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NONLINEAR DYNAMIC SOIL-STRUCTURE INTERACTION ANALYSIS FOR ENERGY PROJECTS

Yoshitaka Sato(1), Akira Nakashima(2)

(1) *JGC Corporation, Japan, sato.yoshitaka@jgc.com*
(2) *JGC Corporation, Japan, nakashima.akira@jgc.com*

Abstract

This paper discusses the structural nonlinear effects on Soil-Structure Interaction (SSI) and introduces a simple equivalent linear structural modeling for nonlinear Dynamic Soil Structure Interaction (DSSI) analysis in energy projects.

In accordance with Chapter 19 of ASCE 7-16, the SSI effect is permitted to be considered in the seismic design with the procedures of equivalent lateral force, linear dynamic analysis, or nonlinear response history. Among them, in order to achieve further seismic design optimization, it is expected that the application of nonlinear response history will be established, where the structure and soil shall be modeled nonlinear.

A difficulty in energy projects is, however, the nonlinear modeling of various mechanical structures and equipment. Therefore, a practical design procedure of DSSI analysis with nonlinear soil and nonlinear structural modeling is required, namely, nonlinear DSSI analysis.

To practically enable the nonlinear modeling of mechanical structures and equipment for energy projects, a simple procedure of equivalent linear modeling is proposed to address the reduction of structural stiffness in relation with R-factors.

An example of nonlinear DSSI analysis of LNG storage tanks demonstrated the interaction of structural stiffness reduction with the inertial interaction and resulted in decreasing or increasing the response accelerations. It is the proposed procedures of nonlinear DSSI analysis to be applied for energy projects.

Keywords: Soil-Structure Interaction; Nonlinear Response History Analysis; Structural Nonlinear Effects

1. Introduction

In seismic design, the SSI effect is one of the most important subjects to capture the dynamic behavior of structures, especially in case of heavy mass on soft ground, which the damping and stiffness as a soil-structure system are strongly influenced by the foundation. In energy projects, there are many heavy structures among the facilities such as tanks, boilers, generators, pipe-racks etc. and therefore, the SSI effects should be considered for their seismic design.

In accordance with Chapter 19 of ASCE 7-16 [1], the SSI effect is permitted to be considered in the seismic design with the procedures of equivalent lateral force, linear dynamic analysis, or nonlinear response history. Among them, it is specified that the first two procedures have the limitation of potential base shear reduction caused by SSI, because these procedures are based on linear models of the structure and subsoil and the understanding of how the SSI effect interacts with the nonlinear effects is limited. In order to achieve further seismic design optimization, it is desired to establish the nonlinear response history procedure, where the structure and soil shall be modeled nonlinearly.

While the application of nonlinear soil modeling becomes a feasible option owing to the development of FEA technologies, a difficulty, however, still exists in the nonlinear modeling of various, especially mechanical structures and equipment in energy projects. There are several researches and design applications of the response history analysis with nonlinear soil modeling, so called DSSI analysis, e.g., those applied for liquified natural gas (LNG) storage tanks [2]. However, the structural nonlinear effects are not taken into account. The conventional seismic design methods of using the response modification factors (R-factors) have been commonly used in the industry. With that, the structural ductility after yielding are simply considered in the design by dividing the response accelerations by the R-factors specified for the structures.

A practical design procedure of DSSI analysis with nonlinear soil and nonlinear structural modeling is required, namely, nonlinear DSSI analysis. Therefore, this paper discusses how the structural nonlinear effects interact with the SSI and then introduces a simple procedure of equivalent linear structural modeling to be applied for nonlinear DSSI analysis in energy projects.

2. Interaction of Structural Nonlinear Effects with SSI

2.1 SSI Effects

To discuss the interaction with structural nonlinear effects, the SSI effects are firstly described as below.

The SSI effects are divided into kinematic interaction and inertial interaction [3]. The kinematic interaction is to deviate the seismic motions at the foundations from free-field motions due to base-slab averaging and embedment effects. The inertial interaction is explained as the effects of fundamental period (simply referred to as “period” hereafter) lengthening and damping increase of the soil-structure system, in comparison with those of the structure only. Hereafter, the inertial interaction is focused on and further elaborated since it is influenced by the structural nonlinear effects.

The inertial interaction is expressed as a lumped-mass with the combination of the stiffness of the foundation and structure and their damping. The period and damping ratio of the soil-structure system are simply calculated from those of the foundation and structure as described in Figure 1(a), basing the translational modes. In the conventional design with the low period ratio of foundation and structure (T_1/T_0), the period and damping ratio of the soil-structure system (T_2 and β_2) are controlled by those of structure (T_0 and β_0) and therefore the SSI effects may be ignored. However, when the system has the high period ratio (T_1/T_0), e.g., a structure with high stiffness and heavy mass on soft ground, the period and damping ratio of the soil-structure system (T_2 and β_2) are influenced by those of the foundation (T_1 and β_1) and therefore, the SSI effects become significant.

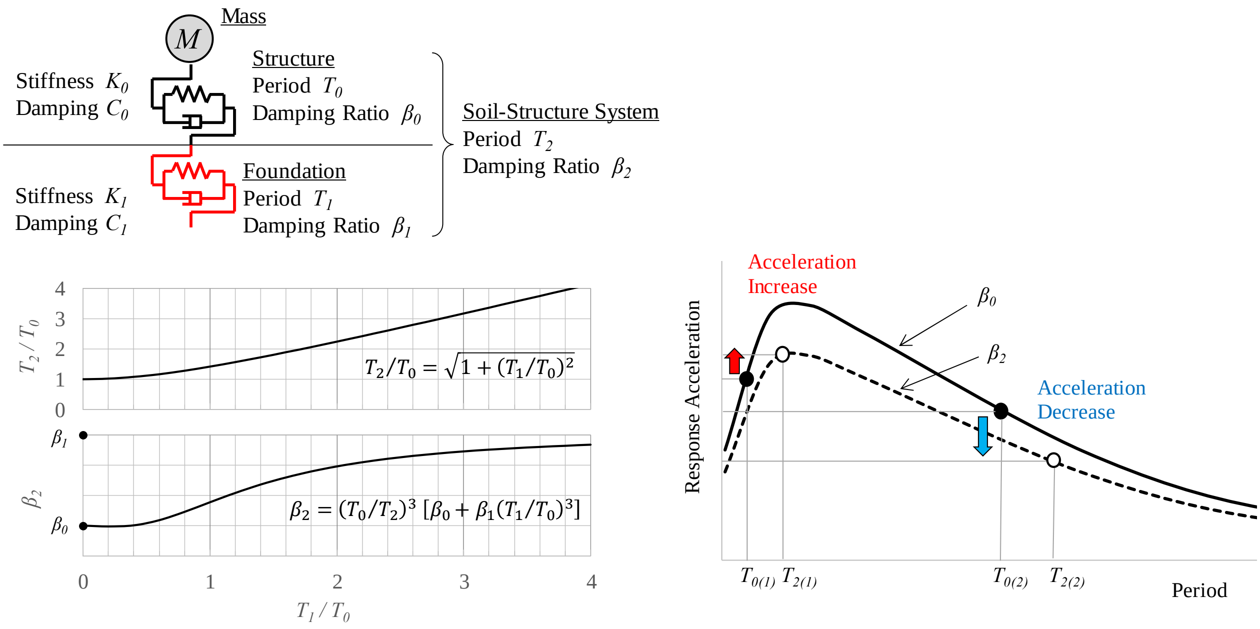
The SSI effects of inertial interaction in the response spectra are illustrated in Figure 1(b). As the result of period lengthening and damping increase, the response accelerations may increase or decrease depending on the spectrum shape and the period and damping ratio of the soil-structure system, in comparison with the structure only.

2.2 Structural Nonlinear Effects

Based on the understanding of the SSI, it is discussed how the structural nonlinear effects affect the inertial interaction as below.

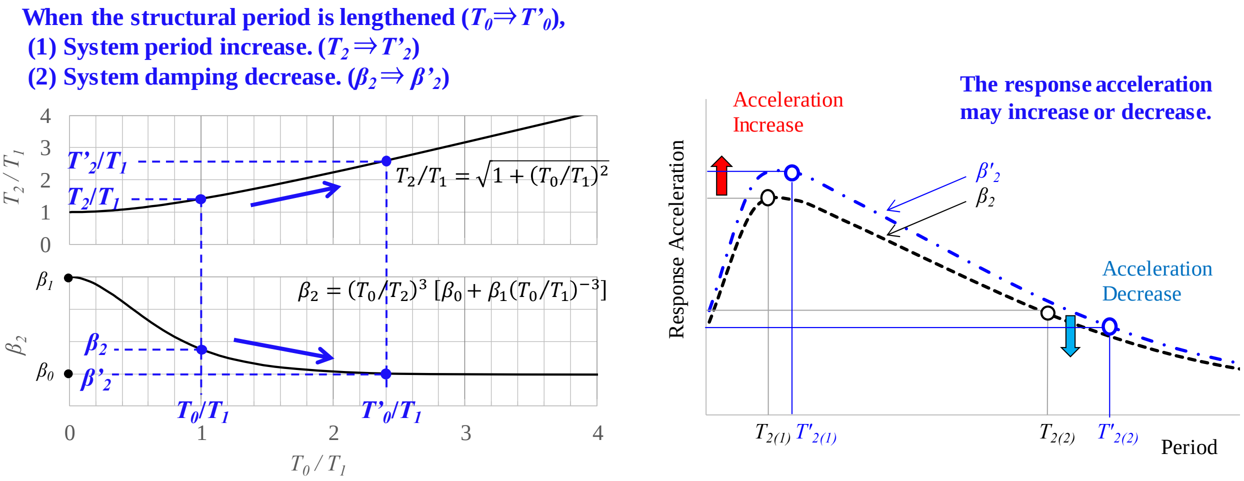
One major aspect for the interaction of structural nonlinear effects with the inertial interaction is the reduction of structural stiffness after yielding. If the structural stiffness is reduced, the period of the soil-structure system increases, but the damping of the system decreases. This is illustrated in Figure 2(a).

The effects of structural stiffness reduction in the response spectra are shown in Figure 2(b). As the result, the response accelerations may increase or decrease depending on the spectrum shape and the period and damping ratio of the soil-structure system, in comparison with the linear structure case.



(a) Theoretical period and damping calculation (b) Plot on Response Spectrum

Fig. 1 – Inertial Interaction



(a) Theoretical period and damping calculation (b) Plot on Response Spectrum

Fig. 2 – Interaction of Structural Stiffness Reduction with Inertial Interaction

3. Proposed Nonlinear DSSI Analysis Procedure

3.1 Structural Nonlinear Modeling – Equivalent Linear

In accordance with the discussion above, the reduction of structural stiffness affects the inertial interaction. This may result in increasing or decreasing the response accelerations of structures. It is not always conservative to ignore the reduction of structural stiffness, and therefore, shall be taken into account in the SSI design. To practically realize the nonlinear modeling of mechanical structures and equipment for energy projects, a simple procedure of equivalent linear modeling is proposed to address the reduction of structural stiffness in related with R-factors. The equivalent linear stiffness is estimated based on the equivalent energy theory [4] as described in Figure 3 and Equation (1). The yield force is estimated using R-factors specified for the structures.

$$K_B = K_A \times 2 / (R^2+1) \qquad (1)$$

The use of equivalent linear stiffness enables the capture of the interaction of structural yielding on inertial interaction, however, to maintain the seismic design philosophy of using R-factors.

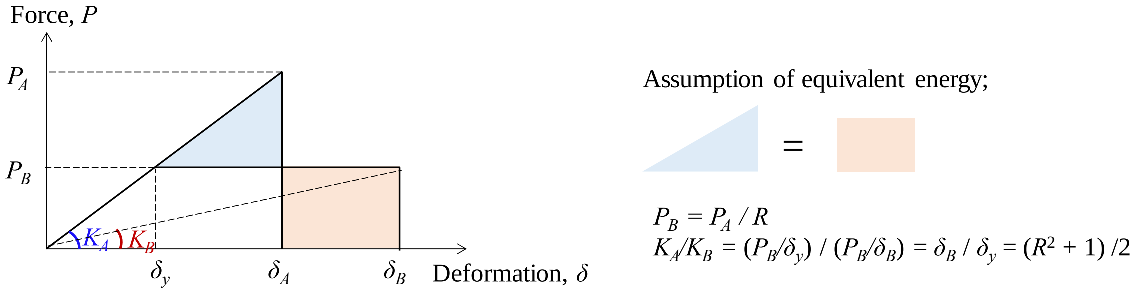


Fig. 3 – Equivalent Linear Stiffness Modeling

3.2 Proposed Nonlinear DSSI Analysis Procedure

With the equivalent linear structural model, the nonlinear DSSI analysis procedure is proposed as below;

- FEA is applied with nonlinear soil and linear structural elements as described in Figure 4. Superstructures are modeled in lumped-masses and connected with the spring and damping to the base slab as modeled in rigid shells. The earthquake time history wave is inputted at the bedrock layer as an outcrop motion. The maximum accelerations of the response history of the masses will be outputted, adjusted with R-factors and used for the superstructure's seismic design.
- The stiffness of structural lumped-masses is studied in accordance with the stiffness reductions after yielding. Due to the uncertainty of the structural yielding, the parameter studies cover the different yield levels and the maximum response accelerations will be used from among all the results.

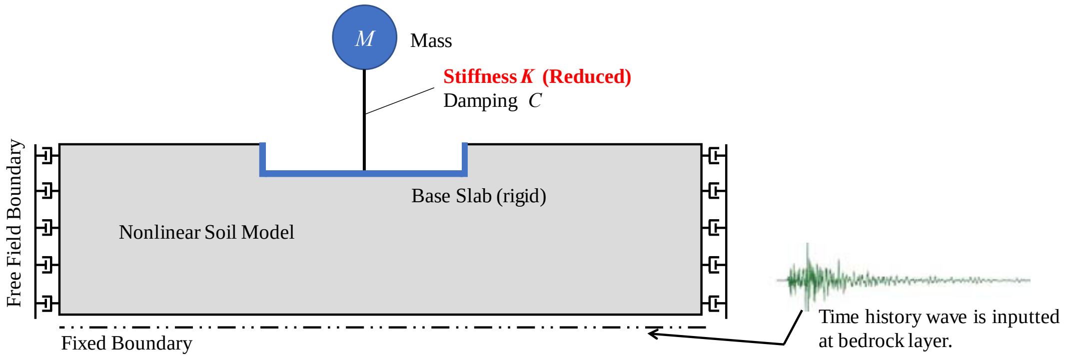


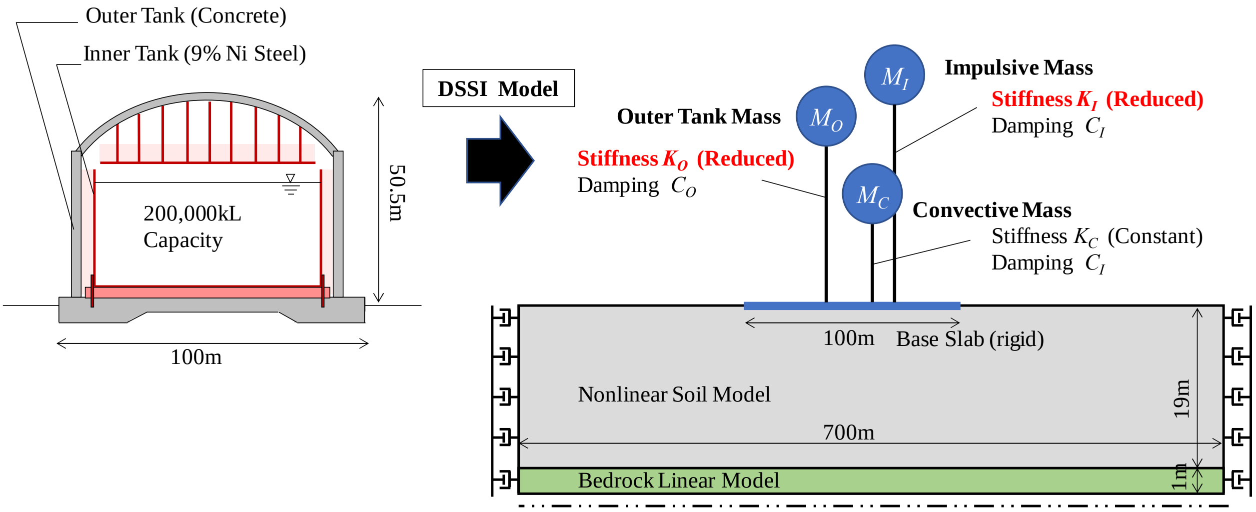
Fig. 4 – DSSI Analysis Model with Consideration of Structural Nonlinear Effects

4. Analysis Example – LNG Storage Tank

4.1 Analysis Model

The analysis example is selected for a raft foundation of an LNG storage tank. It consists of an inner 9% nickel steel tank and an outer concrete tank with a net storage capacity of 200,000kL. The base slab diameter is 100m and the tank height is 50m.

The FEA was conducted with the software *PLAXIS 2D* [5]. The inner tank and the liquid are represented in two masses; the impulsive motion of the inner tank plus liquid, and the convective motion of the liquid (known as sloshing mode). The outer concrete tank is modeled as a separate mass and therefore, the total three masses represent the tank structures. The base slab is modeled in the rigid shell element. Due to shallow foundation depth, the embedment effects are ignored. The nonlinear soil properties are modeled in *PLAXIS Hardening Soil Small Model with Small-Strain Stiffness (HS SMALL)* and the extent of the soil model is 700m having the distances of 3 times of foundation diameter each side and the boundary conditions of free-field, so that the radiation of energy is effectively considered. The model sketch and parameters of lumped-mass and nonlinear soil material are presented in Figure 5.



Lumped-Mass	**Mass (ton)**	**Period (sec)**	**Damping Ratio (%)**
Impulsive Mass	M_I=40,100	T_I=0.454	β_I=5
Convective Mass	M_C=58,300	T_C=10.865	β_C=0.5
Outer Tank	M_O=46,000	T_O=0.166	β_O=5

Nonlinear Soil Parameters for *PLAXIS HSSMALL*		
$E_{50;ref}$= 60,000kN/m^3	$E_{oed;ref}$= 60,000kN/m^3	$E_{ur;ref}$= 180,000kN/m^3
P_{ref} = 100kN/m^2	C'_{ref} = 10kN/m^2	Φ'= 32°
$\gamma_{0.7}$ = 0.0004	$G_{0;ref}$ = 87,120kN/m^3	ν_{ur} = 0.15

Fig. 5 – Example Analysis Model – LNG Storage Tank

4.2 Structural Nonlinear Effects

The structural nonlinear effects are considered using the equivalent linear model in accordance with Section 3.1. Three cases of different yield levels are examined based on the various R-factors. Table 1 shows R-factors, stiffness reduction ratios and the corresponding structural periods for each mass. It is assumed as the convective mode is not influenced by structural nonlinearity due to its long period.

Table 1 – Analysis Cases

Case	**R-factors**	**Stiffness Reduction Ratio, K_A/K_B**	**Impulsive Mass *Ti* (sec)**	**Convective Mass *Tc* (sec)**	**Outer Tank Mass *To* (sec)**
1	1 (Elastic)	1.00	0.454	10.865	0.166
2	1.5	1.63	0.579	10.865	0.212
3	2.0	2.50	0.718	10.865	0.262

4.3 Input Motions

The design response spectrum was defined for Safe Shutdown Earthquake (SSE) at the bedrock level as a result of seismic hazard assessment. Three time-history waves, i.e., Loma Priesta (M6.93, 1989), Northridge (M6.69, 1994) and Tottori, Japan (M6.61, 2000) were selected based on the hazard disaggregation and spectrally matched with the design response spectrum as presented in Figure 6.

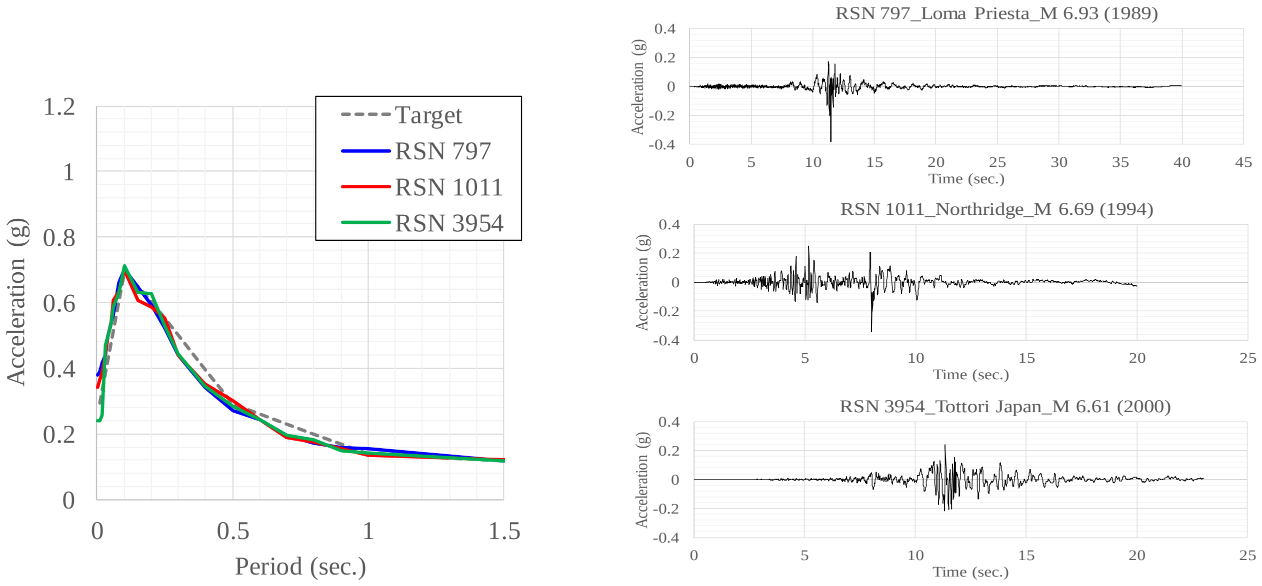


Fig. 6 – Input Motions

4.4 Analysis Results

The DSSI analysis results are presented in Table 2 and Figure 7. To verify the radiation damping of the DSSI model, the site response analysis (SRA) using the soil column model was also conducted.

Table 2 shows, as the results of DSSI analysis, the maximum accelerations of response history of each mass as an average of three input motions. Figure 7(a) shows the response spectrum at the bedrock and ground surface as the results of SRA. Figure 7(b) to (d) describes the results of DSSI analysis for cases 1 to 3, respectively. Each figure shows the comparison of the response spectrum at bedrock, free-field surface and the bottom of the LNG tank.

The response spectra at the free-field surface resulted from the DSSI analysis in Figure 7(b) to (d) to well match with those of the SRA in Figure 7(a). Therefore, it is verified that the radiation damping of DSSI analysis is appropriately modeled.

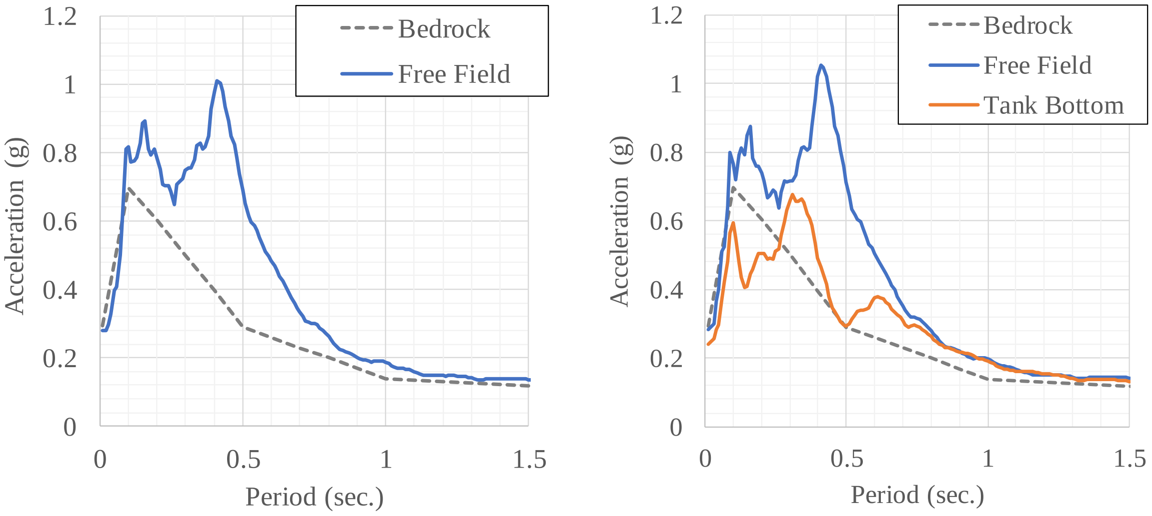
From Table 2, the results show that, as the structural stiffness reduces, the acceleration of the impulsive mass decreases from 0.343g in case 1 to 0.267g in case 3, but that of the outer tank mass increases from 0.301g in case 1 to 0.348g in case 3. This can be explained by referring to the shape of the free-field surface response spectra. The period of the impulsive mass moves out of the spectrum peak from the 0.454sec in case 1 to 0.718sec in case 3, but that of the outer tank mass reaches the peak from the 0.166sec in case 1 to the 0.262sec in case 3 as the structural period increases.

By comparing the surface response spectra at the free-field and the tank bottom in Figure 7(b) to (d), the soil-structure system damping can be investigated. The peak accelerations of the surface response spectra at the tank bottom are 0.676g at T=0.31sec, 0.727g at T=0.38sec and 0.800g at T=0.41sec in cases 1, 2 and 3, respectively in comparison with 1.05g at T=0.41sec of the surface response spectra at free-field. The reduction of response spectra due to the system damping is observed as about 36%(=1-0.676/1.05), 31%(=1-0.727/1.05) and 24%(=1-0.800/1.05) for cases 1 to 3, respectively.

As the structural stiffness reduces, the damping effects decrease. This result demonstrates the point discussed in Section 2.2. The interaction of structural stiffness reduction with inertial interaction is captured in the nonlinear DSSI analysis.

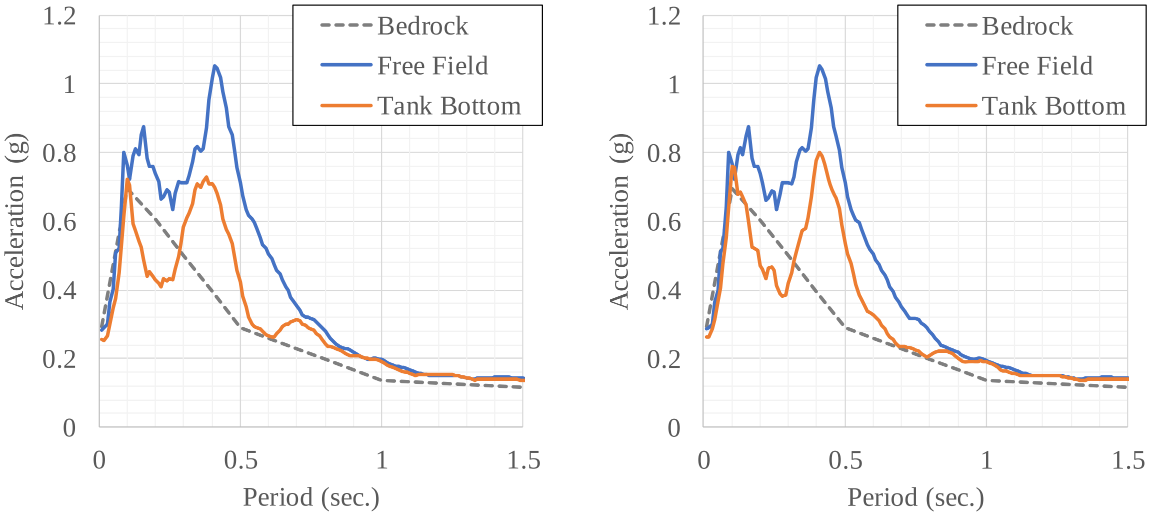
Table 2 –Response Accelerations of Each Mass

Case	**Response Acceleration (g)**		
	Impulsive Mass	**Convective Mass**	**Outer Tank Mass**
1	0.343	0.011	0.301
2	0.309	0.011	0.332
3	0.267	0.011	0.348



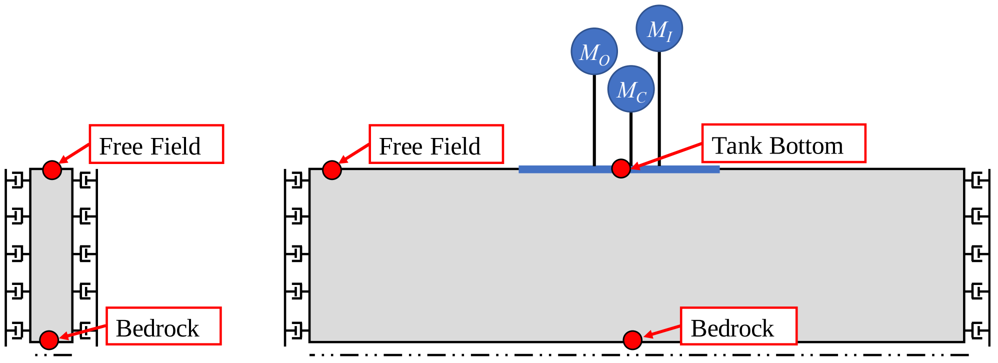
(a) 1D Soil Column

(b) DSSI Case 1: R=1(Elastic)



(c) DSSI Case 2: R=1.5

(d) DSSI Case 3: R=2.0



1D Soil Column Model

DSSI Model

Fig. 7 – Response Spectra Resulted from DSSI and Site Response Analysis

5. Conclusion

To achieve further seismic design optimization, the application of nonlinear response history will be established, where the structure and soil shall be modeled as nonlinear.

To practically realize the nonlinear modeling of mechanical structures and equipment for energy projects, a simple procedure of equivalent linear modeling is proposed to address the reduction of structural stiffness as related with R-factors.

In the proposed nonlinear DSSI analysis, the reduction of structural stiffness will be studied with several different yield levels of structures considering the uncertainty. As the results of parameter studies, the maximum response accelerations will be used from among all the results.

An example of nonlinear DSSI analysis of an LNG storage tank demonstrated the interaction of structural stiffness reduction with the inertial interaction and resulted in decreasing or increasing the response accelerations. It is the proposed procedures of nonlinear DSSI analysis to be applied for energy projects.

6. References

[1] *ASCE/SEI 7 Minimum Design Loads and Associated Criteria for Buildings and Other Structures,* American Society of Civil Engineers and Structural Engineering Institute, US (2016)

[2] Jesper van Es (2014): Seismic Behaviour of a LNG Tank Foundation, *MSc Thesis, Delft University of Technology, Faculty of Civil Engineering and Geoscience, Geo-engineering Section*

[3] *NIST GCR 12-917-21 Soil-Structure Interaction for Building Structures,* NEHRP Consultants Joint Venture, *A partnership of the Applied Technology Council and the Consortium of Universities for Research in Earthquake Engineering*, US (2016)

[4] *Specifications for Highway Bridges Part V Seismic Design ver. 2012,* Japan Road Association, Japan (2016)

[5] Brinkgreve, R.B.J., Kumarswamy, S., Swolfs, W.M., Zampich, L., Manoj, N.R.(2019)*, PLAXIS 2019, Bentley Systems*