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Division V

SOIL-STRUCTURE INTERACTION ANALYSIS OF LILW SILO

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ABSTRACT

This Soil-Structure Interaction(SSI) Analysis is for LILW (Low to Intermediate Level Waste) disposal facility in Gyeongju as a branch of Research & Development Project - Development of Evaluation Technology for Abnormal Scenarios in LILW Disposal Complex. A final purpose of the R&D project is to calculate the dose of radiation by external events such as earthquake. The LILW is a Silo-type disposal facility deep underground. It is necessary the SSI analysis of Silo to provide the damage level by severe earthquake. As the seismic input motions, a DGRS (Design Ground Response Spectrum, US NRC Reg. Guide 1.60) and a site specific GMRS (Ground Motion Response Spectrum) from the seismic hazard analysis around Gyeongju area are inputted. For SSI analysis, the DGRS and GMRS are converted to the artificial time histories by a EQUAKE module of ACS SASSI base on the random vibration theory within the bounds of the criteria. The site response analyses are performed for the equivalent linear concepts of the soil properties. PRO-SHAKE is used for the site response analysis, and two soil case are applied to the site response analysis – BE (Best Estimated Case), LB (Lower-Bound Case) of Shear Modulus G. In SSI analysis, the Silo and Tunnels are modelled by Finite Element of ACS SASSI. The SSI analysis cases are 12 considering the Input Motions, Concrete Cracking, and Soil Cases (BE, LB). The stress levels of Silo are presented and compared with the allowable stress of the reinforced concrete, lower than the allowable at 0.6g GMRS input motion.

INTRODUCTION

The LILW disposal facility is a unique disposal facility for Low to Intermediate Level Waste in KOREA. Wolseong LILW Disposal Centre (WLDC) has been under construction with a total capacity of 800,000 drums. The 1st phase of the construction, which is underground silo disposal with 100,000 drum capacity, was completed in 2014 (Figure 1). The 2nd phase for surface disposal with 125,000 drum capacity will be completed by 2022.

- Location: Bonggil-ri, Munmudaewang-myeon, Gyeongju, Gyeongbuk, KOREA
- Area: 2,060,000 m^2
- Project Name: 1st Phase of LILW Disposal Facility Construction
- Capacity: 100,000 drums
- Type: Underground Silo
- Period: Jul. 2007 ~ Dec. 2014
- Approval to use: Dec. 2014

Figure 1. LILW disposal facility in Wolseong

This study is a branch of Research & Development Project - Development of Evaluation Technology for Abnormal Scenarios in LILW Disposal Complex. A final purpose of the R&D project is to calculate the dose of radiation by external event such as earthquake.
It is necessary the SSI analysis of Silo to provide the damage level by severe earthquake. Therefore, three seismic motions are inputted – DGRS and two GMRS. The DGRS is matched with US Reg. Guide 1.60 response spectrum, two GMRS are investigated and derived from seismicity of Wolseong area by KAERI (Korea Atomic Energy Research Institute) that participated in same R&D project. The strongest motion is the second GMRS that have $1x10^{-5}$ hazard UHRS (Uniform Hazard Response Spectrum).
For the equivalent linear SSI analysis, the BE (Best Estimated) and LB (Lower-Bound) soil cases are applied as soil supporting media properties. The stress level of Silo was evaluated using SSI program – ACS SASSI.

SITE SOIL CONDITION

The site soil of LILW Silo has 3 layers as shown Table 1 and Figure 2 below.

Table 2. Soil Layer Properties

Layer	Poisson Ratio	Elasticity (kPa)	Shear Wave Velocity (m/sec)	Damping Ratio
Weathered Soil	0.33	$1.2x10^6$	500	0.02
Weathered Rock	0.30	$3.5x10^6$	800	0.02
Rock(IV)	0.28	$21.7x10^6$	1,920	0.02

The soil layers of LILW Silo area are 3. The ground surface layer is the thin weathered soil, and the second layer is the thin weathered rock. The main layer is the rock and IV level – slightly weathered.
Following US NRC SRP (Standard Review Plan) 3.7.2, the properties of each layer of the site profile are typically defined in terms of its low-strain shear modulus and strain-dependent modulus degradation and strain-dependent hysteretic damping properties. These may be determined from dynamic laboratory testing of the site materials, information obtained from the published literature, or both.

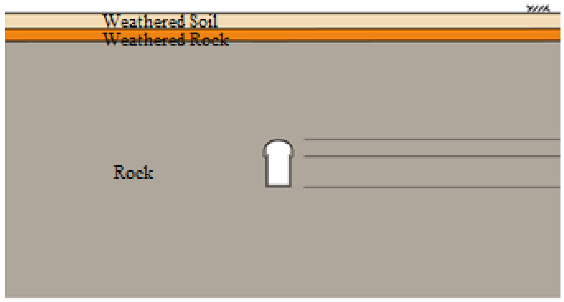


Figure 2. Soil Layer Feature

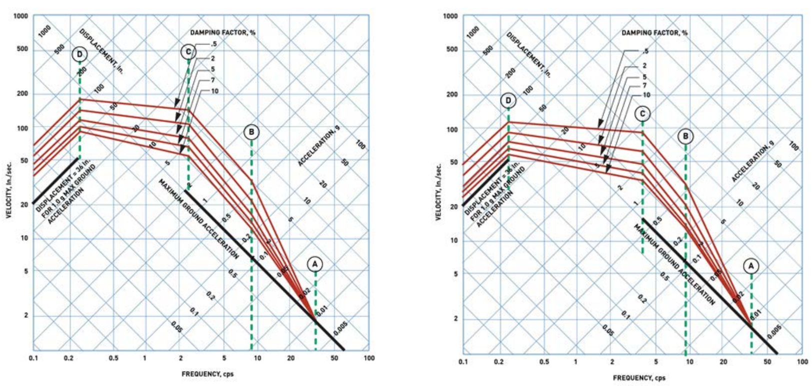
For a particular site, the iterated shear modulus and damping values are typically determined from the results of a number of free-field site response analyses, which are intended to account for the effects of the site-specific design ground motions as well as the site nonlinear properties. If only a single site response calculation is performed, with the low strain property of each material layer selected at its BE value, the resulting iterated property is then determined. The LB values of soil/rock shear modulus (G) can then be defined in terms of their BE values as:

$$GLB = GBE / (1+COV) \quad (1)$$

where COV is the coefficient of variation considered appropriate for the site materials. The corresponding damping properties should be defined at the compatible strains associated with the shear moduli.
For well-investigated sites (see RGs 1.132 and 1.138), the COV should be no less than 0.5. For sites that are not well investigated, the COV for shear modulus shall be at least 1.0.
In this study, the BE and LB cases are analysed because UB (Upper-Bound) case may be sufficiently strong and expected to lead to smaller response than BE, LB. Also, the COV value is adopted 1.0.

SEISMIC INPUT MOTION

In this study, three seismic motions are inputted as seismic motion – DGRS and two GMRS. Basically the DGRS is matched with Reg. Guide 1.60 response spectrum (Figure 3). Two other input motions are GMRS that investigated and derived from the seismic hazard analysis of Wolseong area by KAERI (Figure 4).
The first GMRS has $1x10^{-4}$ hazard UHRS (Uniform Hazard Response Spectrum), and 0.3g ZPA (Zero Period Acceleration). The strongest motion is the second GMRS that has $1x10^{-5}$ hazard UHRS (Uniform Hazard Response Spectrum) and 0.6g ZPA.



(a) Horizontal Direction (b) Vertical Direction

Figure 3. DGRS matched with Reg. Guide 1.60 Response Spectrum

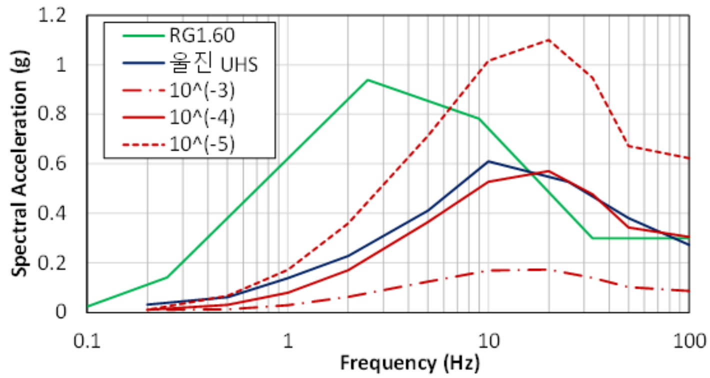
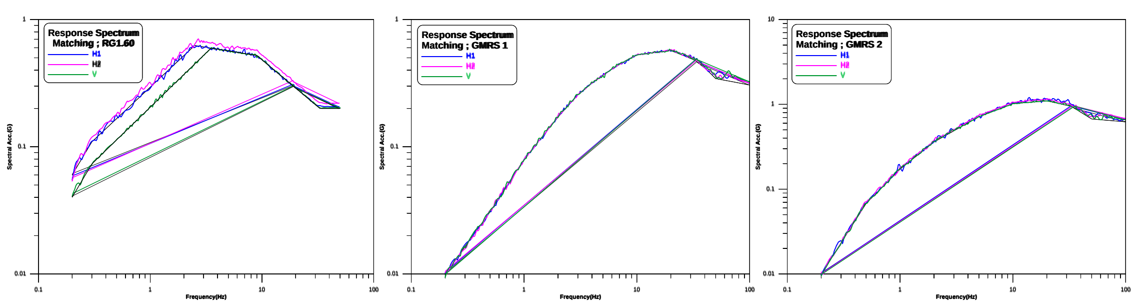


Figure 4. GMRS 1 (10^{-4}) and GMRS 2 (10^{-5})

The SSI analysis by ACS SASSI in frequency domain needs time history acceleration data as input. Therefore, the input response spectra are converted to the corresponding artificial time histories. In artificial time history generation process, the response spectrum of generated time history is compared with the given response spectrum. The cross-correlation between each time history set (X, Y and Z) is calculated and checked whether it is smaller than 0.16 following SRP 3.7.1.
In Figure 5, the response spectra of generated time histories are well matched with the given spectra. The cross-correlations between each direction are also smaller than 0.16 (Table 3). The generated time histories of each design response spectrum are shown in Figure 6 respectively.

Table. 3 Cross-Correlation between each Direction of Generated Time Histories

Directions	RG 1.60	GMRS 1	GMRS 2	Remarks
H1 vs H2	0.083	-0.093	-0.141	< ±0.16
H2 vs VT	-0.040	-0.031	-0.012	< ±0.16
H1 vs VT	0.060	0.041	0.058	< ±0.16

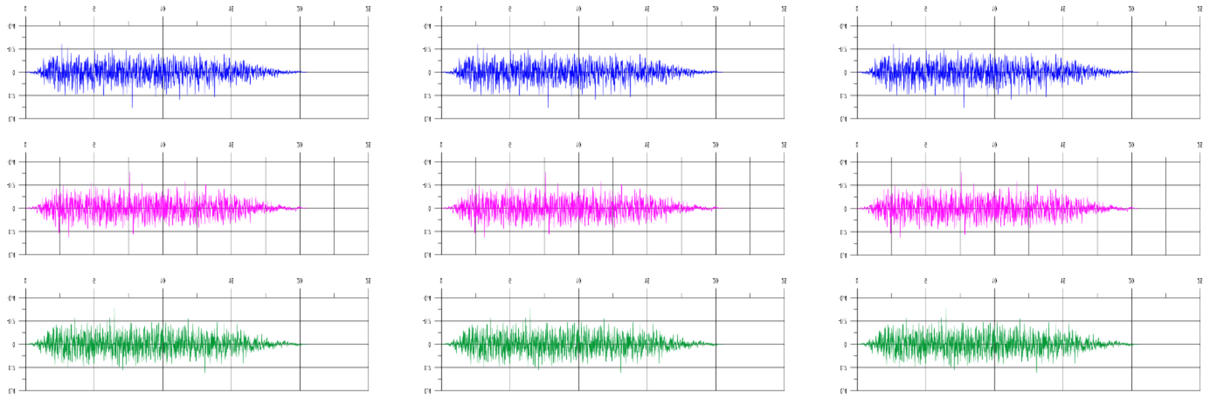


(a) RG 1.60 (b) GMRS 1 (c) GMRS 2

Figure 5. Response Spectrum Matching

ANALYSIS MODELING

The LILW Silo, Construction and Operation Tunnel of Figure 6 are modelled with the thick shell of finite element for ACS SASSI program. The SSI Model has total 17612 nodes and 10588 interaction nodes, and 23540 elements. The model detail is shown in Table 4.

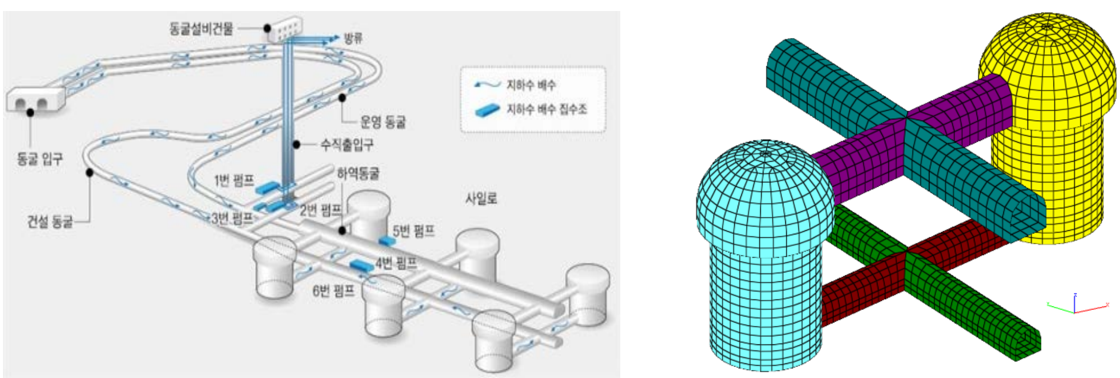


(a)RG 1.60 (b) GMRS 1 (c) GMRS 2

Figure 6. Generated Artificial Time Histories

Table 4. Time Histories

Part	Element #	Remarks
Silo Excavated	9980	Excavated Soil Solid
LILW	4960	Structural Solid
Dome	3040	Fill Concrete Solid
Silo Shell	2040	Thick Shell
Construction, Operation Tunnel	1540	Thick Shell



(a) Facilities Arrangement (b) Analysis Model

Figure 7. LILW Facilities Arrangement and SSI Analysis Model

SSI ANALYSIS PROGRAM

The SSI analysis of LILW Silo is performed by ACS SASSI program. SASSI, a System for Analysis of Soil-Structure Interaction, consists of a number of interrelated computer program modules which can be used to solve a wide range of dynamic soil-structure interaction problems in two or three dimensions.
The basic methods of analysis adopted by the computer program SASSI are called the flexible volume and the recently developed subtraction methods. These methods are formulated in the frequency domain using

the complex response method and the finite element technique.
In the flexible volume method, the complete soil-structure system, shown in Figure 8 (a), is partitioned into two substructures, namely, the foundation and the structure, as shown in Figure 8 (b) and (c), respectively. In this partitioning, the structure consists of the superstructure plus the basement minus the excavated soil; i.e., the soil to be excavated is retained with the foundation. Interaction between the structure and the foundation occurs at all basement nodes. The equations of motion for the flexible volume method are developed by combining the equation of motion for the structure with those of the soil in the frequency domain using the concepts of sub-structuring, thus leading to:

$$\begin{bmatrix} C_{ss} & C_{si} \\ C_{is} & (C_{ii} - C_{ff} + X_{ff}) \end{bmatrix} \begin{Bmatrix} U_s \\ U_f \end{Bmatrix} = \begin{Bmatrix} P_s \\ P_f \end{Bmatrix} \tag{2}$$

from which the final total motions of the structure can be determined. In these equations, the subscripts s, i, and f refer to degrees of freedom associated with the nodes on superstructure, basement, and excavated soil, respectively. Ps and Pf are the amplitudes of external forces at the superstructure and basement nodes, respectively. C is the complex frequency-dependent stiffness matrix:

$$C(\omega) = K - \omega^2 M \tag{3}$$

The all modular and structure configuration of ACS SASSI are shown in Figure 8.

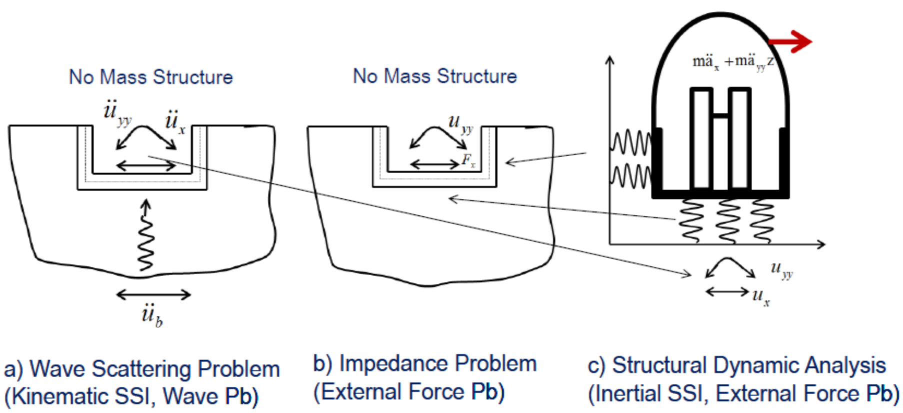


Figure 8. Concept of Flexible Volume Method

ANALYSIS CASES

Total SSI analysis cases are 12 (= 3 motions ⋆ 2 concrete cracks ⋆ 2 shear modulus) in Table 5. ACS SASSI version is V.4.3.3, has the multi-processing function, therefore bigger computing process capacity can give faster analysis results. In this study, 4 Workstations with 48 CPU and 512GB Memory are used for SSI analysis.

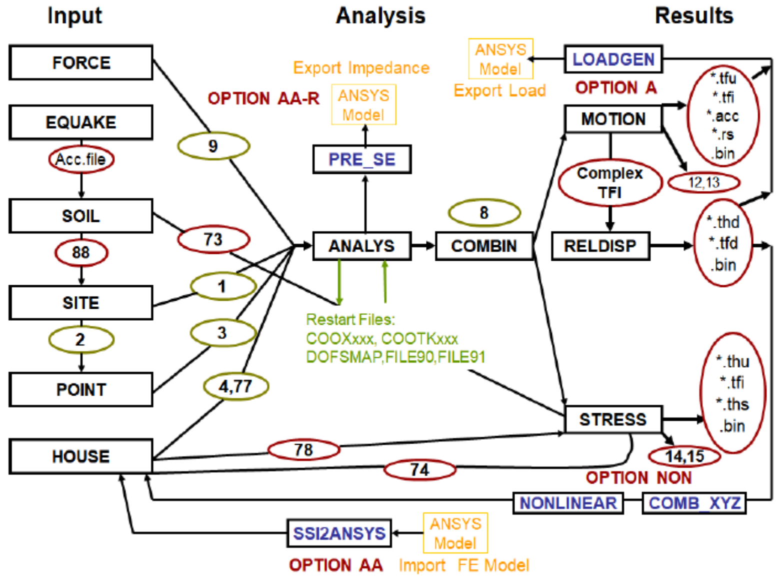


Figure 9. ACS SASSI Modular Configuration

Table 5. SSI Analysis Case

Input Motion	Concrete Crack	Shear Modulus	Case	Remarks
RG 1.60	Un-cracked	BE	1R-UC-MG	
		LB	2R-UC-SG	
	Cracked	BE	3R-CR-MG	
		LB	4R-CR-SG	
GMRS 1	Un-cracked	BE	1G1-UC-MG	
		LB	2G1-UC-SG	
	Cracked	BE	3G1-CR-MG	
		LB	4G1-CR-SG	
GMRS 2	Un-cracked	BE	1G2-UC-MG	
		LB	2G2-UC-SG	
	Cracked	BE	3G2-CR-MG	
		LB	4G2-CR-SG	

ANAYSIS RESULTS

As SSI analysis results, 3 stress components of silo are compared with the concrete allowable stress. The calculated stresses for check are σ_x, σ_y, and τ_{xy}. After SSI analysis, the thick shell element of ACS SASSI will output 3 membrane forces per unit length, 2 transverse shear forces per unit length and 3 plate moments per unit length at the centre of the element. The thick shell element membrane forces and moments are computed in respect to the local element coordinate system. The forces are in units of force/length (F/L), and the moments are in units of moment/length or force-length/length (FL/L).
The 8 output components in the element local system are shown in the following Figure 10:

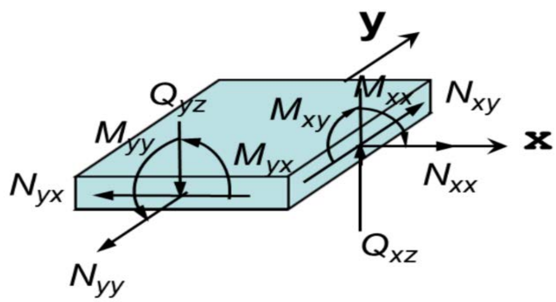


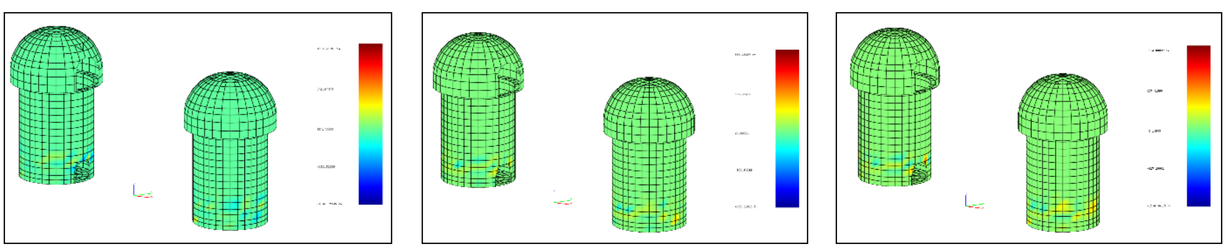
Figure 10. Output Components in the Thick Shell Element Local System

Where the shell stresses are computed as follows:

$$\sigma_x = \frac{N_{x_G}}{t} \pm \frac{6 * M_{x_G}}{t^2} \qquad \sigma_y = \frac{N_{y_G}}{t} \pm \frac{6 * M_{y_G}}{t^2} \qquad \tau_{xy} = \frac{N_{xy_G}}{t} \pm \frac{6 * M_{xy_G}}{t^2} \tag{4}$$

The maximum stress contours of LILW Silo under each input motion are show Figure 11. The maximum stress is 28.9 MPa (Table 6), lower than allowable stress of the re-inforce concrete 37.7 MPa. It's means there is no damage in Silo by the beyond design basis earthquake such as GMRS 2. In Figure 12, it can be seen that Case 1 (Un-cracked concrete and BE) is the largest and Case 4 (Cracked concrete and LB) is the second largest stress generation tendency, where S_x is σ_x, S_y is σ_y, and T_{xy} is τ_{xy}.

For more stress check, '1R-UC-MG' case in Table 5 is identified as critical. This case is an un-cracked concrete and BE under RG 1.60 input. The position where the maximum stress occurred is the dome and shell junction (shell element #694) at Silo #2 (Figure 13). Table 7 is the stress at the shell element # 694, the trend of main component σ_x for each case is very similar to the maximum stress σ_x case (Figure 14).



(a) RG 1.60 (b) GMRS 1 (c) GMRS 2

Figure 11. Stress Contour under each Input Motion (Example)

Table 6. Maximum Stress of Silo of each Analysis Case

[MPa]

Input Motion	σ_x				σ_y				τ_{xy}			
	Un-cracked		Cracked		Un-cracked		Cracked		Un-cracked		Cracked	
	BE	LB	BE	LB	BE	LB	BE	LB	BE	LB	BE	LB
RG 1.60	28.9	9.6	4.9	14.6	28.0	14.1	8.9	17.2	7.8	2.9	2.6	3.5
GMRS 1	11.9	4.3	2.9	9.3	11.9	7.2	4.0	10.5	3.5	1.3	1.4	2.1
GMRS 2	23.0	9.3	4.7	15.4	23.8	14.7	8.1	17.2	5.1	2.4	2.2	3.0

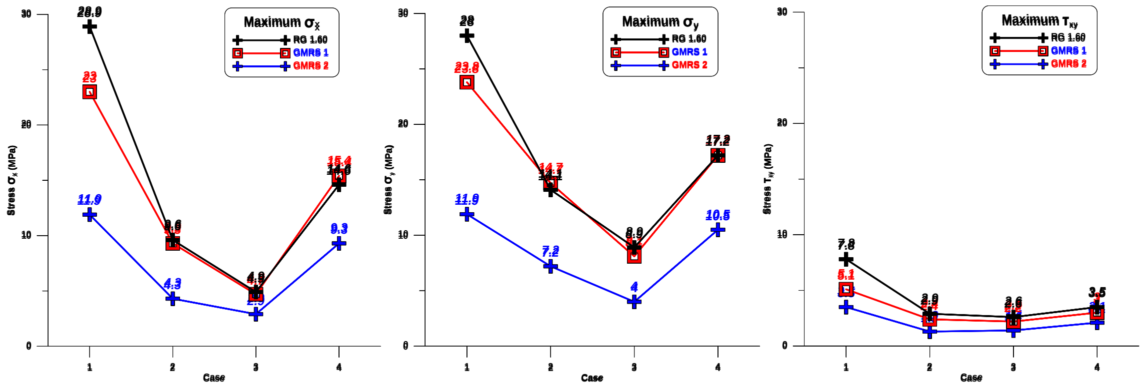


Figure 12. Maximum Stress Graph of each Case

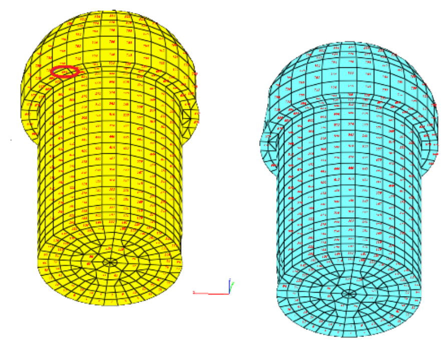


Figure 13. Maximum Stress Part under RG 1.60 - #2 Silo Element 694 Location

Table 7. Maximum Stress at #2 Silo Element 694 in each Analysis Case

[MPa]

Input Motion	σ_x				σ_y				τ_{xy}			
	Un-cracked		Cracked		Un-cracked		Cracked		Un-cracked		Cracked	
	BE	LB	BE	LB	BE	LB	BE	LB	BE	LB	BE	LB
RG 1.60	28.9	8.6	3.9	13.3	2.1	0.3	0.8	0.1	3.5	1.3	1.4	0.5
GMRS 1	11.8	4.0	2.0	9.0	0.9	0.6	0.1	0.6	0.1	1.2	0.5	1.2
GMRS 2	22.7	7.7	1.8	11.8	1.7	0.1	0.2	1.0	0.3	0.8	0.8	0.6

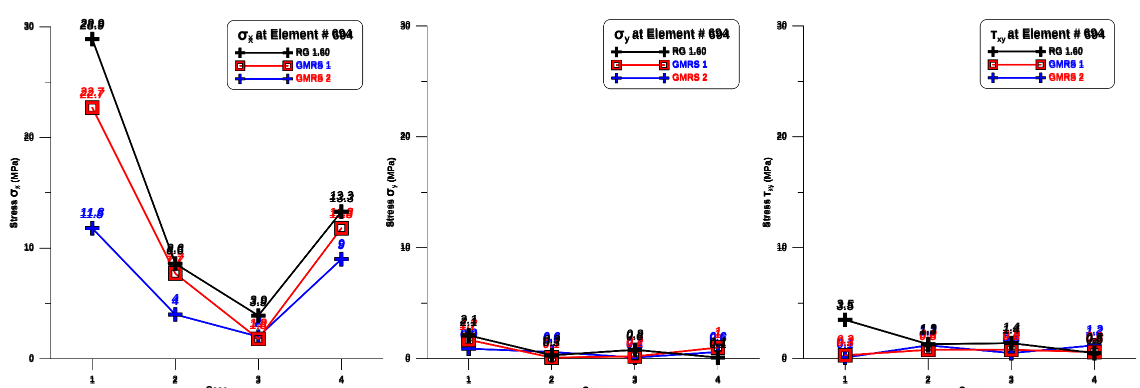


Figure 14. Stress Graph of each Case at #2 Silo Element 694 in each Analysis Case

CONCLUSION

In this study, SSI analysis of LILW disposal facility in Gyeongju was performed to provide the damage level by severe earthquake for calculation the dose of radiation. In SSI analysis process, several parameters such as the input motion, concrete crack condition, and variation of soil media. To consider the parameters in SSI analysis, total 12 combination cases are selected and analysed.

Under severe conditions, the following conclusions could be drawn.

- The un-cracked concrete and BE case under RG 1.60 Spectrum is critical.
- The maximum stress of the critical case is smaller than the concrete allowable stress.
- Therefore, there is no damage in LILW Silo under the beyond design basis earthquake.

Through more study, it is necessary to further interpret topics such as the Non-linear SSI analysis and Probabilistic SSI analysis.

ACKNOWLEDDGEMENT

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