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Comparison of the Results from Theoretical Formula and Dynamic Analysis of a Seismically Isolated Structure

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ABSTRACT

In domestic construction of NPPs (Nuclear Power Plants), the seismic resistance design has generally been adopted because it has been found to be sufficient to guarantee the seismic safety. However, the S.I. (Seismic Isolation) technique is expected to be additionally needed for NPPs in high seismicity regions because it can mitigate the effects of an earthquake by isolating the structure from strong ground motion.

In this study, responses of a seismically isolated structure, such as displacement and shear force, were obtained based on the design guides of non-nuclear industries and then the results of time domain non-linear analysis were compared to the previously calculated results.

1. INTRODUCTION

The E.L.F. (Equivalent Lateral Force) procedure including fundamental dynamic formula is mainly used in the preliminary design step of seismic isolation structures in non-nuclear industries. In the method, properties of the isolation device, such as the damping ratio and period, are firstly determined and then the results, such as displacements and shear forces, can be additionally obtained through the procedure. In the next step, the dynamic analysis is performed to improve and check the validity of prior calculations and design. In the step, either non-linear time domain analysis or frequency domain analysis can be selected. However, most of the recently published overseas S.I. guidelines have recommended the non-linear time domain analysis(JNES, 2010; Bozidar, 2011).

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2. Input Motion

In this study, the input motion set CMS1+ was applied on the basis of Reg. Guide 1.60 spectrum but enriched in the high frequency ranges. A single set of acceleration time histories composed of two horizontal components and one vertical component was artificially generated to match the spectrum. The peak ground acceleration was set as 0.3g corresponding to the SSE(Safety Shutdown Earthquake) level. Each component had 20.48 second total duration with strong motion duration of 7 seconds. The cross-correlation coefficients between the 3 components of the time histories were less than 0.16. All the input motions were developed to meet the requirements in SRP section 3.7.1(2007) including requirement for power spectral density function.

3. RESPONSES CALCULATED BY E.L.F. PROCEDURE (Theoretical Formula)

Fictitious NPP (Nuclear Power Plant) was modeled for the analysis and total weight of the structure used was approximately 4,700,000 kN and Isolators (210 EA.) were used to support the foundation and superstructure. In the E.L.F. procedures, one of the two structure periods in T^2(=TxT) is fixed at 1 second and therefore T^2 becomes T. The acceleration coefficient for the calculation of displacement in the S.I. system was also obtained with 1 second period of the design response spectrum. In this study, the damping ratio of the S.I. system was set at 10 % and effective period of the system used was 2 sec.

3.1. Maximum Displacement (D_M)

The maximum displacement of the S.I. system can be calculated by using the following equation.

$$D_M = \frac{g}{4\pi^2} \bullet \frac{S_{M1}T}{B} \quad (1)$$

Here, D (m) denotes the displacement of the S.I. system and g (m/sec^2) is the gravitational acceleration. S_{M1} is the acceleration coefficient of the design response spectrum at 1 second period considering the ground characteristics. T (sec) is the effective period of the S.I. system, and B is the damping coefficient related to the damping ratio of the seismic isolation system. However, the additional accidental eccentricity was not considered to induce the total maximum displacement. The maximum displacement calculated with the known values was 178.262 mm.

3.2. Base Shear of the Basemat (V_{bmax})

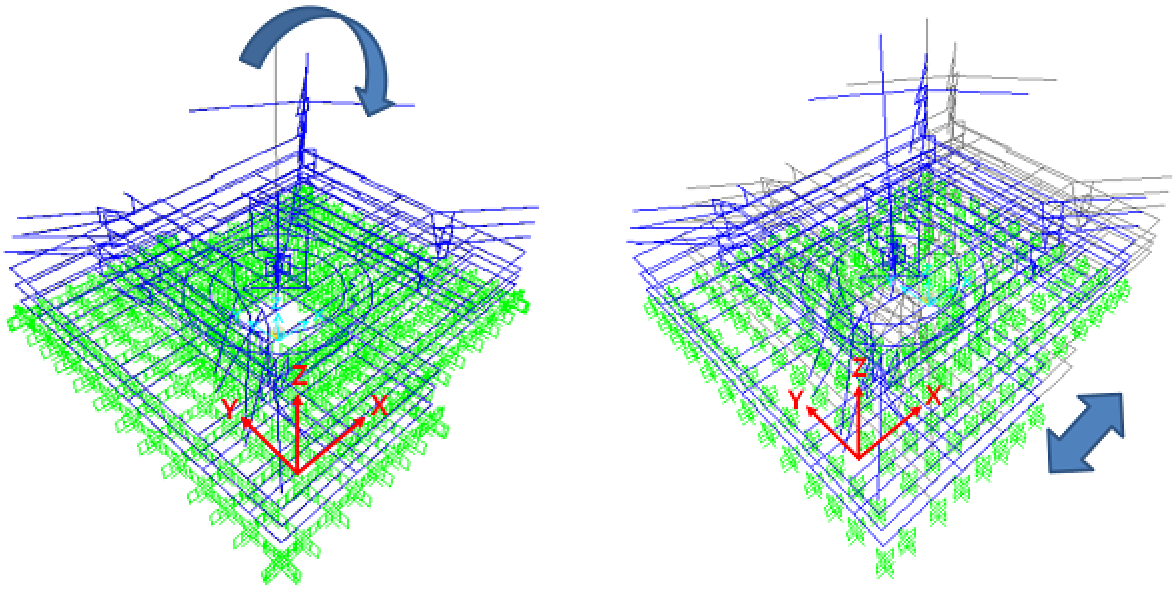
The base shear of the basemat with isolators is reduced up to smaller value in comparison with the foundation without isolators. The smaller base shear can be obtained from the following equation.(2),

$$V_{b\max} = [1.3 \times (\frac{4\pi^2}{g} \times \frac{W}{T^2})] \times D_M \quad (2)$$

Here, W denotes the total weight of the S.I. system and a 30% margin is included in the calculation to consider the variation of the stiffness. In common isolator design processes, a value of the base shear (V_{bmax}) is divided by the total number of isolators. It is the shear force of each isolator. The shear force of each isolator calculated with known values was 5218.095 kN.

4. MODAL ANALYSIS

The superstructure of the target NPP structure was modeled as a lumped mass beam stick and was combined with the finite element mat foundation model. The 1st mode period of the fixed-base structure shown in Fig 1(a) was about 0.1881 seconds and it shows a rocking mode shape. On the other hand, the 1st mode period of the seismically isolated structure, shown in Fig 1(b), is about 2.0 seconds and it shows a translational mode shape.



(a) 1st mode of fixed base structure **(b) 1st mode of base isolated structure**

Fig. 1 Mode Shapes of Fixed Base and Seismically Isolated structure

Table.1 Modal Analysis Results of Structure considering Isolators

Mode	Frequency (Hz)	Period (Sec)	Modal Participating Mass Ratio			Mode Shape	
			Ux	Uy	Uz		
1st	0.50327	1.98701	0.99998	9.42E-6	3.917E-13	Translation	Ux
2nd	0.50372	1.98524	9.42E-6	0.99998	1.063E-15		Uy
3rd	5.45242	0.18340	9.814E-15	2.322E-6	5.747E-14	Rocking	Ry
4th	5.47635	0.18260	2.767E-6	1.786E-14	1.794E-11		Rx

5. DYNAMIC ANALYSIS

Table.2 shows the dynamic analysis cases performed in this study and each case shows different coupling of seismic loading and directions. Mokha et al.(1993) demonstrated that the S.I. system without coupling between components of motions under-predicts the value of displacement, whereas it over-predicted the value of shear forces. Furthermore, coupling effects between the horizontal plane and vertical axis can exist. Therefore, fully coupled 3D models are preferred for the analysis.

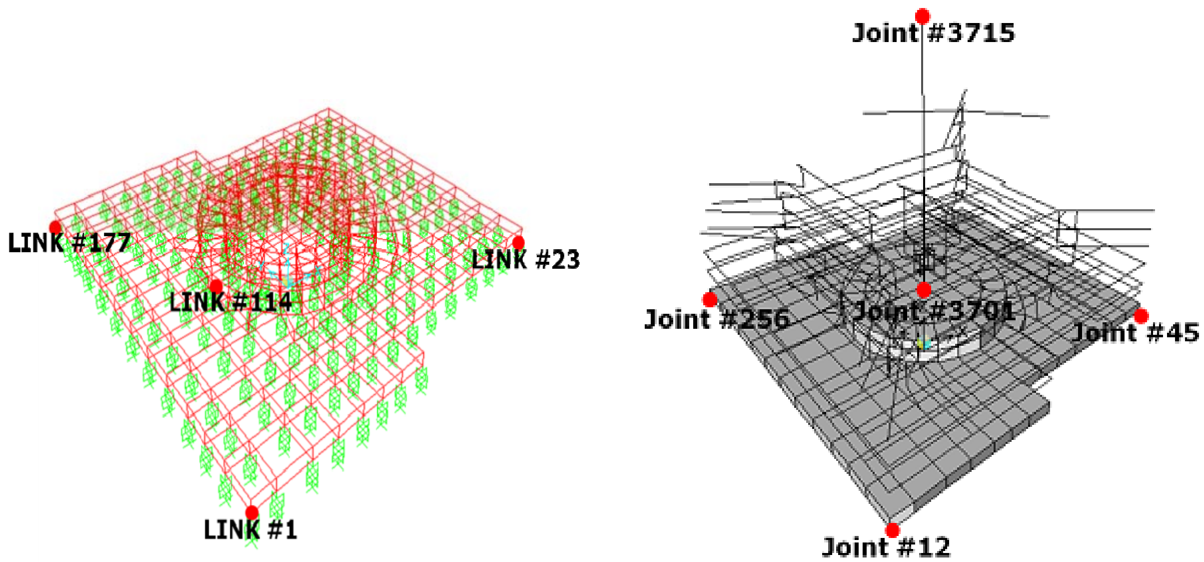
Table.2 Dynamic Analysis Results

Loading Direction	Case.I	Case.II	Case.III	Case.IV
Ux	0.3 g	-	0.3 g	0.3 g
Uy	-	0.3 g	0.3 g	0.3 g
Uz	-	-	-	0.3 g

※ PGA=0.3g / Direction of Sampling Response : Case.I, III, IV(Ux), Case.II(Uy)

5.1. Acceleration Responses

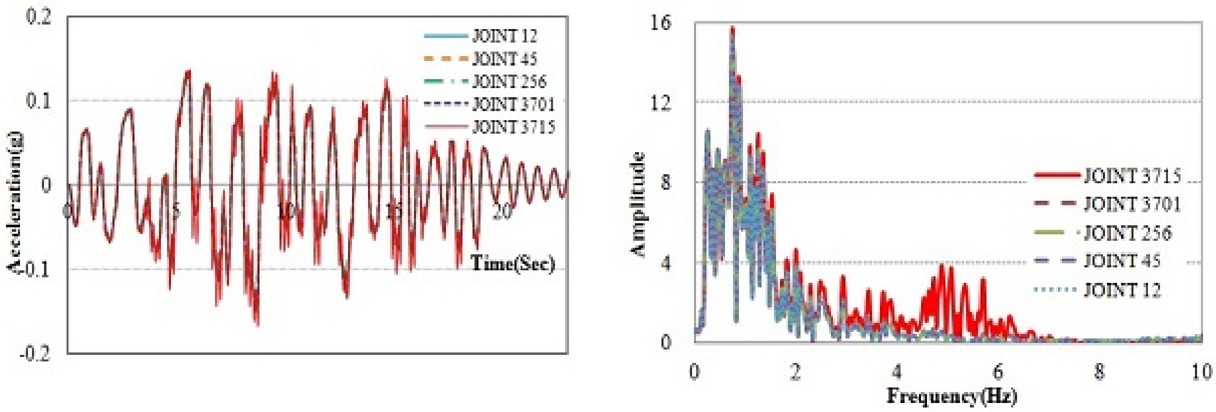
Fig.2 shows the sampling location of the response results. The acceleration responses as well as displacement responses were obtained from specific joints of the finite elements. As for the shear forces of isolators, the analysis results were obtained from link elements as shown in Fig 2.



(a) Arrangement of Isolator Units (b) Superstructure supported by Isolators

Fig. 2 Locations of Sampling Data

Fig.3(a) shows the acceleration responses in the time domain and high frequency contents can be found in the results. In the frequency domain, it is found that the main frequency ranges are shifted and the frequency ranging of 4~6 Hz are partly increased.



(a) Acceleration Response-Time Histories **(b) FFT of Acceleration Responses**

Fig. 3 Acceleration Responses of Fully Coupled 3D Analysis(Case.IV)

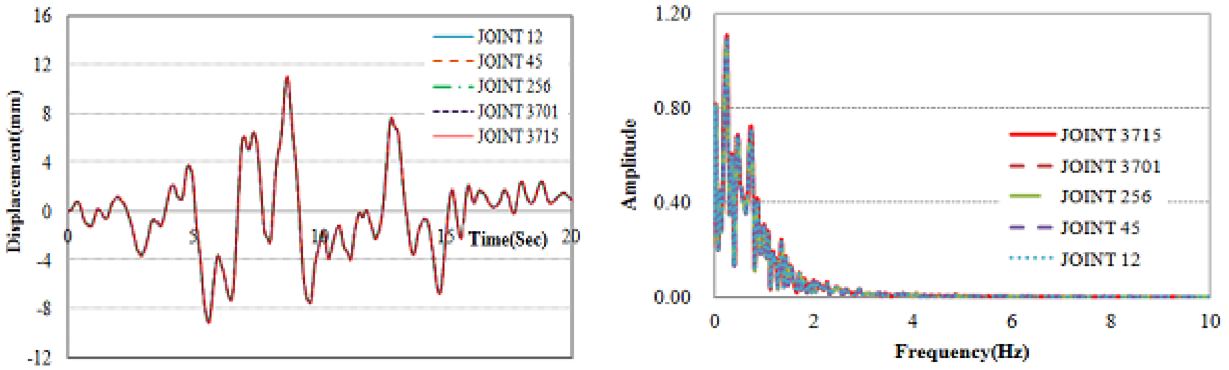
The reason for the main frequency shifting is assumed to be the non-linear characteristics of the isolator unit and the high frequency contents are due to the Rocking mode of the structure. Table.3 shows the acceleration response results of all analysis cases. The coupled seismic motion tends to make less acceleration responses than the uncoupled motions. Because all the results show little difference in different joints, the S.I. system shows good performance.

Table.3 Absolute Maximum Acceleration Responses of Dynamic Analysis

	Joint 3715	Joint 3701	Joint 256	Joint 45	Joint 12
Case.I	0.1857 g	0.1594 g	0.1597 g	0.1597 g	0.1597 g
Case.II	0.1837 g	0.1606 g	0.1606 g	0.1606 g	0.1606 g
Case.III	0.1679 g	0.1475 g	0.1473 g	0.1473 g	0.1474 g
Case.IV	0.1678 g	0.1475 g	0.1502 g	0.1469 g	0.1502 g

5.2. Displacement Responses

Fig.4 shows displacement results in time and frequency domain and Table.4 summarizes the displacement results for all the analysis cases. The S.I. system without coupling of components of motions in horizontal plane under-predicts the value of the displacement, which is consistent with conventional research (Mokha et al., 1993). However, little coupling effect between the horizontal plane and vertical axis exist in this study.



(a) Displacement Response-Time Histories **(b) FFT of Displacement Responses**

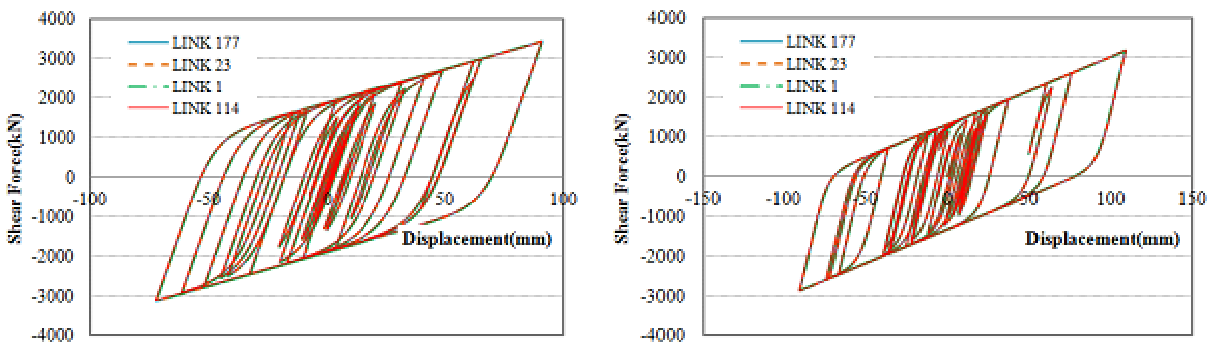
Fig. 4 Displacement Responses of Fully Coupled 3D Analysis(Case.IV)

Table.4 Absolute Maximum Displacement Responses of Dynamic Analysis

	Joint 3715	Joint 3701	Joint 256	Joint 45	Joint 12
Case.I	92.807 mm	91.182 mm	90.950 mm	90.927 mm	90.950 mm
Case.II	92.666 mm	91.054 mm	90.819 mm	90.802 mm	90.819 mm
Case.III	110.851 mm	109.169 mm	108.935 mm	108.917 mm	108.949 mm
Case.IV	110.851 mm	109.169 mm	108.926 mm	108.921 mm	108.940 mm

5.3. Shear Forces of Isolators

Fig.5 shows hysteresis loops of the analysis case.I and case.IV to evaluate the effects of coupling motions and Table.5 summarizes force and displacement results of all analysis cases. In the results, on the contrary to the displacements, it is found that S.I. system without coupling of components of motions in horizontal plane over-predict shear forces, which is consistent with conventional research (Mokha et al., 1993). However, little coupling effects between the horizontal plane and vertical axis exist.



(a) Hysteresis Loops(Case.I) **(b) Hysteresis Loops(Case.IV)**

Fig. 5 Hysteresis Loops of the Isolators

Table.5 Absolute Maximum Shear Forces and Displacements of the Isolators

		Link 177	Link 23	Link 1	Link 114
Case.I	Shear Force (kN)	3429.789	3429.399	3429.789	3430.878
	Displacement (mm)	90.950	90.930	90.950	91.010
Case.II	Shear Force (kN)	3427.570	3427.289	3427.570	3428.650
	Displacement (mm)	90.820	90.800	90.820	90.880
Case.III	Shear Force (kN)	3182.603	3182.233	3182.830	3183.790
	Displacement (mm)	108.940	108.920	108.950	109.010
Case.IV	Shear Force (kN)	3181.742	3182.524	3182.719	3183.721
	Displacement (mm)	108.930	108.920	108.940	109.010

6. Comparison of the Results between Theoretical Formula and Analysis

Table.6 shows comparison of the displacements between the dynamic analysis and theoretical formula cases. In the results, the displacements obtained from theoretical formula are much larger than that of the dynamic analysis. As referred in the previous part, the torsion induced by eccentricity is not considered in the calculation using theoretical formula. Actually, the modal analysis and dynamic analysis results show that rocking motion is not critical. Therefore, at least in this study, it can be said reasonable that no torsion is considered in the calculation using theoretical formula.

Table.6 Comparison of Displacements between Theoretical Formula and Analysis

	Theoretical Formula	Dynamic Analysis(Case.IV)				
		Joint 3715	Joint 3701	Joint 256	Joint 45	Joint 12
Displacement (mm)	178.262	110.851	109.169	108.940	108.926	108.921

In the calculation using theoretical formula, a value of the base shear (V_{bmax}) is firstly calculated and then shear force of each isolator is finally obtained. Table.7 shows comparison of the shear forces between the dynamic analysis and theoretical formula cases. The shear force results from theoretical formula are also much larger than that of the dynamic analysis, which is caused by the conservative assumption of isolator stiffness and conservatively obtained displacement.

Table.7 Comparison of Shear Forces between Theoretical Formula and Analysis

	Theoretical Formula	Dynamic Analysis(Case.IV)			
		Link 177	Link 23	Link 1	Link 144
Shear Force (kN)	5,218.095	3,181.742	3,182.524	3,182.719	3,183.721

※ Shear Force : Base Shear/Total Numbers of Isolators

CONCLUSIONS

1. Fixed base structure was compared with seismically isolated structure in terms of structural period. The result showed that structural period of the latter was approximately 11 times as large as the former due to the decreased structural stiffness.
2. Displacement of the structure and shear force of the isolators were obtained by using both theoretical formula and dynamic analysis. The results calculated by the theoretical formula were more conservative than analysis results.
3. Acceleration responses of dynamic analysis showed little differences from top to the bottom of the structure and the values of the structures above the isolators were rapidly reduced, which means good performance of S.I. system.
4. Coupling of motions in horizontal plane were found to be important, but the coupling effect by vertical motion was so small that it could be negligible.

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