A PRACTICAL METHOD TO ESTIMATE DYNAMIC SOIL IMPEDANCE FOR SEISMIC ANALYSIS OF NUCLEAR POWER STRUCTURES DEEPLY EMBEDDED IN HALFSPACE SOIL

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SUMMARY

In Japan, a practical seismic response analysis model called "Embedded Sway-Rocking Model" is often used in the seismic design of nuclear power structures deeply embedded in soil. It is found that the response accuracy of this model decreases under certain soil conditions due to the evaluation method of sidewall soil stiffness. In this paper, the characteristics of the soil impedance matrix obtained from axi-symmetric FEM model is investigated. From the result of the study, a simple method to approximate full matrix soil impedance of homogeneous halfspace soil is proposed. By carrying out the seismic response analyses using the proposed soil impedance, the efficiency of the model is confirmed.

INTRODUCTION

In order to evaluate the design seismic force for the deeply embedded nuclear power structures, a seismic response analysis model called "Embedded Sway-Rocking (SR) Model" is often used in Japan. In this model, the dynamic soil-structure interaction is evaluated by the input-motion from soil, the dynamic stiffness of soil (soil impedance) and the lumped-mass system corresponds to a structure, illustrated in Fig.-1.

The soil impedance is treated as bottom-springs and side-springs. The former consist of the horizontal (Sway) and the rotational (Rocking) degree of freedom, and they are calculated by the theorem of a rigid surface foundation on the surface of semi-infinite elastic medium. The latter have only horizontal degree of freedom, and are calculated by the dynamic stiffness of the rigid massless cylinder in elastic plane-strain infinite medium [Novak et al, 1978], called "Novak's soil springs". Since no coupling is supposed for all springs, the total soil impedance matrix becomes a diagonal one.

This model was applied to the design of nuclear power structures embedded in soft rock. It was confirmed that the response accuracy of this model is high for these cases. However, it is indicated that the response accuracy of this model decreases in different soil conditions. If the soil consists of the soft surface layer above the hard rock, it shows the resonance effect of the surface layer, and the impedance shows the cut-off-frequency which can not be expressed by Novak's soil springs. For such soil condition, the modified methods are proposed and efficiency of the methods is confirmed [Hijikata et al, 1996].

On the other hand, even if the soil is homogeneous, the response accuracy of the deeply embedded structure decreases corresponding to the rigidity of soil. It is not due to the resonance effect, but it is considered that evaluation of sidewall impedance is the cause of the difference, similarly. For this case, there are not enough prospects that the diagonal impedance matrix can express the characteristics of the soil well. In general, the soil impedance is a full matrix essentially, and the diagonal matrix is equivalent to the full matrix only when a single vibration mode is assumed. If the response behavior of soil during earthquake fits the mode well, the response accuracy obtained with the diagonal matrix will be good. However, if it does not correspond to the mode assumed for the diagonalization, the accuracy of this response can not be secured.

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In this paper, a simple method to approximate full matrix soil impedance of homogeneous halfspace soil is proposed. First, the characteristics of the soil impedance matrix obtained from axi-symmetric FEM model that is considered as a more precise method is investigated. Next, the method to calculate the soil impedance matrix is described. Finally, earthquake response analyses are done for homogeneous soil conditions by the conventional embedded SR model and the proposed method and compared with the axi-symmetric FEM, and the efficiency of this method is shown.

CHARACTERISTICS OF FULL MATRIX SOIL IMPEDANCE

Fig.-2 shows the soil and the structure model of the example nuclear power plant. Table-1 shows the specifications of the structure. The characteristics of horizontal components of the soil impedance matrix obtained from axi-symmetric FEM model are investigated.

The properties of full matrix soil impedance

Fig.-3 shows the dimensionless horizontal components of the 5×5 full matrix soil impedance obtained from the FEM and diagonal matrix soil impedance evaluated by the embedded SR model. Since the matrices are symmetric, only the half parts are shown.

The characteristics of the full matrix soil impedance can be seen as follows:

i) At imaginary parts, all components of the matrix show positive values. They are almost proportioned to the frequency.

ii) With regard to real parts, the diagonal part shows positive values and the non-diagonal part shows negative values. In particular, large values are discernible at tri-diagonal parts. When considering that real parts correspond to spring stiffness, shear springs connect each grid point of the soil can be assumed. These springs are neglected in the embedded SR model.

iii) At both real parts and imaginary parts, the full matrix soil impedance does not correspond to the diagonal matrix of the embedded SR model.

Investigation into total sum of soil impedance matrices

Fig.-4 shows the comparison between the total sum of horizontal components of the soil impedance obtained from the FEM model and the embedded SR model. The sum value is equivalent to the concentrated soil impedance in cases the embedded part of the structure is supposed as a massless rigid body and the horizontal uniform deformation mode is assumed. At the real parts, values of both models are nearly constant for the frequency and at the imaginary parts values of them are in proportion to the frequency. Furthermore, both models correspond quite well to each other in the real parts and the imaginary parts.

As a result, it can be thought that the assumption of the bottom springs (three-dimensional theoretical surface solution) + side springs (Novak's springs) of the embedded SR model possesses satisfactory characteristics as the total sum of matrix of the soil impedance. Under the assumption that the bottom spring components of the FEM model correspond to those of the embedded SR model, it is thought that the total sum of side spring components of the axi-symmetric FEM model can be evaluated by the Novak's springs. Then it becomes important to understand how the values of the FEM model distribute in the matrix. By following the characteristics of the distribution of the FEM matrix, a good approximation method will be lead.

Moreover, the total sum for the real parts of the FEM model shows a small value. This is so because the positive values at the diagonal parts and the negative values at the non-diagonal parts offset each other. Consequently, it is considered that in order to indicate the characteristics of the real parts of the FEM model, shear springs which are neglected in the embedded SR model are necessary to be added.

PROPOSAL OF NEW METHOD FOR ESTIMATING SIDE SPRINGS

Based on the above investigation, the following are proposed as a new method for the evaluation of side impedance.

Distribution of Damping Characteristics

The Novak's springs show the viscous damping characteristics and the imaginary parts are predominant. Therefore, the ratio of the imaginary parts to the matrix soil impedance of the FEM model is investigated and a method for distributing the Novak's springs based on the results is studied.

As shown in Fig.-5, when a unit motion is given only on an underground grid point (point i) of the axi-symmetric FEM model, reaction forces occur throughout the entire underground area as can be seen in figure (a). As for the side springs of the embedded SR model, it is assumed that reaction force occurs only at the point as shown in figure (b). The coupling terms with the other layers are neglected in the Novak's springs so that the impedance matrix is diagonal. In figure (c), it is assumed that uniform reaction force occurs throughout the entire underground area.

Assuming that H and h_i show the total embedded depth and the thickness of the corresponding layer at grid point (i) respectively, the ratio (R_{ij}) of each component of the matrix to the total sum of the impedance matrix can be obtained using equation (1) as shown in (c).

The solid line in Fig.-6 shows the ratio of the imaginary part of each component to the total. The horizontal bottom spring and the values corresponding to the material damping of soil (2%) are subtracted from the matrix. The dotted line shows the ratio of R_{ij} calculated using equation (1).

Both lines correspond quite well to each other. It can be said that the assumption in (c) is valid. The soil impedance matrix value of (K_{ij}) can be expressed as equation (2) using the Novak's spring for the unit thickness (K_N). Equation (3) expresses equation (2) as a matrix form.

$$R_{ij} = \frac{h_i \cdot h_j}{H^2} \quad \text{.......................................} (1)$$

$$K_{ij} = \frac{h_i \cdot h_j}{H} \cdot k_N \quad @ \quad \text{.......................................} (2)$$

$$[K_{ij}] = \begin{bmatrix} \frac{h_1 \cdot h_1}{H} \cdot k_N & \cdots & \frac{h_1 \cdot h_i}{H} \cdot k_N & \cdots \\ \vdots & \ddots & \vdots & \\ \frac{h_i \cdot h_1}{H} \cdot k_N & \cdots & \frac{h_i \cdot h_i}{H} \cdot k_N & \cdots \\ \vdots & & \vdots & \ddots \end{bmatrix} \quad @ \quad \text{.......................................} (3)$$

Where @

$$K_N = -\pi G a_0^2 \, \frac{4K_1(b_0^*)K_1(a_0^*) + a_0^* K_1(b_0^*)K_0(a_0^*) + b_0^* K_0(b_0^*)K_1(a_0^*)}{b_0^* K_0(b_0^*)K_1(a_0^*) + a_0^* K_1(b_0^*)K_0(a_0^*) + b_0^* a_0^* K_0(b_0^*)K_0(a_0^*)} \quad @$$

$$a_0^* = \frac{a_0}{\sqrt{1 + i \cdot 2h}} \cdot i, \qquad b_0^* = \frac{a_0^*}{\sqrt{2(1-\nu)/(1-2\nu)}}$$

a_0 : Dimensionless frequency ($= \omega \cdot r_0$/Vs), r_0 : Equivalent radius of basemat

G : Shear modulus of soil, h : Damping of layer, ν : Poisson's ratio of layer

$K_n(.)$:@Modified Bessel's function of order n

Addition of shear springs

Fig.-7 shows the concept of shear springs. The portion of the soil between two grid points is considered as a "Shear Layer" which thickness is L_i in Fig.-5(a). The displacement is assumed anti-symmetric figure in the layer, the displacement becomes 0 at the center. Then the shear layer can be divided to two anti-symmetric sub-layers whose thickness is $L_i/2$. They can be considered as a combination of two Harada's springs jointed anti-symmetric style and able to express with a submatrix of 2×2. The Harada's spring is a theoretical solution calculated under the assumption that shear deformation occurs in a cylinder which is embedded in a surface layer above rigid basement rock [Harada et al, 1981].

The solid line in Fig.-8 shows the real parts of the full matrix soil impedance obtained from the FEM model. The dotted line indicates the superposing of the above-mentioned submatrix for all layers as a tri-diagonal matrix. This shear springs agree well with the real parts of full matrix soil impedance especially in the low frequency area. Equations (4) and (5) show the formulas to obtain the submatrix [Ks_i] for each layer.

$$[Ks_i] = \begin{bmatrix} Si & -Si \\ -Si & Si \end{bmatrix} \quad \text{..(4)}$$

$$S_i = \frac{2r_0^{\,2}G_i}{t} \cdot \sum_{n}^{N} \frac{\xi_{ns}^2 \Omega_n}{n^3} \cdot (-1)^{\frac{n-1}{2}} \qquad (n = 1,3,5\cdots N)\text{.................................(5)}$$

Where

$$\Omega_n = \frac{4K_1(\gamma_n r_0)K_1(\beta_n r_0) + r_0\beta_n K_1(\gamma_n r_0)K_0(\beta_n r_0) + r_0\gamma_n K_0(\gamma_n r_0)K_1(\beta_n r_0)}{\{r_0\gamma_n K_0(\gamma_n r_0) + K_1(\gamma_n r_0)\}\{r_0\beta_n K_0(\beta_n r_0) + K_1(\beta_n r_0)\} - K_1(\gamma_n r_0)K_1(\beta_n r_0)}$$

$$\beta_n = \frac{\pi}{2t} \cdot \frac{1}{\sqrt{1+2i\cdot h}} \cdot \xi_n, \qquad \gamma_n = \frac{\pi}{2t} \cdot \sqrt{\frac{1-2\nu}{2(1+\nu)}} \cdot \xi_n$$

$$\xi_n = \sqrt{(1+2i\cdot h)n^2 - (\omega/\omega_g)^2}, \qquad \omega_g = \frac{\pi Vs}{2t},$$

t : 1/2 of layer thickness, Vs : Shear wave velocity in layer

Comparison of soil impedance

Fig.-9 shows the comparison between the soil impedance matrices obtained from the FEM and calculated by the proposed method. Both matrices correspond quite well to each other. The CPU time to calculate the FEM impedance matrix was about 2 hours by our Engineering Work Station, but it was reduced to less than 1/1000 by the proposed method.

SEISMIC RESPONSE ANALYSES

Seismic Responses of the embedded structure model shown by Fig.-2 are analyzed and compared to each other in cases where the soil impedance is obtained from the FEM model, from the embedded SR model and from the improved model. Response analyses are carried out in the following homogeneous soil cases: Vs=500m/s, 1000m/s and 2000m/s. Elcentro NS wave (Maximum Acceleration = 300gal) was applied as incident seismic wave, which was defined at GL-24.0 m as the twice of upward wave.

Fig.-10 shows the comparison of the maximum response acceleration. The case of soft rock (Vs=500m/s), the maximum response accelerations of all models correspond well to each other. It is clear that the embedded SR model possesses a high degree of accuracy when it is embedded in soft rock. But its response value differs from that of the FEM model in hard rock. On the other hand, the proposed model has a good agreement with the FEM model in all cases. It shows that the proposed model can be used for the soil of various rigidity.

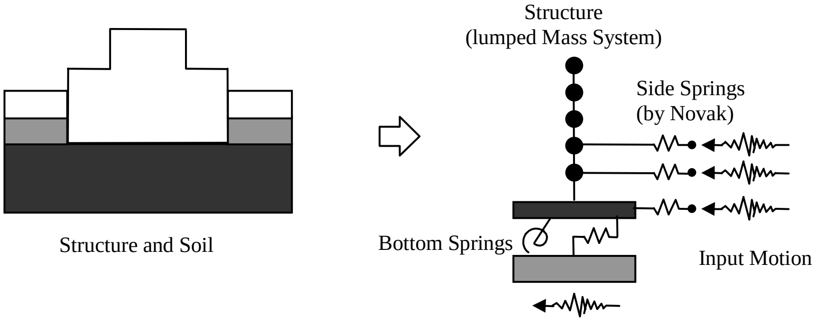


Fig.-1 Concept of Embedded SR Model

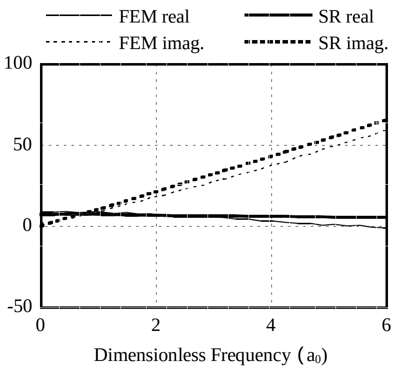
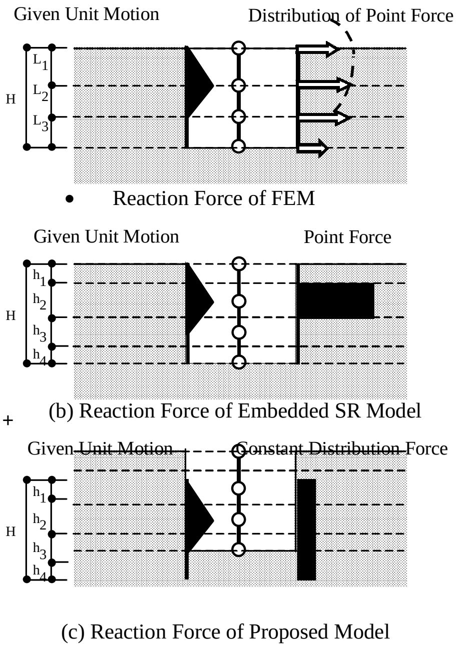


Fig-4 Total Sum of Matrices



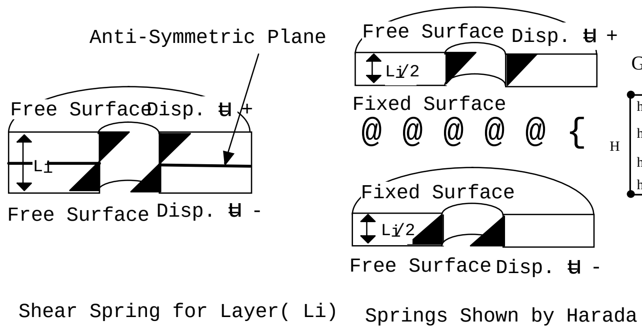


Fig-7 Shear Component

Fig-5 Assumption of Reaction Force

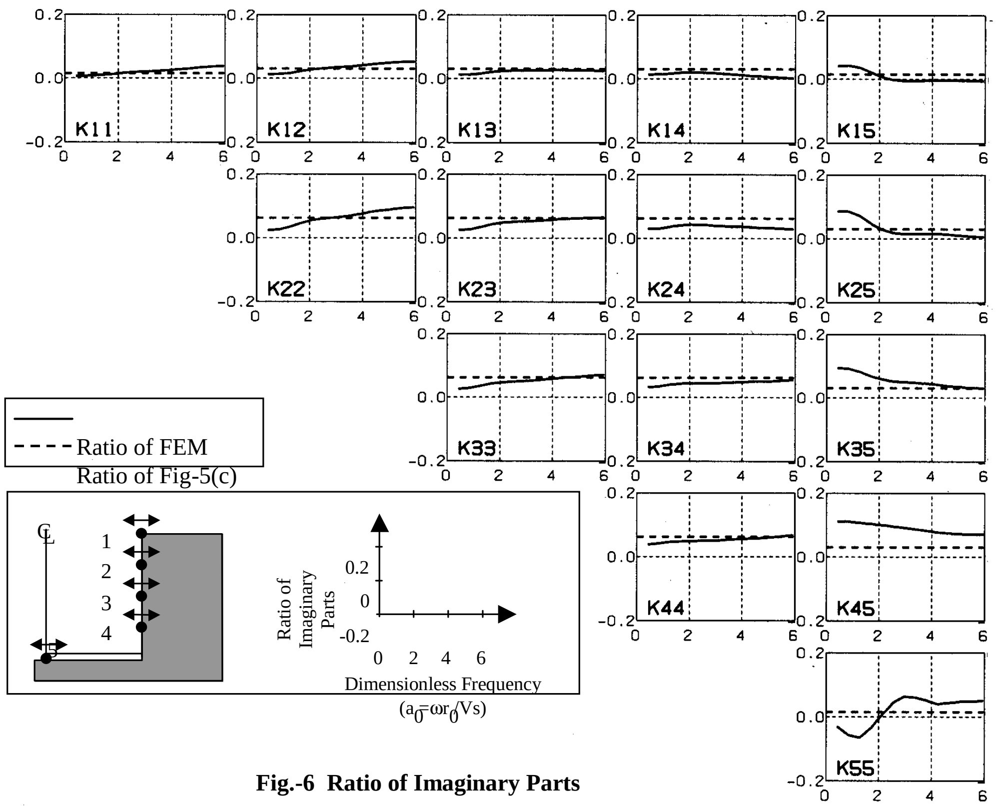


Fig.-6 Ratio of Imaginary Parts

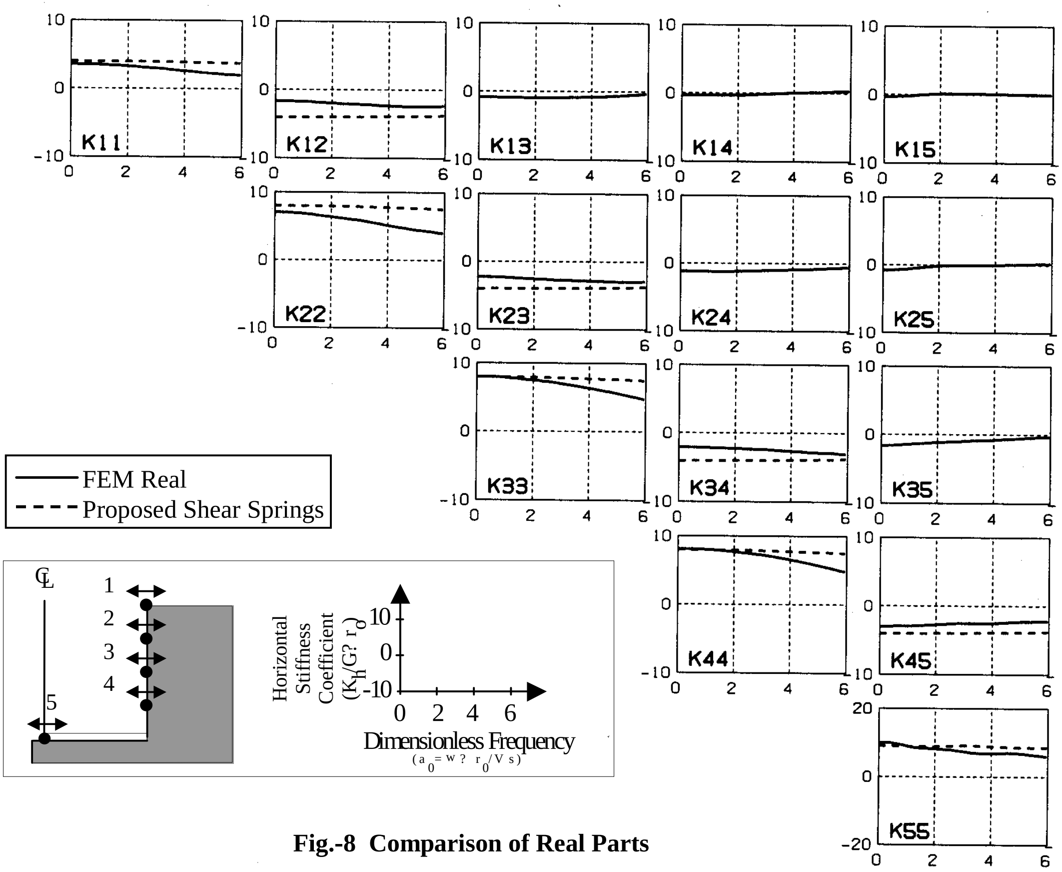


Fig.-8 Comparison of Real Parts

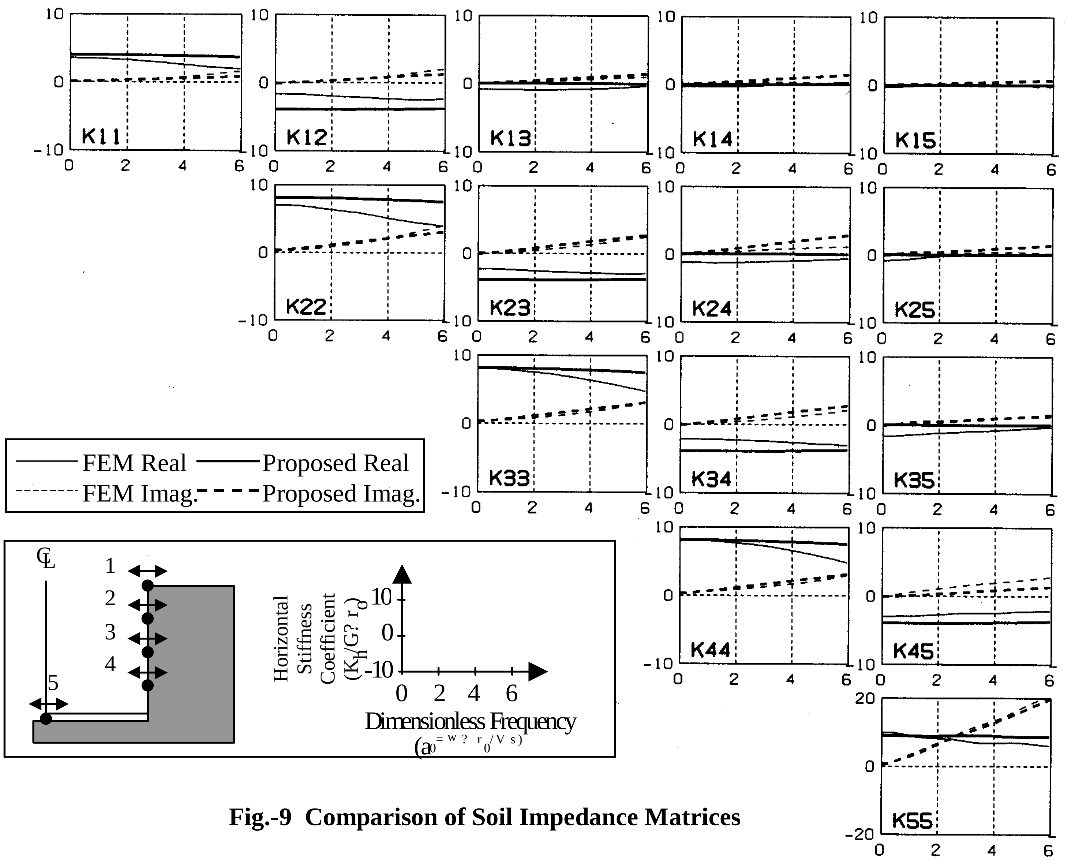


Fig.-9 Comparison of Soil Impedance Matrices

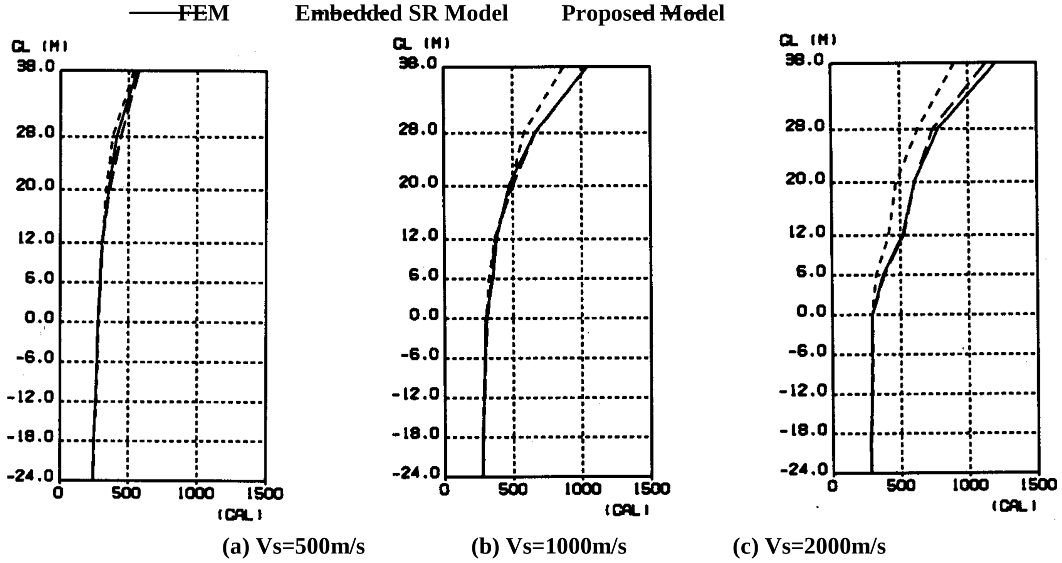


Fig.-10 Maximum Acceleration of Structure

CONCLUSION

In this paper, the characteristics of the soil impedance matrix obtained from axi-symmetric FEM, that is employed as a precise method was investigated. From the result of the study a simple method to approximate full matrix soil impedance of homogeneous halfspace soil was proposed. The proposed soil impedance is the combination of the damping parts and the shear parts. For the damping parts, Novak's springs are distributed to all embedded points and a full-matrix is made instead of a diagonal matrix used in the conventional embedded SR model. And for the shear parts, which are neglected in the conventional method, Harada's springs are used and a tri-diagonal matrix is made. The total soil impedance matrix obtained from this method corresponded well to that obtained from FEM.

Earthquake response analyses were conducted for some soil condition by using conventional method and proposed method and were compared with axisymmetric FEM results. Homogeneous semi-infinite soil condition was assumed in all cases, and rigidity of soil varied from soft rock to very hard rock. The differences of response behaviour between conventional method and FEM were shown in the cases of rigid soil. The response calculated by the proposed method met fairly well to that by FEM in all cases, and the efficiency of it is confirmed.

It is studied that this model is also effective for the layered soil and that will be presented in the other paper.

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