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A STUDY ON SEISMIC STABILITY OF LARGE SCALE EMBEDDED RIGID STRUCTURES

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SUMMARY

A discussion of the seismic stability of large scale embedded rigid structures by using a simple analytical model is presented. The model studied here considers the response of the structure embedded in the horizontal linear elastic layers. The system is idealized into the rigid body supported by ground springs and to be excited by the free field displacement through the ground springs. The applicability of the model was confirmed by comparing with results of experiments, FEM analysis and earthquake observation.

INTRODUCTION

Recently, large scale embedded rigid structures are constructed in Japan. A seismic design of the embedded structures is one of the important engineering research subjects. In order to propose rational earthquake resistant design procedure, the estimation of external forces acting on the structure during earthquakes is very important.

It is widely recognized that the embedded structure is subjected to the seismic excitation from the surrounding ground that has phase difference at the different depth, on the other hand, the surrounding ground play a role in reducing the dynamic response of the structure. Much interest has developed in recent years to analyze embedded structure and surrounding ground interaction during earthquakes. So far, inertia force of structure and earth pressure used in the design works are often independently estimated, the dynamic soil structure interaction is not taken into consideration. Therefore, the main objectives of this paper are: to point out that the dynamic earth pressure depends on the relative displacement between structure and ground; to present a simple analytical model that enable to calculate dynamic earth pressure and dynamic response of the structure simultaneously; to make clear the effects of the ground motion on the external forces.

DYNAMIC BEHAVIOR OF EMBEDDED RIGID STRUCTURE BY FEM ANALYSIS AND EXPERIMENT

Example of the dynamic response of the embedded rigid structures by FEM analysis

Fig.1 shows the geometry and the physical property using in FLUSH program, that is a computer program for analyzing the soil structure interaction by FEM analysis (Ref.1). A 40X40m square rigid foundation is embedded in homogeneous layer its shear wave velocity is 100m/s. Input motion at -60m is an incident wave of actual earthquake record. Fig.2 shows the distribution of acceleration and stress of some nodes and elements at 3.41s when the maximum horizontal acceleration occurs at node 559. It is found that the distribution of the acceleration vary continuously from the free field ground to the rigid structure. The horizontal normal stress distribution at the left side of the structure is very similar to the distribution of the free field acceleration. The vertical normal stress distribution of ground element under the structure corresponds to the rotation of the structure.

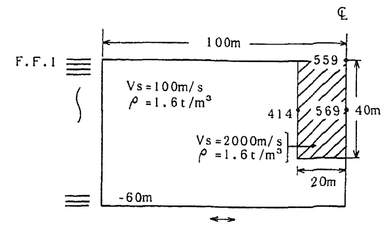

Fig.1 Geometry and physical property.

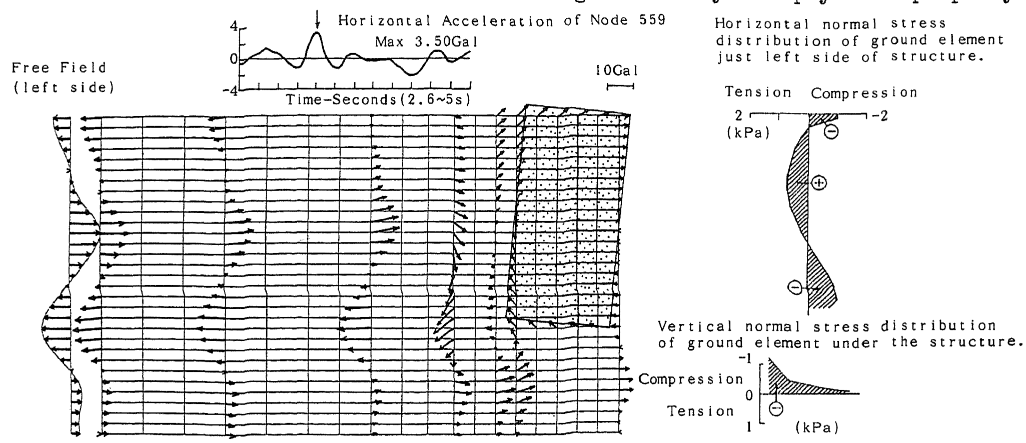

Fig.2 Distribution of acceleration and stress at 3.41s.

Characteristics of the dynamic earth pressure by experiments   Authors developed a model caisson that enable to measure the dynamic earth pressure and carried out experiments using a vibration table. The dimensions of the model caisson are 80cm in height, 44cm in length and 50cm in width including three aluminum plates. Each aluminum plate is supported by three biaxial load cells and has several earth pressure cells. In order to account for characteristics of the dynamic earth pressure influenced by the ground vibration , the frequency of an input sinusoidal wave was chosen very wide. Fig.3 shows the resultant force of the dynamic earth pressure with frequency. The cross section of the model is also shown in Fig.3. The following trends about the dynamic earth pressure are found in this figure.

1. The dynamic earth pressure is amplified nearby the resonant frequency of the back fill sand.
2. The larger the input acceleration is, the lower the peak frequency appears. That is because of nonlinearity of the back fill sand.
3. The dynamic earth pressure can not be negligible to compare with the static earth pressure.

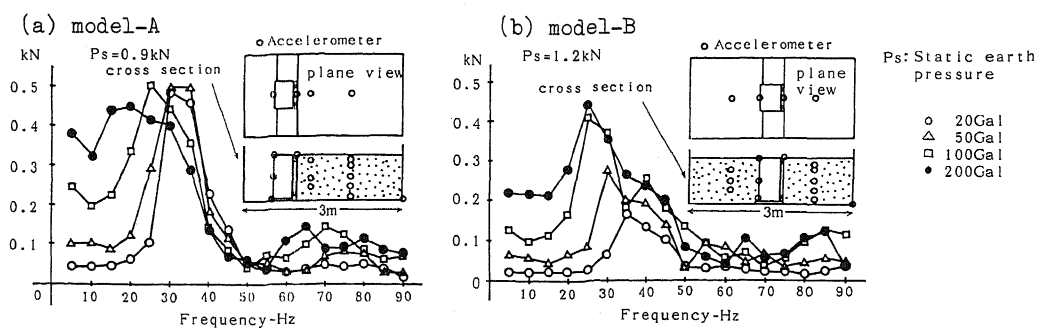

Fig.3 Resultant force of the dynamic earth pressure with frequency.

Fig.4 shows the distribution of acceleration and dynamic earth pressure recorded at the same time when the friction force at the base indicates maximum value. As we use steady sinesoidal wave, the displacement is easily obtained from the acceleration. The information from such analysis note us the following.

1. The dynamic earth pressure distribution is consistent with the relative displacement between ground and caisson.
2. The spring constants per unit area obtained from the experiment data were from 5 to 70 MN/m^3.
3. There is a phase difference between inertia force of the caisson and resultant force of the dynamic earth pressure.

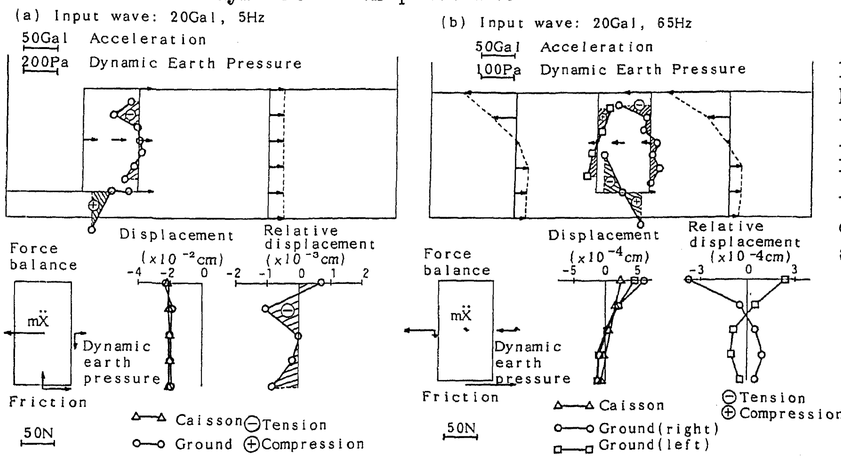

Fig.4 Relation between the dynamic earth pressure distribution and the relative displacement of groundand structure.

THE MODEL

Based on the FEM analysis and the experiments described above, the ground between structure and free field plays a role in transmitting the seismic force of the free field ground to the structure. Furthermore, as the dynamic earth pressure is supposed to be explained by the relative displacement between ground and structure, we present a simple analytical model as follows.

The model studied here considers a rigid structure embedded in the linear elastic layers that extend to infinity in the horizontal direction shown in Fig. 5a. Each layer is characterized by thickness, h, mass density, ρ, and shear wave velocity Vs. In order to estimate the soil structure interaction exactly, the whole system has to be modeled with considering mass density of the surrounding ground such as FEM, BEM, etc. However these modeling are not general in the present design level and are difficult to adopt for qualitative analysis because of its complexity and implicit formulation. Therefore, authors idealized structure and surrounding ground into the rigid body supported by springs. The free field displacement is directly applied through the ground springs as shown in Fig.5.

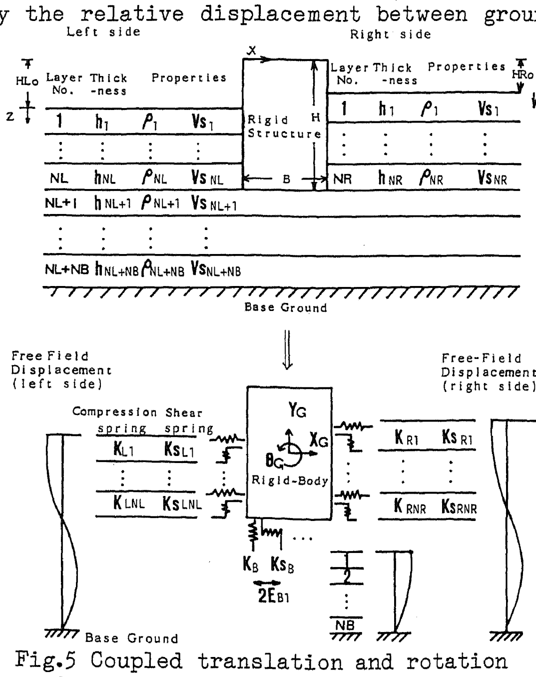

Fig.5 Coupled translation and rotation model of the rigid - body spring system.

Equations of Motion With the notation given in Fig.5 and Fig.6, the equation of the vibration of rigid body in coupled horizontal translation X_G, vertical translation Y_G and rotation θ_G about a center of gravity are:

$$m\ddot{X}_G+R_{NL}+R_{NR}+R_{SB}=0$$

$$m\ddot{Y}_G+R_{SL}+R_{SR}+R_{NB}=0$$

$$I\ddot{\theta}_G+M_L+M_R+M_B-(Gx)R_{SL}+(B-Gx)R_{SR}+(H-Gz)R_{SB}=0$$

in which m: total mass of the rigid body, I: mass moment of inertia about center of gravity, R_{N*}: resultant force of the reaction force, R_{S*}: friction force at the rigid body surface, M_*: moment of the reaction force about center of gravity, (Gx,Gz): the position of gravity center. The dots represent differentiation with respect to time. With the consideration of spring constant per unit area, k, each force and moment can be formulated as following integrals respectively.

$$R_{NL}=\int_0^{H-HLo}k_L(z)[X_G-(Gz-z-HLo)\theta_G-u_L(z)]dz$$

$$R_{SL}=\int_0^{H-HLo}k_{SL}(z)[Y_G-Gx\theta_G-v_L(z)]dz$$

$$R_{NB}=\int_0^{B}k_B[Y_G+(x-Gx)\theta_G-v_B]dx$$

$$R_{SB}=\int_0^{B}k_{SB}[X_G+(H-Gz)\theta_G-u_B]dx$$

$$M_L=\int_0^{H-HLo}k_L(z)[X_G-(Gz-z-HLo)\theta_G-u(z)](Gz-z-HLo)dz$$

$$M_B=\int_0^{B}k_B[Y_G+(x-Gx)\theta_G-v_B](x-Gx)dx$$

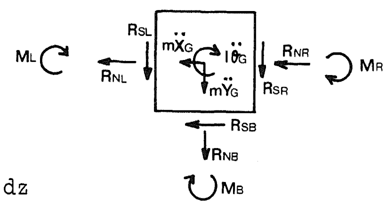

Fig.6 Force balance

in which u_L,v_L: horizontal and vertical free field displacement at the left side, u_B,v_B: horizontal and vertical free field displacement at the bottom surface without rigid body. The resultant force and the moment at the right side are obtained by alternating the suffix of the left side respectively. The contents of the integration represent the distribution of the dynamic earth pressure and reaction force. If it is assumed that each layer has constant coefficient of subgrade reaction, and that the free field displacements are represented by one-dimensional multiple reflection theory, the equation of motion can be analytically described in the frequency domain.

APPLICABILITY OF THE MODEL

When we apply the present model to a practical problem, estimation of a complex ground spring constant is very important. It is known that the dynamic ground spring constant depends on frequency and strain of the ground material, etc. However we leave a detailed discussion about this point for another opportunity, we assumed the ground spring constant as follows:

1. The ground spring constant only depends on the shear wave velocity that is determined by the shear modulus obtained from the response analysis using equivalent linear method. Concretely, the compression spring constant per unit area whose converged shear wave velocity Vs is assumed following equation.

$$k=30(Vs/100)^2 : MN/m^3 \qquad \text{unit of Vs : m/s}$$

2. The shear spring constant is one third of the compression spring constant.
3. The damping is considered only in calculating the free field motion. Therefore, we mainly regarded the effective seismic input as a rigid body response, because the massless structure response is almost the same as rigid body response with mass if the resonant phenomenon of the system dose not appear remarkably.

Comparison of the FEM analysis In the present model the mass of the surrounding ground is neglected. Therefore we do not consider the soil structure interaction in a strict sense in which wave energy feed-back exist. In order to make clear this point, we compared result of the present model with that of FLUSH program using the condition as shown in Fig.1. Fig.7 shows the transfer function by both FEM and the present model. It is found from Fig.7 that the phase effect of the ground motion at the different depth on the response of the rigid embedded structure is the loss effect in regard to translation, but the amplification effect in regard to rotation. The good agreement of both analysis indicates that the effect of the surrounding ground mass is small and the value of spring constant dose not so much influence on the rigid structure response. With regard to detailed discussion about this point, another report of the authors is available.(Ref.2)

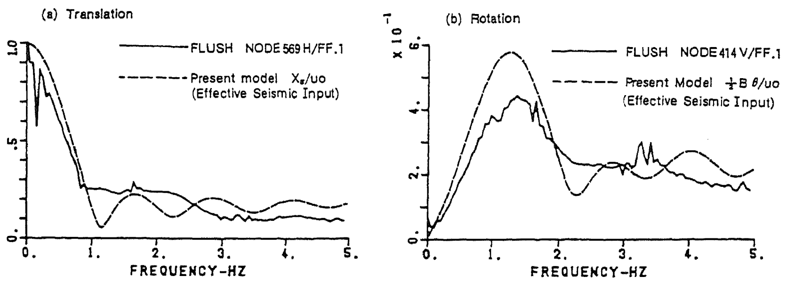

Fig.7 Transfer function between the free field response at the surface and that of the rigid body by FEM and the present model.

Comparison with observation of earthquake response We have carried out earthquake observation of two improved grounds by deep mixing method(D.M.M.) at Daikoku in Yokohama Port whose section are different from each other(Ref.3). The arrangement of the seismographs is illustrated in Fig.8. The improved ground by D.M.M. can be regarded as the rigid body embedded in a soft ground. Fig.9 shows comparison of transfer function between model and observation during earthquake which occurred on August 8, 1983, the maximum acceleration at A-4 point was about 15 Gals. In the present model we calculated the transfer function under taking no account of caisson and back-fill for simplification. The observed translation motion of the improved ground at the gravity center was calculated from records at point A-5,6,8. In spite of simple assumption, results of the model harmonize with those of the observation.

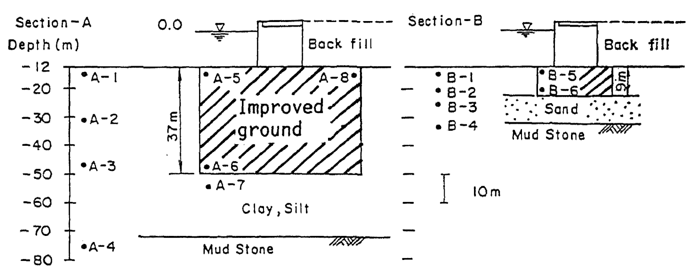

Fig.8 Arrangement of the seismographs.

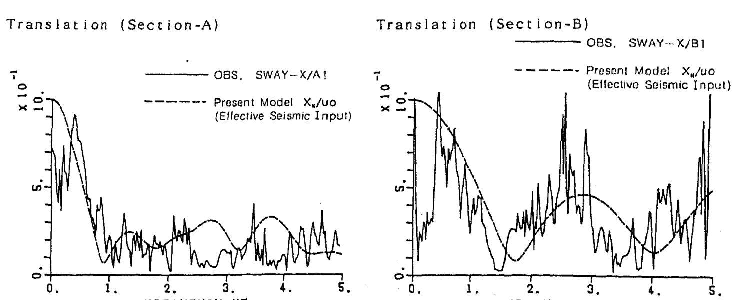

Fig.9 Comparison of transfer function by present model and observation.

Comparison with experiments We simulated model-B experiment described in Fig.3(b) by the model. First shear wave velocity and damping ratio of the ground which can explain measured ground response were identified in each acceleration level. The second, we assumed that spring constant is independent of frequency and an imaginary part of the spring constant is equal to that of real part.

Fig.10 shows the resultant force of the dynamic earth pressure subjected to sinusoidal excitation with constant acceleration level. In this figure, the value is modified into that of per 50cm depth for comparison with Fig.3(b). The trend of the resultant force of the dynamic earth pressure calculated by the model agrees with that of experiment. But in low frequency range, the value obtained by the model is overestimated. Fig.11 shows the effects of the bottom spring constant on the dynamic earth pressure. The bottom spring constant varies from 5 to 30 MN/m^3 in this simulation. In the low frequency range the dynamic earth pressure increases with increasing the bottom spring constant. The result with small bottom spring constant is more consistent with experiment result than that with larger one. This is a reasonable result because we placed the model caisson on the rubber mat in the model-B experiment.

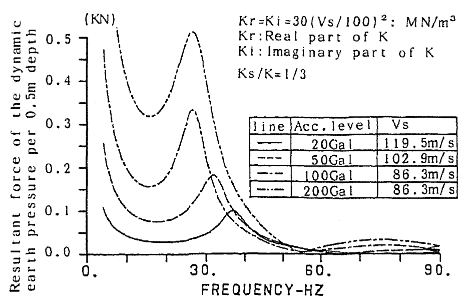

Fig.10 The simulation of the dynamic earth pressure experiment by the model.

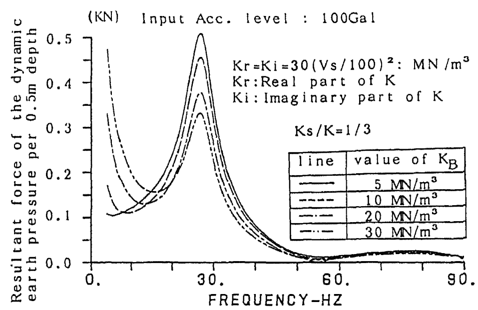

Fig.11 The effect of the bottom spring constant on the dynamic earth pressure

CONCLUSIONS

1. The dynamic earth pressure distribution acting on the rigid embedded structure depends on relative displacement between free field ground and structure.
2. The dynamic earth pressure is very influenced by ground vibration and is amplified nearby resonant frequency of the ground.
3. But phase difference exists between inertia force and resultant force of the dynamic earth pressure.
4. The phase effect of the ground motion at the different depth on the response of rigid embedded structure is the loss effect in regard to translation, but the amplification effect in regard to rotation.
5. The results obtained from the present model, in which embedded rigid structure and surrounding ground are idealized into the rigid body supported by springs, were consistent with those of experiments, FEM analysis and actual earthquake records.
6. If spring constant in frequency domain is identified practically, the model is effective for general design works.

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