A Study on the Criterion of Fixed Base Condition in Soil-Structure Interaction Analysis of Nuclear Power Plant Structures

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ABSTRACT

The major concern of this study is a criterion associated with fixed base condition in seismic analysis of nuclear power plant (NPP) structures. The parametric studies are performed to validate that the criterion described in the industrial design code is reasonable in engineering sense. The various shear wave velocities of foundation medium and the various stiffnesses of super-structure are considered as parameters. The comparative objects are the dynamic characteristics and the dynamic responses obtained from modal analyses and harmonic load analyses for several idealized structural models. The study results indicate that the soil-structure interaction effect is governed by the relative stiffness between structure and foundation medium. It is justified that the criterion presented by the industrial design code is reasonably applicable to engineering practice.

INTRODUCTION

Flexibility of foundation medium may give considerable influences on the seismic response of structure constructed on it. The soil-structure interaction (SSI) effect due to the foundation soil requires large engineering efforts to construct the analytical model and to perform the seismic analysis. The fixed base condition excludes these additional efforts to pay in process of SSI analysis. Furthermore, the fixed base analysis could eliminate the various uncertainties resulted from SSI analysis. Therefore, the structural engineer who designs the nuclear safety-related structures takes interest in the fact that the SSI analysis is required. A simple criterion to judge the fixed base condition of foundation medium is very useful to structural engineers.

According to the current Korean industrial guidance [1] for seismic analysis of NPP structures, a foundation medium is assumed as fixed base condition based on its shear wave velocity. However, it is unreasonable that the extent of firmness of foundation soil just determines whether the SSI analysis is required or not. It is known that the relative stiffness between the super-structure and the foundation is more rational criterion on this matter. The ASCE 4-98 standard [2] presents a simplified criterion for determining that a structure is supported by fixed base.

This study performs the parametric analyses to validate the fixed-base criterion of ASCE 4-98 in engineering sense. The various shear wave velocities of foundation medium and the various stiffnesses of super-structure are considered as parameters. Several analytical models were constructed as parameters and dynamic analyses were carried out to obtain their dynamic properties and responses. This paper discusses on the parameters, the analytical models, and the types of analyses. The dynamic characteristics of the models and the acceleration responses obtained from harmonic load analyses are comparatively investigated.

CRITERION FOR FIXED BASE CONDITION

The current Korean industrial guidance [1] specifies that the foundation medium having a shear wave velocity of 1100 m/sec or greater at a shear strain of 0.003 or smaller is considered as fixed base condition in seismic analysis of structures. As mentioned above, it is unreasonable to judge the fixed base condition by considering just stiffness of foundation soil. The previous studies [3, 4] indicate that the SSI effects are governed by the relative stiffness between the structure and the foundation.

Meanwhile, the ASCE 4-86 standard [2] describes that a fixed-base support may be assumed in modeling structures for seismic response analysis when the frequency obtained assuming a rigid structure supported on the flexible foundation medium is more than twice the dominant frequency obtained from a fixed base analysis of the flexible structure representation. The flexible foundation is modeled by the equivalent spring constants and the equivalent damping coefficient as shown in Table 1 [2]. Fig. 1 illustrates the schematic configuration of three different models representing the following structures:

1) Flexible structure supported on fixed base: (a) of Fig. 1
2) Rigid structure supported on flexible foundation medium: (b) of Fig. 1
3) Flexible structure supported on flexible foundation medium: (c) of Fig. 1.
Table 1. Lumped Representation of Structure-Foundation Interaction at Surface for Circular Base [2]

<table>
<thead>
<tr>
<th>Motion</th>
<th>Equivalent Spring Constant</th>
<th>Damping Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>$K_x = 32(1-\nu)\frac{GR}{7-8\nu}$</td>
<td>$C_x = 0.576K_xR\sqrt{\frac{\rho}{G}}$</td>
</tr>
<tr>
<td>Rocking</td>
<td>$K_\nu = \frac{8GR^3}{3(1-\nu)}$</td>
<td>$C_\nu = \frac{0.30}{1 + B_\nu}K_\nu R\sqrt{\frac{\rho}{G}}$</td>
</tr>
<tr>
<td>Vertical</td>
<td>$K_z = \frac{4GR}{1-\nu}$</td>
<td>$C_z = 0.85K_z R\sqrt{\frac{\rho}{G}}$</td>
</tr>
<tr>
<td>Torsion</td>
<td>$K_t = \frac{16GR^3}{3}$</td>
<td>$C_t = \frac{\sqrt{K_tI_t}}{1 + \frac{2I_t}{\rho R^5}}$</td>
</tr>
</tbody>
</table>

Notes: $\nu$, $G$, and $\rho$ = Poisson’s ratio, shear modulus, and mass density of foundation medium, respectively; $B_\nu = 3(1-\nu)I_o/8\rho R^5$; $R$ = radius of circular basemat; $I_o$ = total mass moment of inertia of structure and basemat about the rocking axis at the base; and $I_t$ = polar mass moment of inertia of structure and basemat.

According to the criterion of ASCE 4-98 standard, the foundation is assumed as fixed base support when the following condition is satisfied:

$$2f_{\text{FIXED}} \leq f_{\text{SOIL}}$$  \hspace{1cm} (1)

where, $f_{\text{FIXED}}$ is the frequency of structure supported by fixed base and $f_{\text{SOIL}}$ is the frequency of rigid structure supported by flexible foundation. The frequency of SSI system $f_{\text{SSI}}$ is obtained by combining the frequencies of $f_{\text{FIXED}}$ and $f_{\text{SOIL}}$ by square root of the sum of squares. Thus, the relation of Equation (1) is expressed by the following form [4]:

$$f_{\text{FIXED}} \leq 1.12f_{\text{SSI}}$$  \hspace{1cm} (2)

From Equation (2), the criterion of ASCE 4-98 standard is interpreted as that the fixed-base analysis of structure is possible if the difference between the natural frequencies of SSI system and structure itself are less than 12%.

**PARAMETRIC STUDY**

For parametric studies, several example structures were selected and modeled as lumped masses-beam sticks with springs and dashpots. The selected structures are as follows:
1) Three simple structures with 2 nodes: see Fig. 1
2) Three shear wall structures with box shape (3, 5, and 7 stories): see Fig. 2
3) Three frame structures with beams and columns (3, 5, and 7 stories): see Fig. 2

(a) Shear Wall Structure  (b) Frame Structure  (c) Lumped Mass Beam Model

Fig. 2 Actual Structure Model

Table 2. Soil Properties for Parametric Study

<table>
<thead>
<tr>
<th>Properties Name</th>
<th>Vs (m/sec)</th>
<th>Mass Density</th>
<th>Poisson’s Ratio</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>228.6</td>
<td>0.194</td>
<td>0.35</td>
<td>Dense Soil</td>
</tr>
<tr>
<td>B</td>
<td>457.2</td>
<td>0.194</td>
<td>0.35</td>
<td>Dense Soil</td>
</tr>
<tr>
<td>C</td>
<td>762.0</td>
<td>0.204</td>
<td>0.30</td>
<td>Soft Rock</td>
</tr>
<tr>
<td>D</td>
<td>1066.8</td>
<td>0.204</td>
<td>0.30</td>
<td>Soft Rock</td>
</tr>
<tr>
<td>E</td>
<td>1371.6</td>
<td>0.204</td>
<td>0.30</td>
<td>Medium Rock</td>
</tr>
<tr>
<td>F</td>
<td>1828.4</td>
<td>0.204</td>
<td>0.30</td>
<td>Medium Rock</td>
</tr>
<tr>
<td>G</td>
<td>2438.4</td>
<td>0.214</td>
<td>0.28</td>
<td>Hard Rock</td>
</tr>
<tr>
<td>H</td>
<td>3048.0</td>
<td>0.214</td>
<td>0.28</td>
<td>Hard Rock</td>
</tr>
<tr>
<td>2N1.0</td>
<td>285.6</td>
<td>0.194</td>
<td>0.35</td>
<td>Twice the super-structure frequency of 1.0Hz</td>
</tr>
<tr>
<td>2N2.5</td>
<td>717.8</td>
<td>0.204</td>
<td>0.30</td>
<td>Twice the super-structure frequency of 2.5Hz</td>
</tr>
<tr>
<td>2N5.0</td>
<td>1434.7</td>
<td>0.204</td>
<td>0.30</td>
<td>Twice the super-structure frequency of 5.0Hz</td>
</tr>
<tr>
<td>2N7.5</td>
<td>2151.6</td>
<td>0.204</td>
<td>0.30</td>
<td>Twice the super-structure frequency of 7.5Hz</td>
</tr>
<tr>
<td>2N10</td>
<td>2833.7</td>
<td>0.214</td>
<td>0.28</td>
<td>Twice the super-structure frequency of 10.0Hz</td>
</tr>
<tr>
<td>2N15</td>
<td>4251.0</td>
<td>0.214</td>
<td>0.28</td>
<td>Twice the super-structure frequency of 15.0Hz</td>
</tr>
</tbody>
</table>
Considering the various stiffness of the structure, the simple structures are idealized as models having 6 natural frequencies of 1.0Hz, 2.5Hz, 5.0Hz, 7.5Hz, 10Hz, and 15Hz. Three different stories are parameters of actual structure models to consider the various stiffness of structure. Eight types of soil are selected to account for dense soil, soft rock, medium rock, and hard rock. The shear wave velocity varies from 230m/sec (750ft/sec) to 3,000m/sec (10,000ft/sec), which are selected to represent the extent of firmness of foundation medium. The soil conditions of the foundation medium are summarized in Table 2. The foundation medium is assumed as an elastic half space. The soil layer and embedded effects are neglected in this study.

Dynamic properties of each model are calculated by modal analyses. In addition, harmonic load analyses were carried out by using the direct integration method [5] to obtain the frequency response functions. The sine sweep waves having a rate of two octaves per minute were used as excitation motions in harmonic load analysis. The frequency ranges of the motion are 0.5Hz to 30Hz. The duration and time interval of the motion are 184.32 sec and 0.005 sec, respectively. The amplitude of the motion \( x(t) \) is defined as Equation (3):

\[
x(t) = x_0 \sin \left( \frac{2\pi}{\log 2} \frac{t}{t_0} \right)
\]

where, \( x_0 \) is the maximum amplitude and \( t \) is time in seconds. Fig.3 shows time history acceleration and power spectral density function of the sine sweep wave.

Typical recorded response time-histories and transfer functions at the top of model with respect to the base motion are shown in Fig. 4 to Fig. 6.
For the purpose, the dynamic characteristics and the harmonic load responses obtained from fixed base analyses are compared to those obtained from SSI analyses. Fig. 7 shows the variation of frequency ratios of two node simple models. The symbols $f_{\text{FIXED}}$, $f_{\text{SOIL}}$, and $f_{\text{SSI}}$ appeared in Fig. 7 are the natural frequencies of (a), (b), and (c) models shown in Fig. 1, respectively. From the review of frequency ratios for idealized two node simple models, it is found that the SSI effect would not be anticipated when $f_{\text{SOIL}}$ are 2.5 to 3.0 times to $f_{\text{FIXED}}$. When the ratio of $f_{\text{SOIL}}/f_{\text{FIXED}}$ is about 2.0, $f_{\text{SSI}}/f_{\text{FIXED}}$ reaches at 0.92.

Fig. 8 shows the variation of fundamental frequencies of the actual structure models in accordance with the extent of firmness of foundation medium. It is found that the natural frequencies of SSI systems for the shear wall structures do not vary when the shear wave velocity is above 1500 m/sec. Meanwhile, the natural frequencies of SSI systems for the frame structures are not governed by the shear wave velocities of foundation medium.
Fig. 9 shows the transfer functions at the top of simple 2 node models with respect to the sine sweep harmonic motion at the base. The following remarks were made from the review of the functions:

1) Both natural frequency and response amplitude of SSI system are increased by increment of shear wave velocity of foundation soil.
2) Even though the structure is supported on foundation medium stiffer than the soil having shear wave velocity of 1100m/sec, the amplitude of harmonic response and the dominant frequency vary with shear wave velocity. These responses are different from those of fixed base model.
3) When the stiff structures whose natural frequency are greater than 5.0Hz are supported on firm foundation having above shear wave velocity of 1,100m/sec, they would be governed by SSI effects.
4) The structure would not governed by SSI effect when the frequency ratio of \( f_{SSI} \) to \( f_{FIXED} \) is in the range of 2.0 ~ 2.5.

In the same manner as simple 2 node models, the transfer functions at the top of actual structure models with respect to the sine sweep harmonic motion at the base were calculated as shown in Fig. 10 and Fig. 11. The following remarks are withdrawn from the comparative evaluation of the analytical results:
1) When the flexible structures having a natural frequency less than 1.0 Hz are supported on the foundation soil whose shear wave velocity is above 305 m/sec, the foundation medium could be assumed as fixed base condition.
2) Stiffer structure such as shear wall structures is affected by SSI effect although that is supported on rock like material having shear wave velocity of 1,100 m/sec or greater.
3) When the frequency ratio of $f_{SSI}$ to $f_{FIXED}$ is equal to 2.0, the difference between the natural frequencies of SSI system and fixed base structure are within 10%.
4) The criterion of ASCE 4-98 standard yields a conservative design since the magnitude of response of SSI system is smaller than that of fixed base structure due to the effects of soil damping.

CONCLUDING REMARKS

This paper discussed on a criterion to determine the foundation condition of structure in SSI analysis. From the parametric studies, it is validated that the criterion of ASCE 4-98 standard is conservatively applicable to engineering practice. The study results also confirmed the fact that it is more reasonable to judge the fixed base condition by considering the relative stiffness between the foundation soil and the structure rather than considering just the shear wave velocity. Further studies are required for the case that two or more structures having different dynamic characteristics share common foundation.
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