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A study on methodologies of time-history analysis of the nuclear power plant piping for the multi-support excitation

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ABSTRACT

In seismic analysis using finite element method, a single set of acceleration data is generally used to consider the primary loads due to inertial effects. However, for the piping system in nuclear power plants having multiple supports that are installed at various heights and location, the anchor motion is not ignorable to obtain the exact seismic responses.

In this research, we studied the multi-support input methods which can applies different seismic loads on each support and feasibility of them in finite element analysis. Especially, mode superposition transient analysis, large mass method and displacement input analysis were considered in this research. The input accelerograms are generated in form of artificial earthquake waves using algorithm, and numerical integrated displacement data were generated using baseline correction.

As a result, all of methods could generate well-matching motion parameters to the original acceleration on each support. Also, we confirmed the similarity of stress-based analysis results between large mass method and displacement input method. In addition, it is considered whether there is an appropriate input method to simulate another type of supports by changing the boundary condition on the support area.

INTRODUCTION

Seismic analysis of nuclear power plant interests the response of the structures as well as specific system. Since the analysis costs of finite element model including both structure and particular system is high, research on performing more precise analysis on system is also widely used.

Seismic loads for specific system are varying installed heights. In other words, it is necessary to specify methods for applying different inputs depending on the height of supporting installation. This issue is particularly pronounced in the nuclear power plant piping system. In general, pipes are located on various ranges in order to connect to the other system. Likewise, the pipe supports are installed in various positions to reduce response. Therefore, seismic analysis of nuclear power plant piping system requires multi-support excitation input method which predicts the response through different input for supporting points.

The multi-support excitation is generally performed by response spectrum analysis due to the cost advantages. However, the response spectrum analysis does not correspond to the whole transient analysis, and the study of time-history analysis which predicts a more precise response is being widely conducted. However, the time historical input acceleration requires not only amplitude but also specific phase information unlike regulations for spectrum analysis. Moreover, the uncertainty of phase information along the heights are significant since the installed buildings have their own dynamic characteristics.

As one way, the time history seismic analysis input uses past earthquake waves or artificial seismic waves generated based on past earthquakes. For instance, Kai, S. and Kaneko, N. modelled the structure using beam elements and generated input seismic waves on each height level by applying seismic wave to the ground(2018). The type of data used in the relevant research and industry fields is acceleration. To perform multi-support excitation analysis, it is necessary to confirm an input method that enables independent acceleration input for each point defined as a support. The acceleration value in the form of data with multiple points need to be integrated and the baseline correction to determine the unknown integration coefficients.

In this research, to conduct multi-support excitation, we intend to apply various input methods that generate acceleration on the target support points, unlike the existing acceleration input method. Specifically, we intended to perform on three methods: the mode superposition method, large mass method and displacement input method. In addition, to determine whether multi-support excitation is conducted in computational environment for each method, the correspondence between generated values and input values for analysis. Furthermore, it is intended to select a suitable method for simulating conditions of various types of supporting through seismic analysis by changed boundary conditions of support area.

FINITE MODEL OF PIPING SYSTEM

Figure.1 shows the analysis target, pressurized tube of APR1400. The analysis target is piping system including 8 elbows, the outer diameter of pipe section is 330.2 mm, and the thickness is 33 mm, the radius of curvature is 495.3 mm. The finite element model is composed with 1st order solid elements, and the number of elements are 60,768.

The material of piping system is stainless steel, and the density corresponding to the fluid was applied to the existing density of 7,800 kg/m^3 of the pipes. Specifically, the input density value for the pipe was determined by calculating the total mass based on the volume and density of the fluid occupying the inside of the pipe and adding it to the density of the structure, the way Lee, C K. and Park, N. C. proposed (2020). In addition, elastic analysis performed without any damping consideration to compare the responses according to methodologies. The elastic modulus and Poisson's ratio corresponds to 175.4 GPa and 0.31.

The supports of piping system assumed installed at three different area according to the height. The difference in installation height of support #1 and #3, based on support #2, is 2.16 m and 2.68 m respectively. In addition, the support behaviour modelled by setting boundary condition for the cross section of the pipe. Before analysing the response according to the supporting area, we compared the methods by assuming that all the nodes on support cross sections constrained. Among them, to determine the characteristic of support #2 placed during the progress of piping structure, finite element analysis performed on the case considering the entire support constrained (all supported) as well as the case only support #1 and #3 (ends supported).

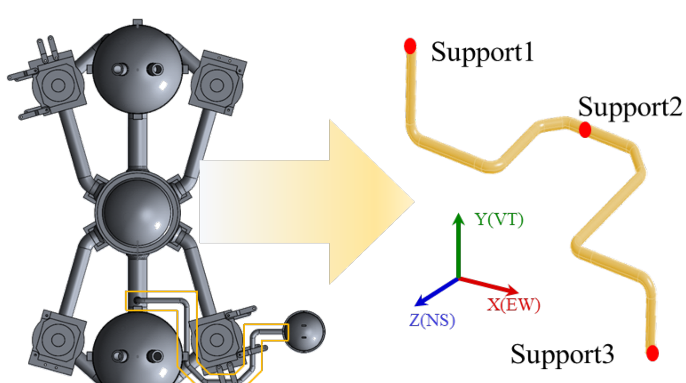

Figure 1. Schematic diagram of target piping system.

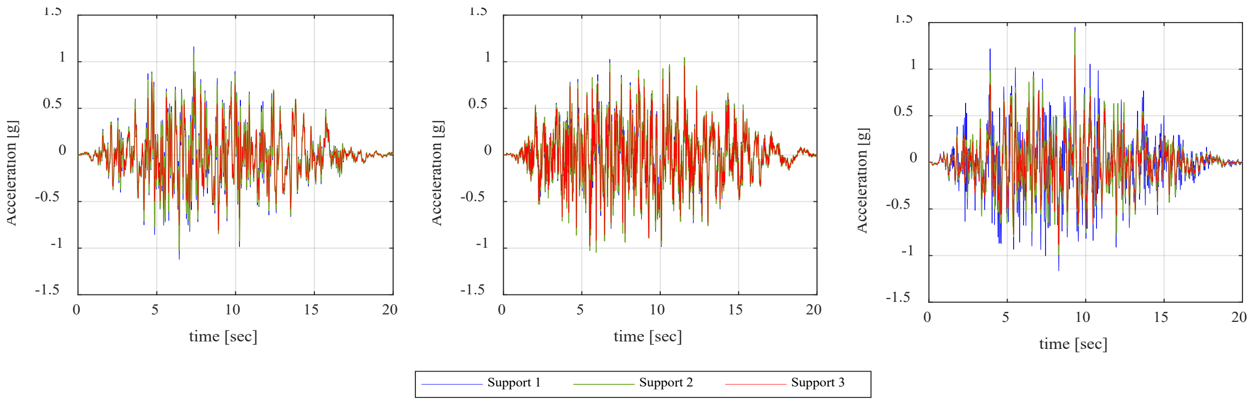

Figure 2. 3-axis input acceleration data on each support.

Lee, S. J. and Park, N. C. generate artificial earthquake wave based in the floor response spectrum (2021). The time historical acceleration data for each support are also artificial earthquake wave and the shape of the acceleration over time is shown in Figure. 2. Based on support #2, the root means square value has a difference of + 5.7 %, and -10.1 %, respectively. The total input time is 20 seconds, and the time step was set to 0.005 s to identify the responses up to 100 Hz. In addition, artificial seismic wave was generated to have the same phase with respect to all supports in this research. Seismic analysis is simulated using ANSYS 2021R2. Here, the analysis is performed with Hilbert-Huang transform (HHT) algorithm for large mass method and displacement input method. The preconditioned conjugate gradient (PCG) algorithm is used for the mode superposition method.

METHODOLOGIES OF MULTI-SUPPORT EXCITATION

At first, input methodologies are divided into whether to perform a full transient analysis. In full transient analysis, all of nodes in finite model participate in every time step, so it is precise to consider the transient responses. On the other hand, mode superposition method uses reduced matrix determined by pre-calculation participate calculation. It leads to cost effectiveness, but it can be only used in linear analysis due to the limitation of superposition.

Also, we studied an input method that generate same acceleration on the supporting area. In other words, generate same acceleration by applying remote loads or displacement without directly applying acceleration to the support. In this research, one method using the load as an input corresponds to large mass method.

Mode superposition method

Craig and Bampton described an equivalent equation of motion for constrained boundary condition based on mode superposition (1968). Therefore, through the mode superposition method, it is possible to input the acceleration independently for each support. The principle of the mode superposition methodology is to reflect the transient responses even with a smaller amount of calculation through modal information. In addition, order of the reflection modes is a factor that directly determines the analysis process. The higher the reflection order, the better the agreement with the full transient analysis, but the opposite relationship with the analysis cost. The reflection order in this study was determined based on the effective mass for the 3-axis determined from the mode analysis results. Specifically, the mode which the cumulative effective mass corresponding to 90% or more was selected, and seismic analysis was performed up to 56th.

Large mass method (LMM)

Kim, Y. W. and Jhung, M. J. developed seismic analysis method that inputs acceleration through virtual mass assignment (2011). The point acceleration input is possible by applying the large mass, which is one of the general methods that use acceleration input in seismic analysis. In this method, relatively large mass compared to the structure is attached to the support area, and the load (acceleration × large mass) could generate acceleration on the support.

Unlike the existing acceleration input, the load type of each point is also possible, so it is possible to input consistently with multi-support excitation, and there is an advantage that the given acceleration data can be used as it is. The mass used in seismic analysis was defined for each support, and the mass was defined as 10^3 times that of the piping system.

Displacement input method

Since the displacement input can predict the relative displacement between supports, this method could analyse the seismic anchor motion more precisely than the other methods. In order to use the time history displacement as an input, numerical integration should be preceded. However, the displacement value at the final moment would be drifted from the initial position depending on the setting of the initial integration point. To reduce this error, Chao P. and Hua, S. suggested proper baseline correction method using traditional polynomials (2016).

Baseline correction was performed and it was confirmed that the two values suggested in the preceding research: Drift ratio and Amplitude ratio, are within the allowable range. As shown in Figure. 3, the acceleration data integrated by Newmark integration and all the displacement data are corrected. In addition, by applying the corrected displacement into the finite element analysis, we confirm that generated acceleration set on analysis have consistency with the existing representative acceleration.

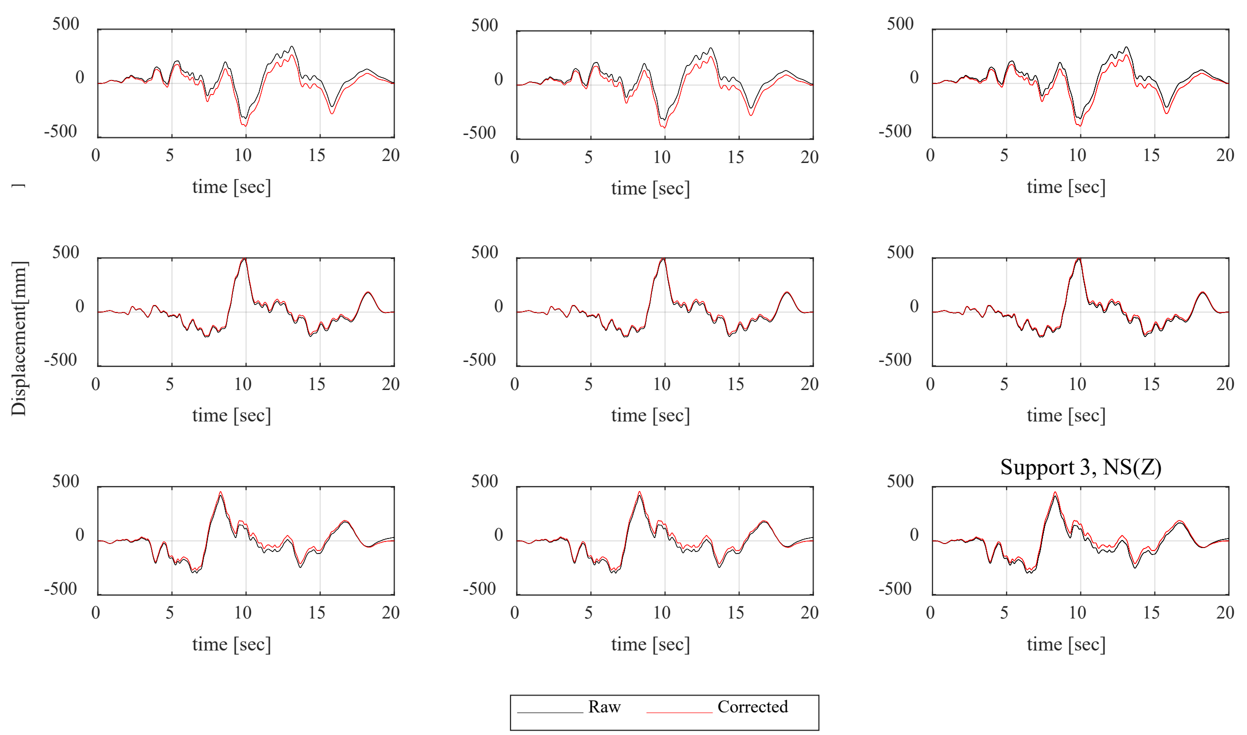

Figure 3. Generated time-historical displacement data using baseline correction

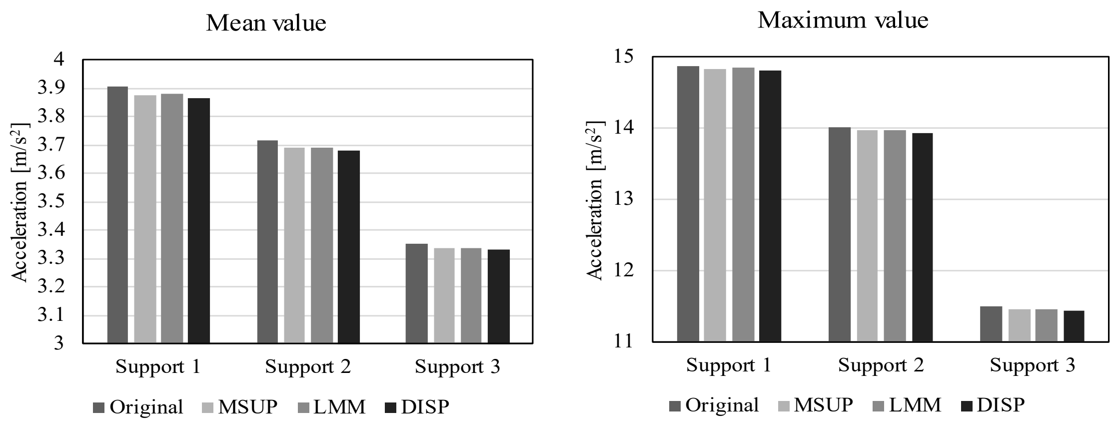

Figure 3. Comparison of the generated acceleration on each support according to the methods.

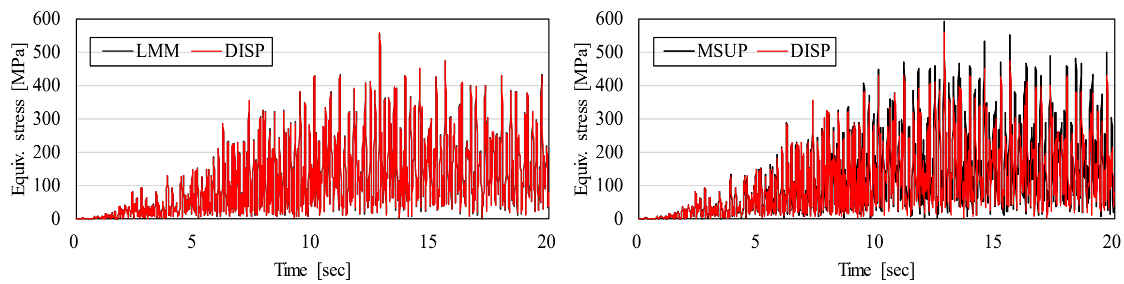

Figure 4. Time-historical analysis results for ends supported case based on von-Mises stress.

ANALYSIS RESULTS

In order to distinguish whether the multi-point excitation condition is satisfied, we compared the input acceleration for each support according to methods. Figure. 3 shows the mean and the maximum value of magnitude of acceleration vectors on each support. The generated acceleration data have an error of up to 1.1% for all methods with respect to the original acceleration, so multi-point excitation was performed with support points as input points so that valid multi-support excitation seismic analysis consistent with the representative acceleration data was performed for all three methodologies.

The maximum value of von-mises stresses was compared for the vulnerable part where the maximum stress appeared. In addition, the values corresponding to the maximum stress occurred are shown in Table 1 for all analysis cases. Also, Figure. 4 shows the time historical stress diagram on the vulnerable node according to the methods for the ends supported analysis case. As shown in Figure 4, the time at which the maximum stress occurs in the large mass method and the displacement input method coincides. Also, for the two input methods, the difference between the maximum stress values is 0.5%, which is consistent with the results. On the other hand, the acceleration input method using the mode superposition method has a similar tendency, but the stress distribution is larger than other methods, specifically it appears to be about 6% larger than the results of other input methods. Also, in the case of ends supported analysis, all weak parts have the same weak part near support #1. In the case of all supported analysis, the consistency between the large mass method and the displacement input method is high and the time at which the maximum stress occurs is the same. However, the difference between the maximum stress generation time and the maximum stress magnitude between the mode superposition method and the other methods is remarkable. The location where the maximum stress occurred is the same as the elbow near support #3. the maximum stress has a difference about 37%. In summary, the coherence of responses to the multi-point

Table 1: Multi-support excitation results for each analysis case.

method	analysis case		
	all supported	ends supported	B.C. changed on support 2
mode superposition	234	591	285
LMM	171	558	256
displacement input	170	556	257

excitation analysis is high in the large mass method and the displacement input method, and the error in the mode superposition method increases as the number of supports increases. The cause of this error is that the degree of freedom that elements can have in the analysis process is limited. Specifically, when compared with the degree of freedom that elements in the full transient analysis can have, an error occurs in predicting the transient behaviour because the limited mode order limits the degree of freedom in the modal coordinate system. Therefore, the input method applying the mode superposition method can be an appropriate input method only for the simulated piping system with a simple support structure such as the 'ends supported' analysis case.

To confirm the responses according to methods, analysis performed under the assumption that the support is completely constrained. Specifically, the analysis model was constructed so that the cross section of the support base defined as the support point was not allowed to be deformed and all the nodes placed on the cross section had the same degree of freedom. However, the actual installation and behaviour of supports are diverse, and different multi-support excitation responses may be derived depending on the boundary condition of support. Therefore, seismic analysis was performed with different boundary condition for support #2. In other words, additional analysis is performed that each node to have an independent degree of freedom. we studied the set-up for inputting the same boundary conditions, and the maximum stress results with multi-support excitation time history analysis are shown on the right side of Table 1. Since the constraints condition is smaller than the 'all supported' analysis case, it is shown that the maximum stress increases with respect to the 'all supported' analysis case.

CONCLUSION

In this research, we conducted the multi-support excitation seismic analysis for piping system having 3 supports with height difference. All finite element analysis is conducted as time history analysis simulating transient behaviours, and we select three different methodologies: transient mode superposition method, the large mass method, and the displacement input method. In order to conduct multi-support excitation in finite element analysis, we generate an artificial seismic acceleration history through some assumption and verify that the acceleration data generated in analysis match the original acceleration based on the root mean square and the maximum value. In other words, it was confirmed that the multi-support excitation is simulated on the finite element analysis for each method. In addition, the results of this analysis case with boundary condition changed shows the similar response tendency in other analysis cases. Furthermore, considering another type of support, additional analysis is performed in which the boundary conditions of the support placed during the progress of piping structure. In this analysis case as well, it was verified that the seismic response tendencies according to the method are the same, and the consistency of the level of response increase / decrease depending on the degree of restraint was confirmed even if there were multi-support excitation seismic analysis.

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