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Parametric study of the embedment and layering effects on soil-structure interaction analysis

Lee, L.H., Kim, J.S., Lee, S.H.
Korea Power Engineering Company, Inc., Seoul, Korea

ABSTRACT: In order to verify and investigate how the embedment of a structure and layered condition of a site affect the structural responses, parametric analyses are carried out for a containment building of the KOREAN standard PWR nuclear power plant. Embedment ratios(depth-to-radius of foundation) are chosen for observing the embedment effect and for evaluating the applicability of currently-recommended provisions on determining input motion and foundation impedance of embedded structures when using the substructure method. The layered site considered in this study is simplified as a uniform single layer on halfspace, and layering effect due to shear wave contrast is investigated for a surface-supported structure.

1 INTRODUCTION

The embedment of a structure and the layered condition of supporting soil media under the foundation are usually thought to be significant factors affecting seismic response of a structure analyzed for soil-structure interaction(SSI). In consequence, there has been a significant effort in investigating the effects of embedment and layering and in incorporating them into SSI problems. In many cases, however, the importance of considering these effects is sometimes overlooked or often simplified due to the limitations resulting from the inherent assumption used in the formulation of commonly applied methods. In this regard, parametric analyses are carried out so as to investigate the effect of embedment and layering from a structural response point of view. A recently-developed SSI analysis computer program SASSI(Lysmer 1981) which employs the finite element method and the flexible volume method of formulation is adopted since it has, to a great extent, remedied the current deficiencies in treatment of embedded foundation. In addition, the computer program CLASSI(Wong 1979) is also used only for comparative purpose with two different methodologies, i.e. flexible volume method and rigid boundary continuum method.

In this paper, seismic SSI responses of the containment building of the KOREAN standard PWR nuclear power plant are examined in terms of response spectrum of an acceleration response time history. The input motion used in parametric analyses is a set of three synthesized acceleration time histories applied in three mutually orthogonal directions, two horizontal and one vertical, which meets the power spectral density function requirement of the Standard Review Plan, 3.7.1 in addition to meeting the USNRC RG 1.60 standard design ground response spectrum. The observed results through parametric studies are summarized into three categories; embedment effect, layering effect, and analysis method. In examining the embedment effect there are some additional comparisons of the responses resulting from the application of currently-proposed approximate approach that can be commonly used on a practical purpose when using the substructure methods, especially soil-spring method.

2 MODELING OF THE SITE AND STRUCTURE

To distinctly investigate the embedment or layering effect by itself, two different site profiles,"uniform halfspace" and "one layer on halfspace," are selected for the embedment and layering cases, respectively. The uniform halfspace represents a typical slightly-weathered rock condition having a shear wave velocity(v_s) of 2,500 ft/sec, whereas the one layer on halfspace is composed of a 30 ft thick single layer(v_s=2,500 ft/sec) and the underlying halfspace of which shear wave velocity varies gradually according to the contrasts between two materials. For applying SASSI on the embedment cases, the soil volume to be excavated is discretized into finite elements by observing the criteria of maximum allowable element size.

The structure used in this study is a typical containment building of the KOREAN standard PWR nuclear power plant. The containment shell is a prestressed concrete structure composed of 4.0 ft thick cylindrical wall with outer radius of 76.0 ft, and 3.5 ft hemispherical dome. The internal structures, on the other hand, are conventional concrete and either house or support important equipment and components such as NSSS of which mass properties are also considered in the mathmatical model of the structure. For the purpose of SSI analyses by SASSI, the containment shell and internal structures are simplified as 3-D lumped mass beam-stick models shown in Figure 1, while rigid links represented by beams of large flexural and axial stiffness are used to connect the stick models to the corresponding locations on the basemat. The basemat is modeled using 3-D solid elements. However, in the application of CLASSI, the stick model of the superstructure is lumped into one reference point on the basemat due to program limitations. The damping values of the structural components are in accordance with USNRC RG 1.61 recommendations.

3 INPUT MOTION AND ANALYSIS CASES

All of the three artificial time histories are scaled to maximum acceleration of 0.2g with duration of 20 seconds and a time interval of 0.005 second. They are also statistically independent because the absolute value of the cross correlation coefficient does not exceed 0.3. Figure 2 shows a typical accelerogram of the input motion applied in the plant E-W direction(x-coordinate in Figure 1), and the corresponding response spectrum is compared with the USNRC RG 1.60 spectrum for 2% damping in Figure 3. The input motion is prescribed at the top of finished grade in the free field. The motion is assumed to be generated by vertically propagating shear waves. The primary nonlinearity in soil properties, shear modulus and damping, is not considered by using the initial values.

To investigate the effect of variation in embedment depth on the structural responses, selected are embedment depth ratios with 0%(surface), 15%(12 ft embedment), 30%(24 ft embedment) and 45%(36 ft embedment) of the foundation radius. The case of 15% depth ratio is reanalyzed by specifying the same input motion directly at the basemat elevation(12 ft below ground surface) in order to evaluate the applicability of currently-recommended provision in determining the input motion(Coats 1980) when using the substructure method. The 30% depth ratio case is also used for verifying the provision of ASCE standard 4-86(ASCE Standard 1986) in obtaining foundation impedance, where the upper soil stratum above the basemat elevation is changed to have a shear wave velocity of 1,000 ft/sec.

To study the layering effect due to shear wave contrast, three cases of shear wave velocity are chosen contrast with 15%, 30% and 45%. Accordingly the shear wave velocity of the underlying halfspace is increased to 2,940 ft/sec, 3,570 ft/sec and 4,550 ft/sec, respectively. Finally, CLASSI analyses are performed for the same three cases as used in SASSI, 0% embedment depth, 15% and 30% contrast layering, in order to compare the SSI responses from different analysis methods and different modelling approach.

4 RESULTS AND COMPARISONS

All the results of analyses are compared in terms of 2% damped response spectrum of an acceleration response time history at the top of containment shell and internal structures, so as to see the variations in the dynamic characteristics of SSI system. To evaluate the effect of embedment depth, all the responses for embedded cases are compared together with the surface structure on halfspace. The layering effect due to shear wave velocity contrast are also deduced by comparing the responses with respect to the uniform halfspace condition. By comparing the SASSI and CLASSI results for the two different analysis methods, the flexible volume and rigid boundary method are reviewd from a methodological and subsequent modelling technique point of view.

The comparisons of the embedment effect are made in Figures 4 and 5 at the top of containment shell and internal structures, respectively, for the horizontal direction. As shown in these figures, the increase of the embedment depth increases the predominant SSI frequencies and reduces the responses. The frequency increase is more significant in case of containment shell since the free-standing height of the shell becomes smaller as a result of deeper embedment, whereas the internal structures stand free on the basemat without confinement by the embedment. As for the vertical direction, a similar trend is observed but the change of resonant frequencies is not as significant.

On the determination of input motion when using substructure method, there is a current recommendation that for a shallow foundation(embedment depth ratio less than 15%) the input motion at the free surface of the soil deposit can be assumed to apply at the foundation. The applicability of this provision is evaluated to be reasonable, because specifying the free surface input motion directly at the foundation elevation in case of the 15% embedment gives nearly the same responses as those at finished grade even though there are minor increases in the vertical direction.(Figures 6 and 7)

The responses of the analysis case to evaluate the provision of ASCE standard 4-86 in obtaining foundation impedance, are compared with those of the 0% embedment depth(soil stratum above the basemat to be excavated) as shown in Figures 8 and 9. ASCE states that for shallow embedments(depth-to-equivalent-radius ratio less than 0.3), the effect of embedment may be neglected in obtaining the impedance functions, provided the soil profile and properties below the basemat elevation are used for the impedance calculations. According to Figures 8 and 9, it can be clearly identified that ASCE provision always give higher responses of the structure.

The results due to the shear wave contrasts are compared with those of the halfspace condition of which soil properties are the same as the upper single layer. As shown in Figures 10 and 11, becoming larger the shear wave contrast, the corresponding peak spectral acceleration is also increased without significant frequency shifts. However, the enlargement in magnitude is remarkable when the SSI system has the higher natural frequency. This phenomenon seems to be attributed to the waves reflected from layered interface.

According to Figures 12, 13 and 14, both SASSI and CLASSI give almost the same responses for the horizontal direction of the shell. The discrepancis in the other responses seem to be caused by the basemat flexibility only considered in SASSI.

5 SUMMARY AND CONCLUSIONS

Effects of embedment and layering on SSI problems have been discussed in terms of the structural responses through parametric analyses for a containment building of the KOREAN standard PWR nuclear power plant. The resulting conclusions can be summarized as follows:

1. As the embedment increases with depth, the amplitude of response decreases and the reson ant frequencies of the SSI system increase.
2. As for the vertical response, the increase in embedment depth does not significantly affect the resonant system frequencies but also reduce the amplitude of response.

3. It is shown to be acceptable that for a shallow embedded foundation(embedment depth ratio less than 15%) the input motion at the free surface of the soil deposit can directly be applied at the foundation.
4. It is also clearly identified that ASCE recommendation in obtaining the impedance for shallow embedment(depth ratio less than 30%) gives always conservative responses for the structure.
5. When becoming larger the shear wave contrast, the corresponding peak spectral acceleration is also increased without significant frequency shifts.
6. Both SASSI and CLASSI, representing different analysis methods, give the same results only for the horizontal direction of the shell, which seems not to be affected by the basemat flexibility.

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Coats, D.W. 1980. Recommended Revision to Nuclear Regulatory Commission Seismic Design Criteria. NUREG/CR-1161, Lawrence Livermore Laboratory.

Lysmer, J., Tabatabaie-Raissi, M., Tajirian, F., Vahdani, S., and Ostadan, F. 1981. SASSI-A System for Analysis of Soil-Structure Interaction. Report No. UCB/GT/81-02, Geotechnical Engineering, University of California, Berkeley, CA.

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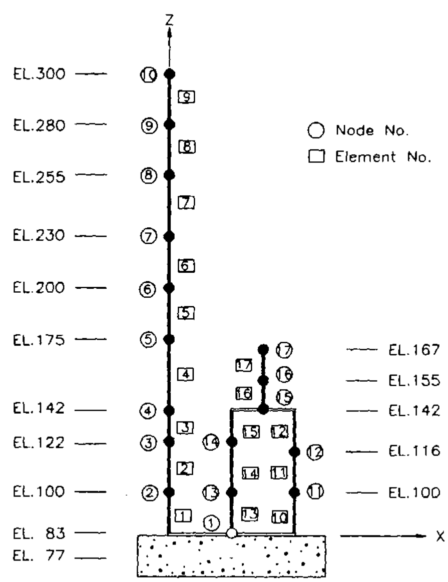

Figure 1. Lumped mass beam-stick model of containment building

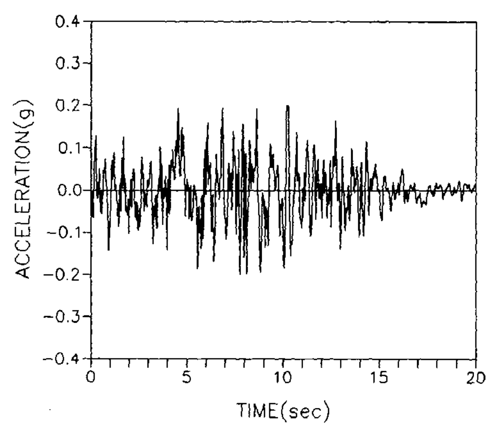

Figure 2. Input motion time history (x-direction)

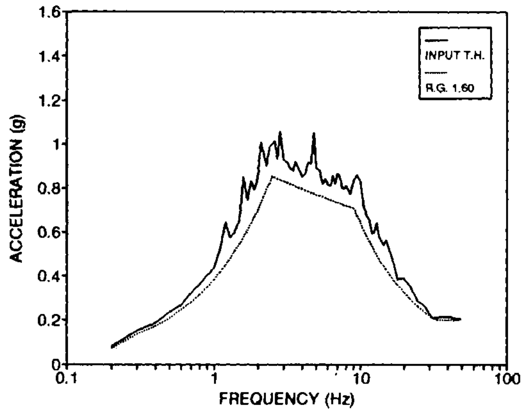

Figure 3. Response spectrum of input motion time history(2%, x-direction)

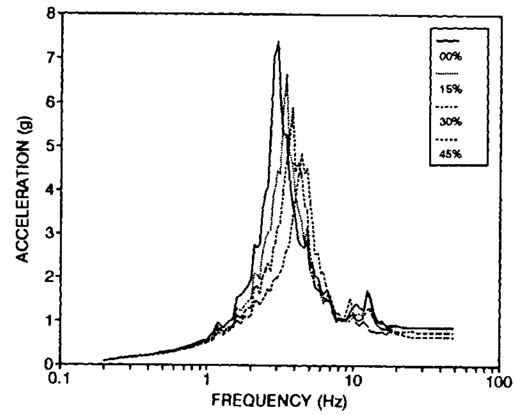

Figure 4. Comparison of embedment effect (at the top of shell, x-direction)

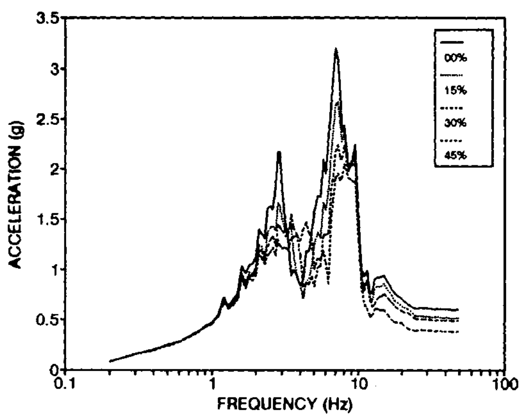

Figure 5. Comparison of embedment effect (at the top of internal, x-direction)

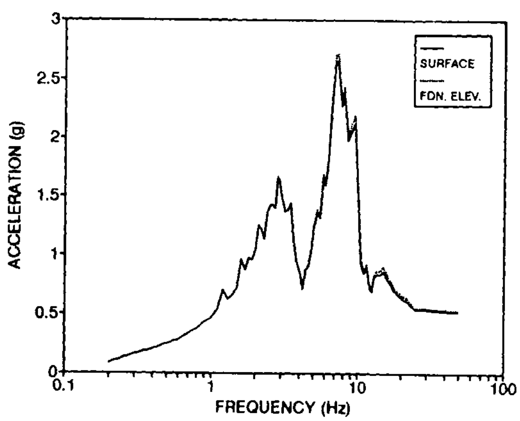

Figure 6. Comparison of control point (at the top of internal, x-direction)

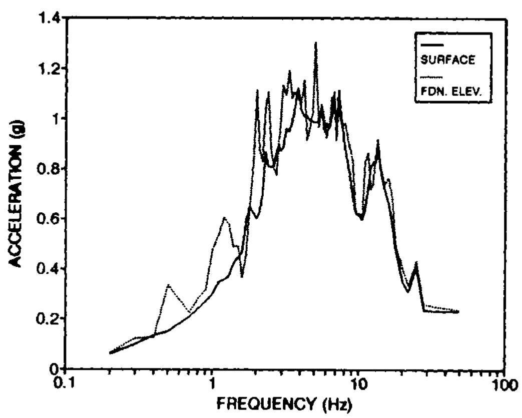

Figure 7. Comparison of control point (at the top of internal, z-direction)

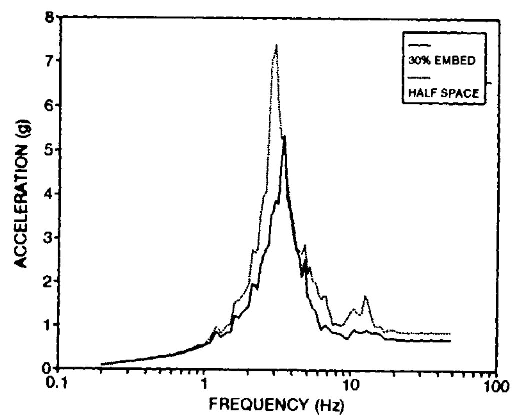

Figure 8. Comparison of impedance calculation(at the top of shell, x-direction)

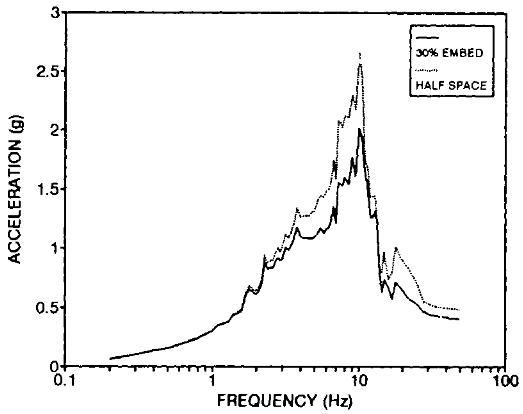

Figure 9. Comparison of impedance calculation(at the top of shell, z-direction)

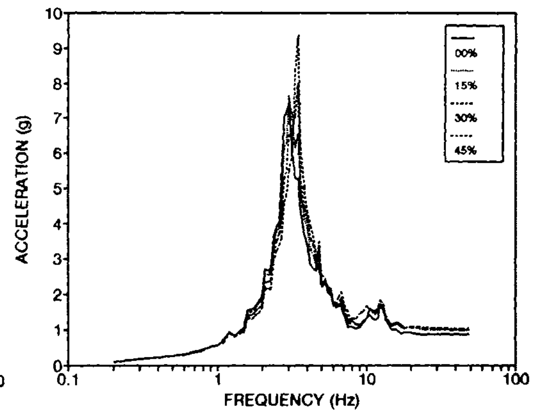

Figure 10. Comparison of layering effect (at the top of shell, x-direction)

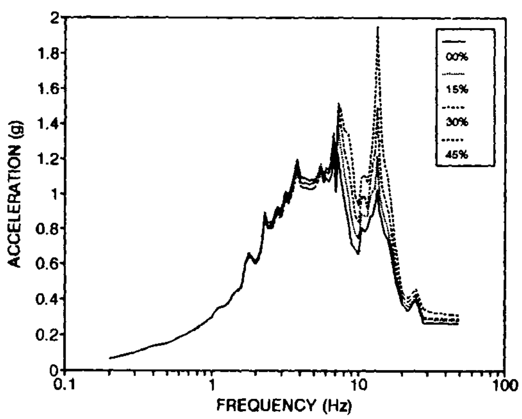

Figure 11. Comparison of layering effect (at the top of internal, z-direction)

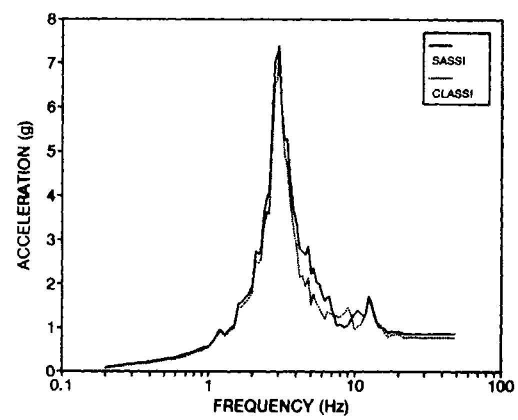

Figure 12. Comparison of SASSI and CLASSI for 0% embed(shell, x-direction)

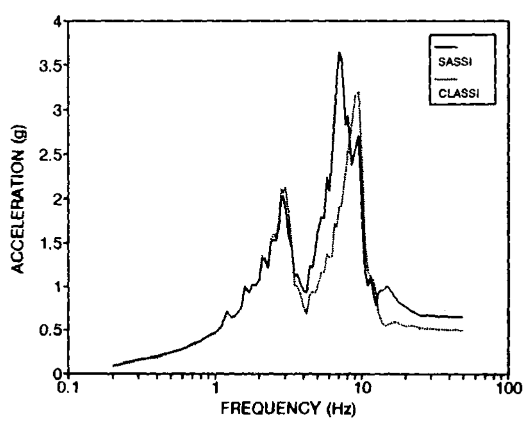

Figure 13. Comparison of SASSI and CLASSI for 15% contrast(internal, x-dir.)

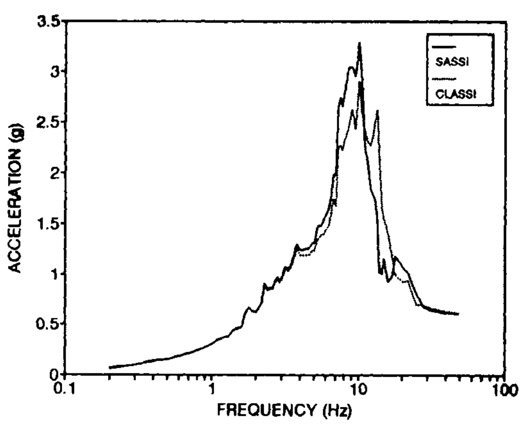

Figure 14. Comparison of SASSI and CLASSI for 30% contrast(shell, z-dir.)