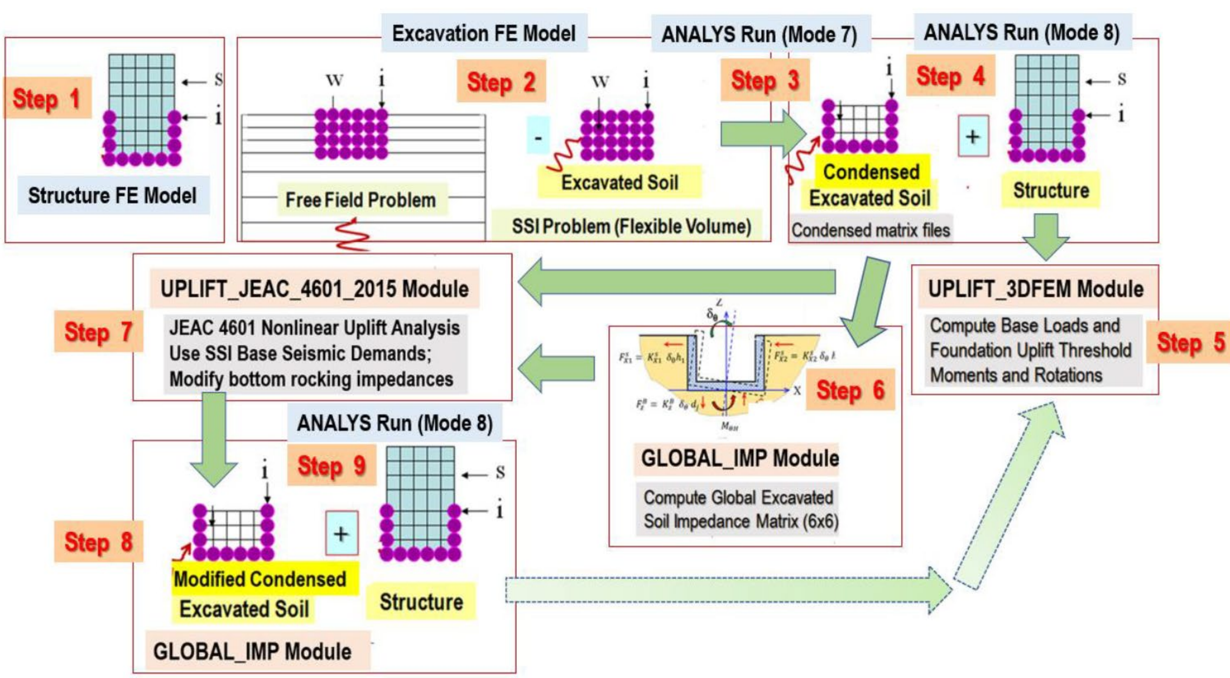
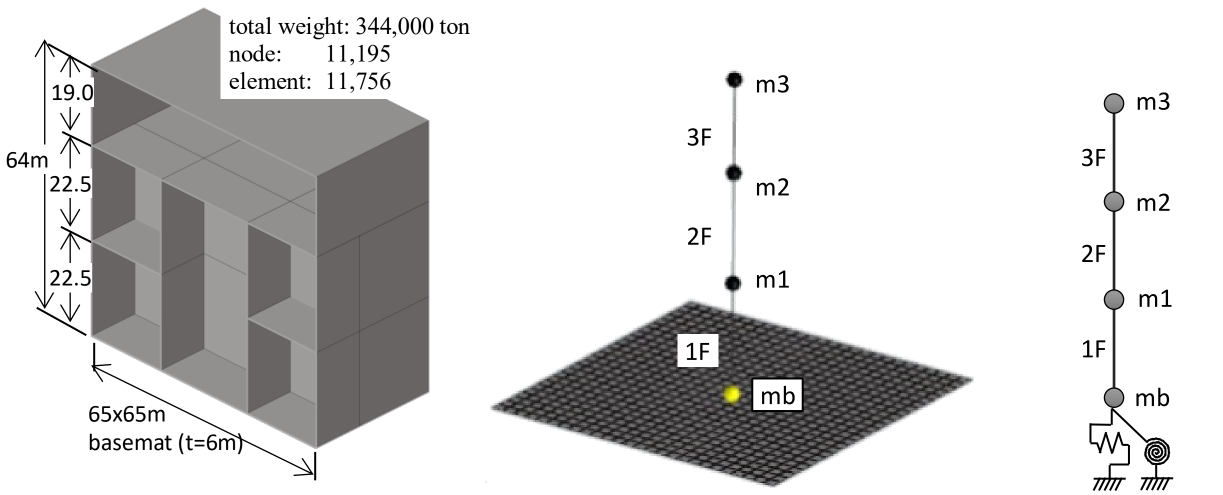


Figure 4 ACS SASSI Option UPLIFT SSI Analysis Implementation per JEAC 4601

ANALYSIS MODEL

Analysis models used for the comparison study are shown in Figure 5. The size of test building is 65 x 65 m, the height is 64 m and the total weight is 344,000 ton. It has a similar size and weight of the RB complex building. The building is assumed a surface mounted structure on the uniform soil. The soil properties are shown in Table 1. ACS SASSI is used for the two models. One is a 3D FE model with a basemat modelled by shell elements with real stiffness. The other is a lumped mass stick model with a basemat modelled by rigid shell elements. On the other hand, DYNA2E model is the same stick model with the SR soil springs, of which spring and dashpot values are calculated from the DGC soil impedance.



(a) ACS SASSI 3DFEM model (b) ACS SASSI Stick model (c) DYNA2E SR model

Figure 5 Analysis Models for Comparison Study

Table 1 Soil Properties

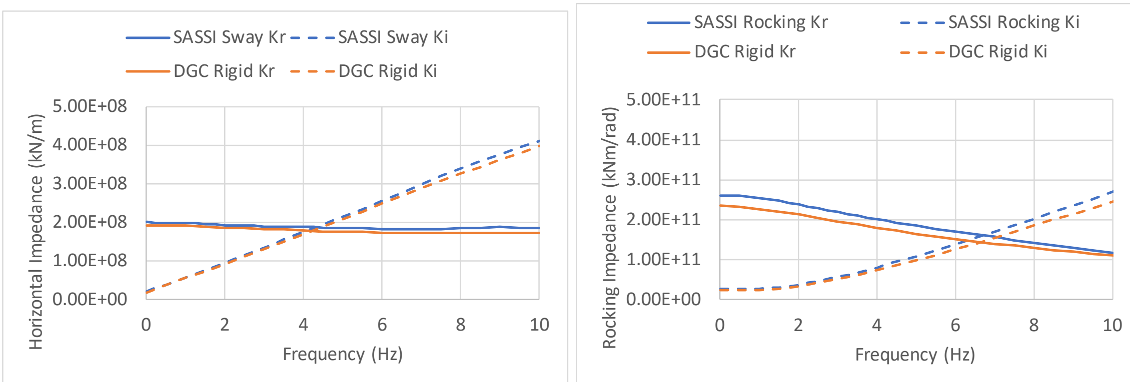
Vs (m/s)	Vp (m/s)	Poisson ratio ν	unit weight (kN/m^3)	damping ratio
720	1900	0.418	19.9	0.05

Table 2 shows a comparison of the natural frequency of the fixed-base model between the 3DFEM model and the Stick model. The frequency of Stick model is very close to the 3DFEM model in the horizontal direction. The vertical frequency of the Stick model is closer to that of the 3DFEM model with rigid slab assumption.

Table 2 Comparison of Frequency of Fixed-base Model

	3DFEM model		Stick model
	Flexible slab	Rigid slab	
Horizontal	4.65 Hz	4.80 Hz	4.70 Hz
Vertical	7.95 Hz	12.52 Hz	12.04 Hz

Figure 6 shows a comparison between sway and rocking mode soil impedance obtained by the DGC theory and the global bottom soil impedance evaluated by ACS SASSI. For the DGC calculation, soil reaction is assumed as a rigid plate distribution. The impedance obtained by both methods has a good agreement.



(a) Soil Impedance for Sway Mode (b) Soil Impedance for Rocking Mode

Figure 6 Comparison of Soil Impedance

SEISMIC INPUT MOTION

Figure 7 shows the time history of input motion used for this comparison study. It is generated based on NRC RG 1.60 spectrum. Input level is scaled as the maximum acceleration 0.1g to 0.5g to see changes in uplift moment and contact ratio.

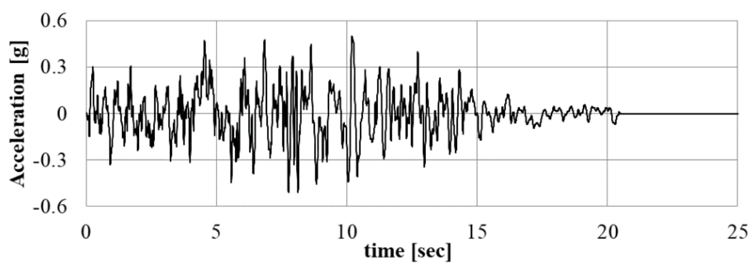


Figure 7 Seismic Input Motion

DYNA2E UPLIFT ANALYSIS RESULTS

θ-M curve and θ–η curve

Figure 8 shows the relationship between the maximum rocking angle θ and overturning moment M and the relationship between θ and contact ratio η when increasing the input motion from 0.2g to 0.5g.

1) At 0.20 g input, the overturning moment M is about to reach the uplift threshold moment M_0.
   where, $M_0 = WL/\alpha = 4.7 \times 10^7$ kNm (α =4.7 rigid plate distribution)
2) At 0.25 g input, the contact ratio η is within the range of 0.75-0.65. Non-linear uplift analysis is required. => Non-linear (I)
3) At 0.3 g input, the contact ratio η is within the range of 0.65-0.50. Non-linear uplift analysis considering induced vertical motion effect is required. => Non-linear (II)
4) At 0.5 g input, the contact ratio η is smaller than 0.50. Special consideration is required according to the JEAC 4601 recommendation. e.g. time-domain Green's function method or 3D FEM model considering joint elements.

Table 3 Contact Ratio obtained from DYNA2E Uplift Analysis

Analysis method	Input Acceleration Level (g)				
	0.20	0.25	0.30	0.40	0.50
Linear analysis	1.000	0.836	0.654	0.292	-0.070
Non-linear (I) neglecting induced vertical motion	1.000	0.748	0.616	0.432	0.364
Non-linear (II) considering induced vertical motion	1.000	0.850	0.711	0.514	0.390

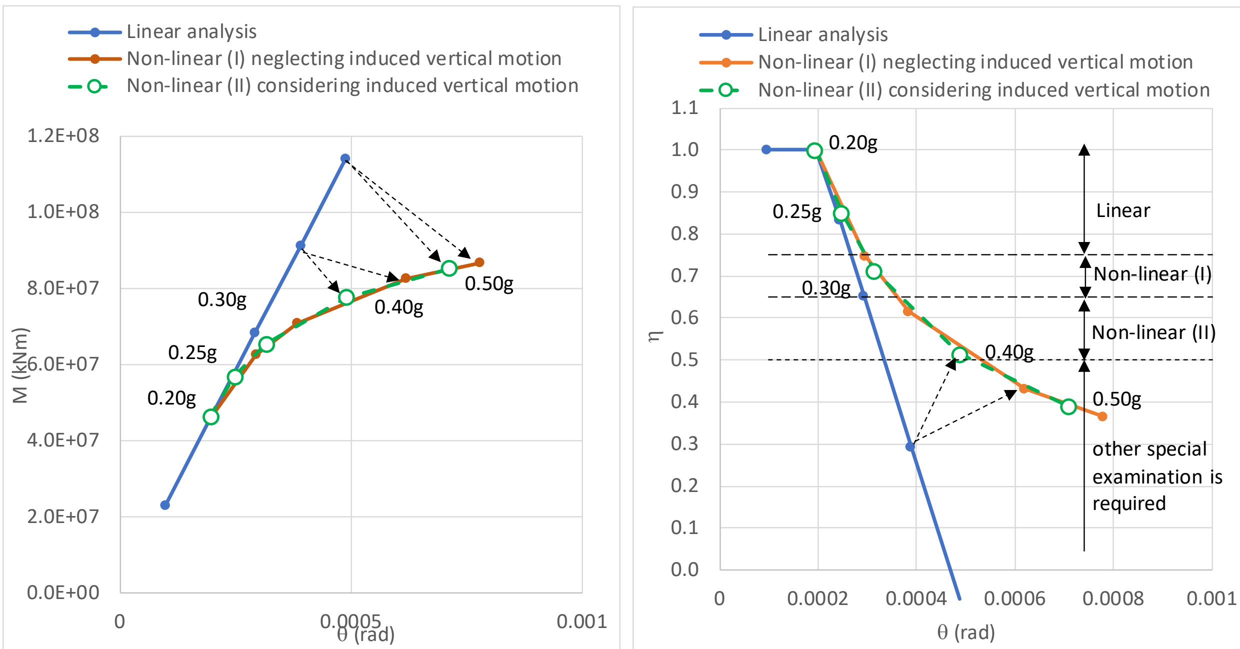


Figure 8 θ-M Curve and θ–η Curve obtained from DYNA2E Uplift Analysis

Time History Response

Figure 9 shows the time history response comparison of θ-M curve obtained by the DYNA2E uplift non-linear analysis between neglecting the induced vertical motion effect (NL(I)) and considering the induced vertical motion effect (NL(II)) at the 0.4g input. By considering the induced vertical motion effects, the peak rotation values are decreased.

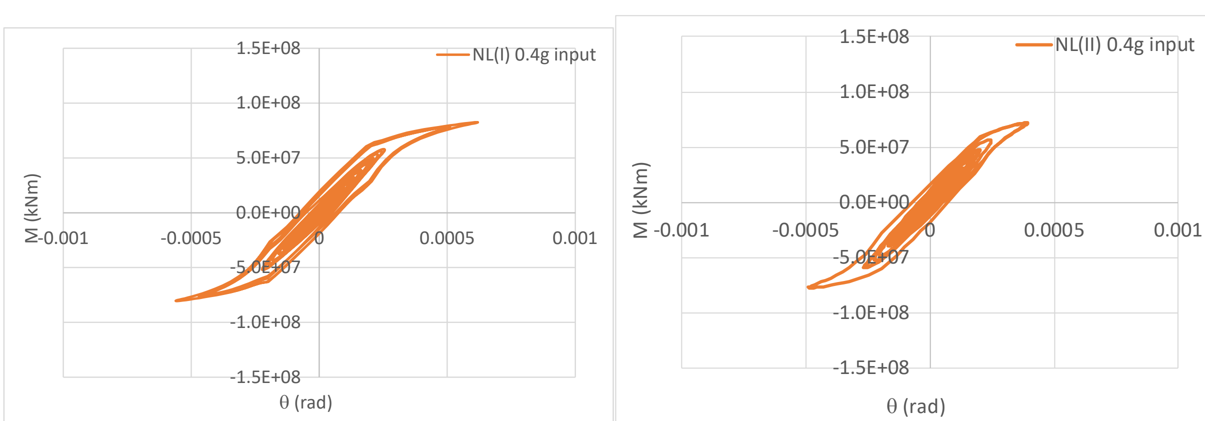


Figure 9 Comparison of Time History θ-M Curve between NL(I) and NL(II)

Response Spectra at RF

Figure 10 shows the response spectra at the roof floor obtained from the Non-linear(I) and Non-linear (II) DYNA2E uplift analyses. When increasing the input motion from 0.2g to 0.5g, the peak frequency is decreasing from the initial frequency 2.6 Hz. It was found that Non-linear(I) method overestimates the response when the input motion increases.

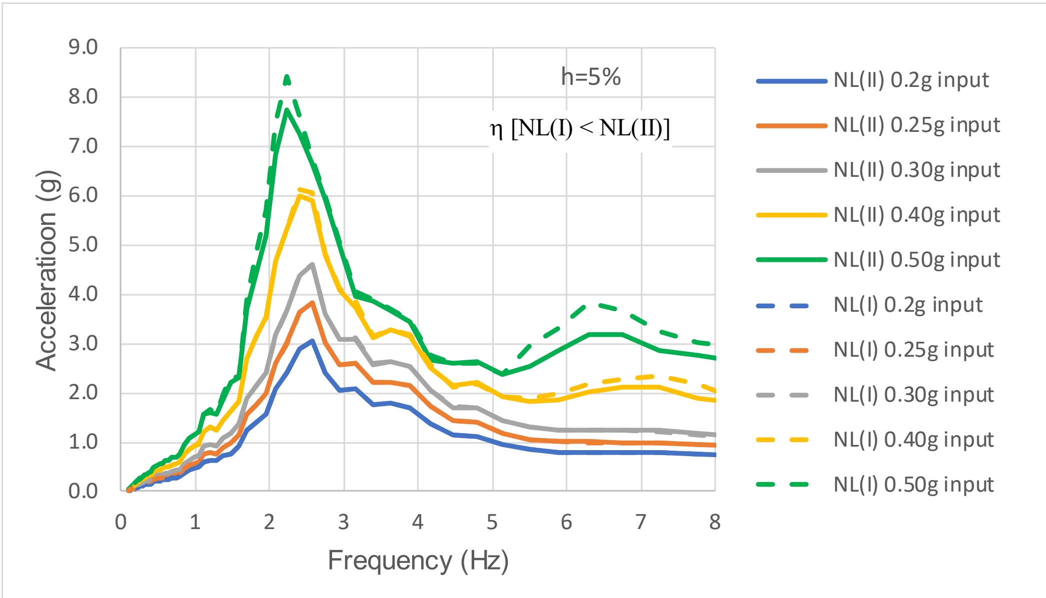


Figure 10 Response Spectra at Roof Floor from DYNA2E Uplift Analysis

COMPARISON WITH ACS SASSI UPLIFT ANALYSIS

Bases on the above DYNA2E uplift analysis, the test building uplift response obtained by the Non-linear (II) for the 0.4g input is selected to perform the comparison study with ACS SASSI UPLIFT Option. As explained in above, ACS SASSI has two models, 3D FE model with a basemat modelled by shell elements with real stiffness (SASSI 3DFEM) and a lumped mass stick model with a basemat modelled by rigid shell elements model (SASSI Stick).

As shown in Figure 2, the JEAC 4615 M-θ skeleton curve is determined based on the uplift threshold moment M_0 and the corresponding rotation θ_0. The threshold moment is calculated per the following equation.

$$M_0 = WL/\alpha \tag{1}$$

Where W is the weight of the building and L is basemat horizontal size. α can vary between 4.7 and 6.0. JEAC 4601 recommends 4.7 value for the rigid foundation assumption (softer soil), and 6.0 value for the linear soil pressure distribution assumption (stiffer soils). The above DYNA2E SR model, the α=4.7 was taken assuming the rigid plate distribution. In the same way, the SASSI Stick model uses α=4.7. On the other hand, SASSI 3DFEM has the basemat modelled by shell elements with real stiffness. Therefore, the threshold moment can be computed from the 3DFEM analysis results using the linearized bottom-soil stress distribution. As a result, α value is calculated as 5.68 and it was used for the 3DFEM uplift analysis.

Comparison of Time History Response

Figure 11 shows the time history response comparison of θ-M curve obtained by the DYNA2E SR model (α=4.7) and ACS SASSI Stick model (α=4.7) and the 3DFEM model (α=5.68).

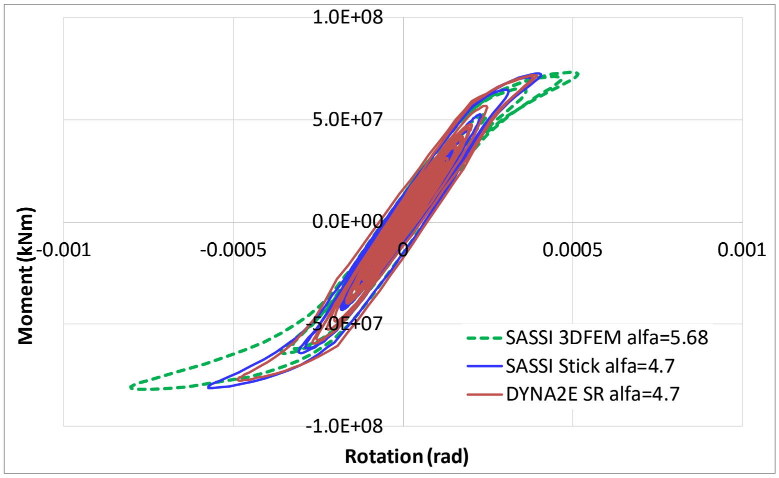
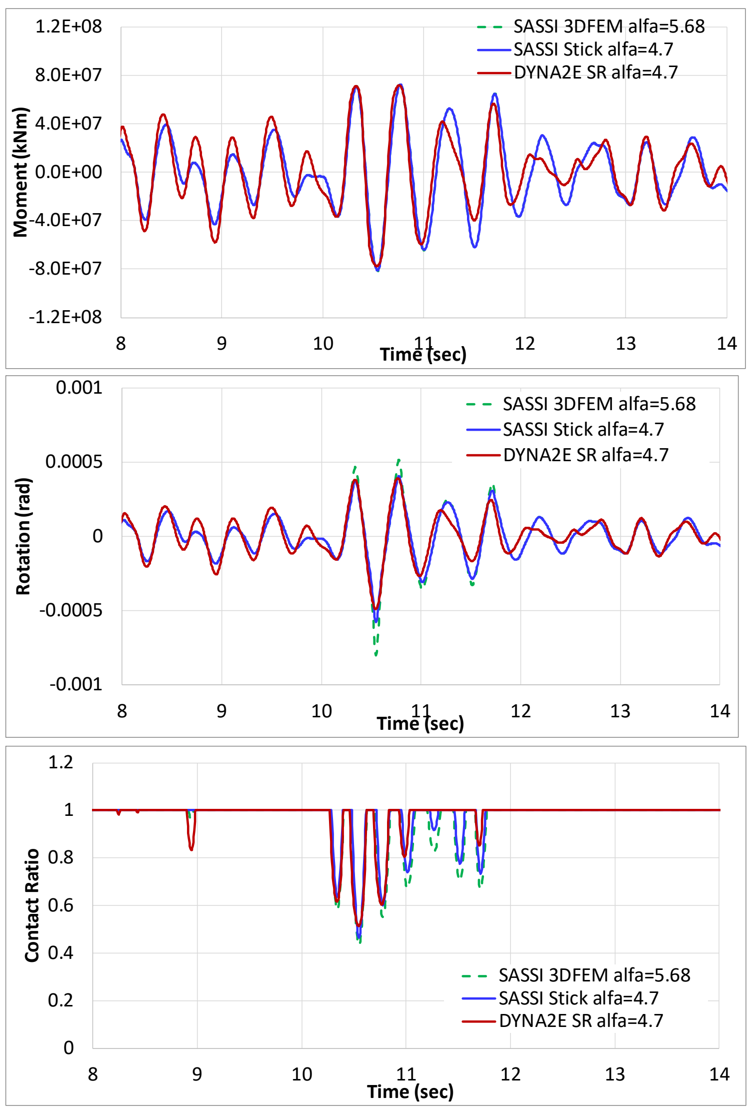


Figure 11 Comparison of Time History θ-M Curve between DYNA2E and ACS SASSI



(a) Moment

(b) Rotation

(c) Contact Ratio

Figure 12 Comparison of Time History of Moment Rotation and Contact Ratio

Figure 12 shows the comparison of time history of moment, rotation and contact ratio between DYNA2E SR model and ACS SASSI Stick model / 3DFEM model. The time history from 8 sec to 14 sec, when the maximum uplift occurs, are shown.

It was found that the θ-M curve time history by the SASSI Stick model is very close to the results from the DYNA2E SR model. The SASSI 3DFEM model results shows larger response than the others. This difference is considered due to the α value used in the analysis.

The minimum contact ratio of the three models are as follows:

DYNA2E SR model: 0.514
SASSI Stick model: 0.469
SASSI 3DFEM model: 0.434

Comparison of Response Spectra

Figure 13 shows the response spectra at the roof floor obtained from the DYNA2E SR model and ACS SASSI Stick model. For the 0.4g input level, both analysis models are analysed by uplift non-linear condition and by linear condition. The peak frequency and acceleration are very close between the DYNA2E SR model and ACS SASSI Stick model. The peak frequencies for uplift non-linear condition obtained by both models are slightly reduced from the linear condition.

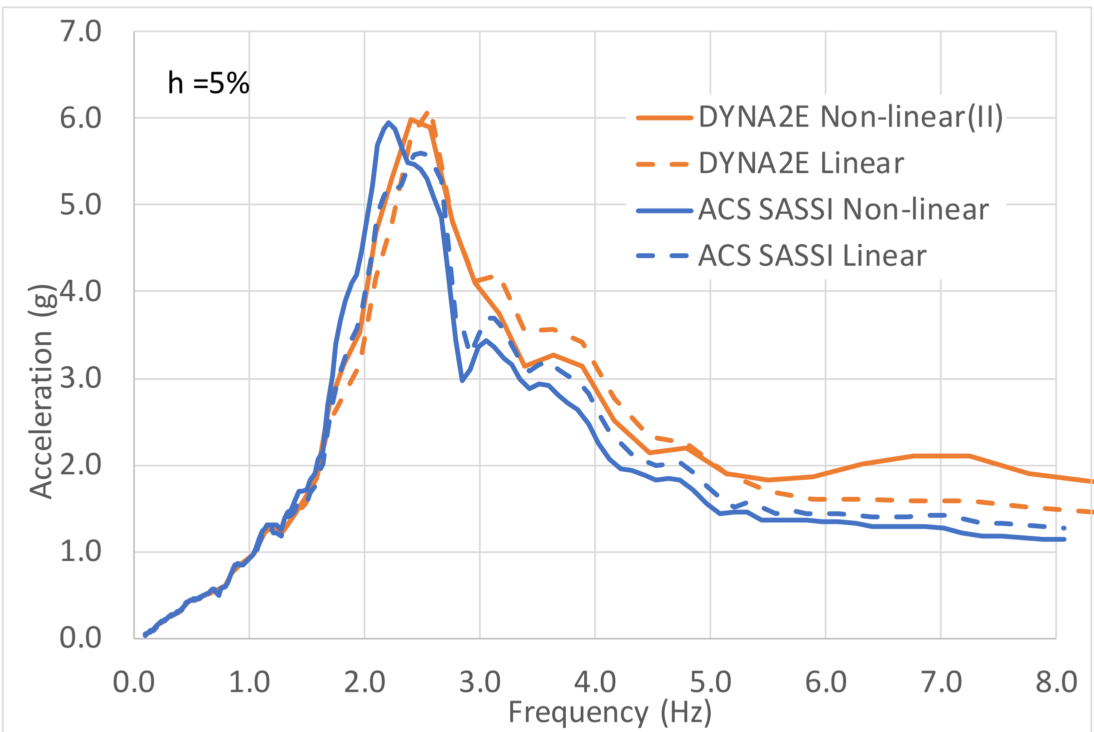


Figure 13 Comparison of Response Spectra at Roof Floor for 0.4 g Input

CONCLUSION

In order to verify the applicability of the new Option UPLIFT function, which implemented the JEAC 4601-2015 foundation uplift approaches, a comparison analysis study was performed for a test building foundation constructed on the uniform soil condition.

Firstly, to evaluate the uplift non-linear response according to the JEAC 4601-2015 approach, the test building is modelled by the stick SR model which is conventionally used in Japan and seismic SSI uplift analyses are performed for the various levels of input motion by using DYNA2E, which is the nonlinear uplift time-domain analysis program broadly used for the uplift SSI analysis of nuclear facilities in Japan. Based on the contact ratio levels obtained from the above analyses, the input motion level 0.4g was selected for the comparison study of the ACS SASSI Option UPLIFT function, because its level produces the significant uplift non-linear behaviour, i.e. contact ratio is 0.514 by DYNA2E.

As a result of the comparison study, it was found that ACS SASSI Stick model with rigid basemat (α=4.7) provide very good agreement with the DYNA2E results. It is considered that the time-domain non-linear analysis results is adequately solved by the iterative equivalent linear analysis implemented in the ACS SASSI Option UPLIFT function. ACS SASSI 3DFEM model with real flexible basemat provides a little conservative uplift response. This difference is considered due to the α value used in the analysis.

In the JEAC 4601-2015 standard recommendations, the seismic input motion is considered separately for each of the two principal directions of the foundation, X and Y. Therefore, in this comparison study, the uplift response was evaluated for the surface mounted structure subjected to one direction input motion. On the other hands, ACS SASSI 3DFEM model can be used for the uplift analysis against the multiple direction simultaneous input. It can also address the uplift analysis for the embedded structure. Those extensive functions should be verified further separately.

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