Fundamental Characteristics and Simplified Evaluation Method of Dynamic Earth Pressure

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1. INTRODUCTION

In Japan, the method developed by Mononobe and Okabe is commonly used in the evaluation of dynamic earth pressure acting on the underground walls of a deeply embedded nuclear reactor building. However, since this method was developed on the basis of the limit state of soil supported by retaining walls, the behavior of dynamic earth pressure acting on the embedded part of a nuclear reactor building may differ from that estimated by this method.

This paper first examines the fundamental characteristics of dynamic earth pressure through dynamic soil-structure interaction analysis. Secondly, a simplified method to evaluate dynamic earth pressure for the design of underground walls of a nuclear reactor building is described. The dynamic earth pressure described here means fluctuating earth pressure during earthquakes.

2. THE GENERAL BEHAVIOR OF DYNAMIC EARTH PRESSURE

In order to grasp the general behavior of dynamic earth pressure acting on a nuclear reactor building, parametric studies were carried out using approximate three dimensional FEM models.

Earthquake response analyses were performed on a BWR Mark II reactor building (width:80m, height:75m), which is the standard model used in Japan. Shear wave velocity of the surrounding soil and the depth of embedment were used as parameters. Input earthquake motion for the FEM models was generated from the standard spectrum used in the design of nuclear reactor buildings in Japan, and linear analyses were carried out.

Fig.2 shows the distribution of maximum dynamic earth pressure and the earth pressure behavior wave (Pc) obtained from the analyses.

Pc defined in Eq.(1), is obtained by changing the sign of the dynamic earth pressure wave on the relationship between acting direction of earth pressure(P) and that of inertia force of the building (F) as follows.

$$Pc = P \times \mathrm{Sign}\ (\ F\ ) \qquad (1)$$

When inertia force and earth pressure are acting in the same direction

$$Pc < 0 \qquad (\text{Fig.1(a)})$$

When they are acting in the opposite direction

$$Pc > 0 \qquad (\text{Fig.1(b)})$$

In Fig.1(a), dynamic earth pressure acts to increase shear force under the ground, while in Fig.1(b), it acts to decrease shear force.

In this paper, the former earth pressure will be called loading earth pressure, and the latter supporting earth pressure.

Fig.2(a) shows that when the surface layer is soft, dynamic earth pressure acts on the loading side, and as it becomes hard, dynamic earth pressure acts on the supporting side. Earth pressure distribution can be seen reaching a maximum in the center part on the loading side, whereas on the supporting side, earth pressure distribution is large at the upper part and small at the lower part.

Fig.3 shows the results of an analysis of a reactor building which was embedded into the bedrock. It can be seen that dynamic earth pressure acts on the loading side in the soft surface layer and on the supporting side in the bedrock.

Fig.2 and 3 indicate that the behavior of the surrounding soil acting either on the loading side or on the supporting side does not change in analysed time history, except when the distinction between the loading side and the supporting side is not clear (when Vs=250m/s shown in Fig.2).

The results of the parametric studies can be summerized as follows.

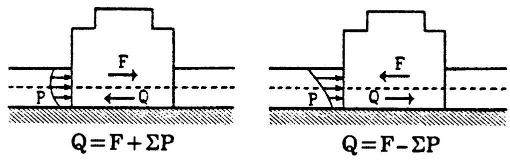
(1) There are two different types of dynamic earth pressure. One acts in the same direction as the inertia force of a building (loading side), and the other acts against it (supporting side).

(2) When the surrounding soil is soft, dynamic earth pressure tends to act on the loading side, and when the surrounding soil is hard, it tends to act on the supporting side.

(3) The behavior of dynamic earth pressure either on the loading side or on the supporting side does not change in time history.

The results of the parametric analyses described above can also be explained by response displacements as shown in Fig.4.

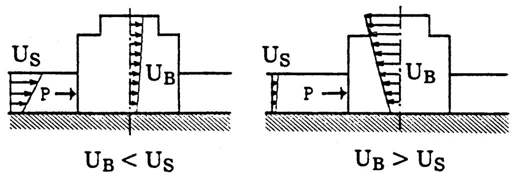
Loading earth pressure is generated when the response displacement of the surrounding soil becomes larger than that of the building. Supporting earth pressure is generated when the displacement of the building is larger than that of the ground.



(a) Loading earth pressure (b) Supporting earth pressure

P : Dynamic earth pressure
Compression (-)
Tension (+)
F : Inertia force
Q : Shear force

Fig.1 Relation of Forces Acting on the Embedded Part



(a) Loading earth pressure (b) Supporting earth pressure

U_B : Displacement of building
U_S : Displacement of surrounding soil

Fig.4 Relation between Displacement of the Building and Surrounding Soil

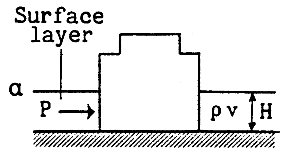
3. SIMPLIFIED METHOD OF EVALUATING DYNAMIC EARTH PRESSURE

A simplified evaluation method was studied for both the loading side and the supporting side, based on the behavior of the dynamic earth pressure mentioned in the previous section.

3-1 Earth Pressure on the Loading Side

When a massive, rigid building is built on bedrock and the surface soil layer is soft, dynamic earth pressure can be calculated approximately by Eq.(2) (Tajimi 1985).

$$P = \frac{\sqrt{3(1+\nu)}}{4} \rho \cdot H^2 \cdot \alpha \qquad (2)$$



where

- P : Dynamic earth pressure (resultant force per unit width)
- ν : Poisson's ratio of soil
- ρ : Soil density
- H : Depth of surface layer
- α : Acceleration

In the simplified method, Eq.(3) is adopted for estimating earth pressure on the loading side. This equation is based on Eq.(2) where coefficient ($\sqrt{3(1+\nu)}/4$) is approximated as constant 0.6 on the safety side. Maximum acceleration at the ground surface level is used for α, and uniform earth pressure distribution is assumed in the vertical direction.

$$Pa = 0.6 \cdot \rho \cdot H \cdot \alpha_{max} \qquad (3)$$

where

- Pa : Loading earth pressure
- α_{max}: Maximum acceleration at ground surface level

3-2 Earth Pressure on the Supporting Side

Supporting earth pressure is generated under the condition that the surrounding soil acts against the inertia force of a building. Force equilibrium condition in this case is shown schematically in Fig. 5.

Eq.(4) was adopted to calculate the supporting earth pressure as a ratio of the total inertia force of the building. In this equation, the equilibrium of forces is considered to be static.

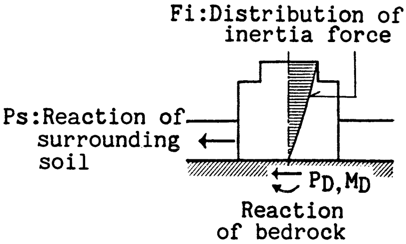


Fig.5 Equilibrium Condition of Forces Acting on a Building

$$Ps = \beta \cdot F \qquad (4)$$

where

- Ps : Resultant force of the supporting earth pressure
- β : Share ratio of the surrounding soil
- F : Total inertia force of the building

β and F were evaluated as follows.

a. Method of Calculating the Inertia Force (F) of a Building

Total inertia force (F) used in Eq.(4) is obtained from the maximum acceleration distribution of the building. However, acceleration distribution when the maximum supporting earth pressure occurs, differs from maximum response acceleration distribution especially in the underground as shown in Fig.6. Therefore, in calculating inertia force of a building, maximum acceleration distribution is reduced in the underground.

b. The Share Ratio of the Surrounding Soil (β)

The share ratio of the surrounding soil was evaluated from the reaction force of the surrounding soil when static unit loading was applied to a building. Static analyses using two dimensional soil structure FEM models were carried out, with the depth of embedment of the building and surrounding soil properties as parameters. Unit force was applied at about 1/2 and 2/3 the height of the building.

Equations for the share ratio were made as shown in Eq.(5) and Eq.(6), so that the results of the FEM analysis could be covered.

$$\beta = \frac{K}{2(1+K)} \qquad (5)$$

$$K = \frac{S}{0.06+0.15S}\left(\frac{V_{SE}}{V_{SD}}\right)^2, \quad S = H/L \qquad (6)$$

H : Surface layer thickness
L : Building width
V_{SE} : Mean shear wave velocity of the surrounding ground
V_{SD} : Shear wave velocity of the bedrock

Fig.7 shows the comparisons of share ratios obtained from above equations and from the FEM analyses.

Earth pressure distribution on the supporting side was assumed to be linear considering the distribution of the response analyses. The earth pressure is 1.5 $\overline{Ps}$ at the top and 0.5 $\overline{Ps}$ at the bottom of the layer, where $\overline{Ps}$ is the mean earth pressure obtained from Eq.(4).

3-3 Application Study

From Eqs.(3),(4) and (5), dynamic earth pressure acting on a nuclear reactor building can easily be estimated if the maximum acceleration on the ground surface and the acceleration distribution of the building are obtained.

In order to confirm the applicability of this simplified evaluation method, dynamic earth pressure estimated by the simplified method and that computed by dynamic FEM analyses were compared. Estimated dynamic earth pressure were obtained by using the maximum response acceleration of the ground and maximum acceleration distribution of the building resulting from earthquake response analysis.

Fig.8 shows the results of this investigation. It can be seen that when the surface layer is soft, the loading pressure calculated by Eq.(3) correspond well to the computed results on the safety side. In the bedrock or when the surface soil layer is hard, the supporting pressure obtained from Eq.(4) correspond closely to the results of FEM analyses.

In the surface layer, since it is difficult to judge whether dynamic earth pressure will be on the loading side or on the supporting side, the equations for both loading and supporting pressures are used, and whichever is greater will be adopted. However, in the bedrock, only the equation for calculating supporting earth pressure will be needed.

4. CONCLUSION

In this report, the general behavior of dynamic earth pressure acting on the underground walls of a nuclear reactor building was investigated by using approximate three dimensional FEM models.

General behavior of dynamic earth pressure can be summarized as follows.

(1) There are two different types of dynamic earth pressure. One acts in the same direction as the inertia force of a building (loading side), and the other acts against it (supporting side).

(2) When the surrounding soil is soft, dynamic earth pressure tends to act on the loading side, and when the surrounding soil is hard, it tends to act on the supporting side.

Taking this behavior into account, a simplified method for evaluating both loading earth pressure and supporting earth pressure was studied.

From the study, the dynamic earth pressure estimated by this simplified method corresponded well to the results of earthquake response analysis, and it was confirmed that this method would be useful in evaluating the dynamic earth pressure for the design of a nuclear reactor building.

More studies on the correspondence between dynamic earth pressures estimated by using the simplified method and those obtained from tests or measurements would be necessary in the future.

5. ACKNOWLEDGEMENTS

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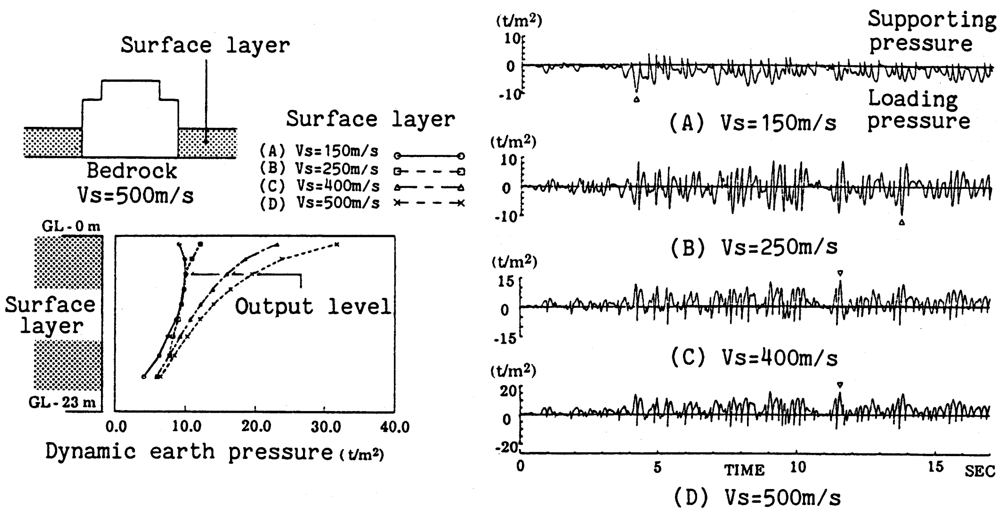
6. REFERENCES

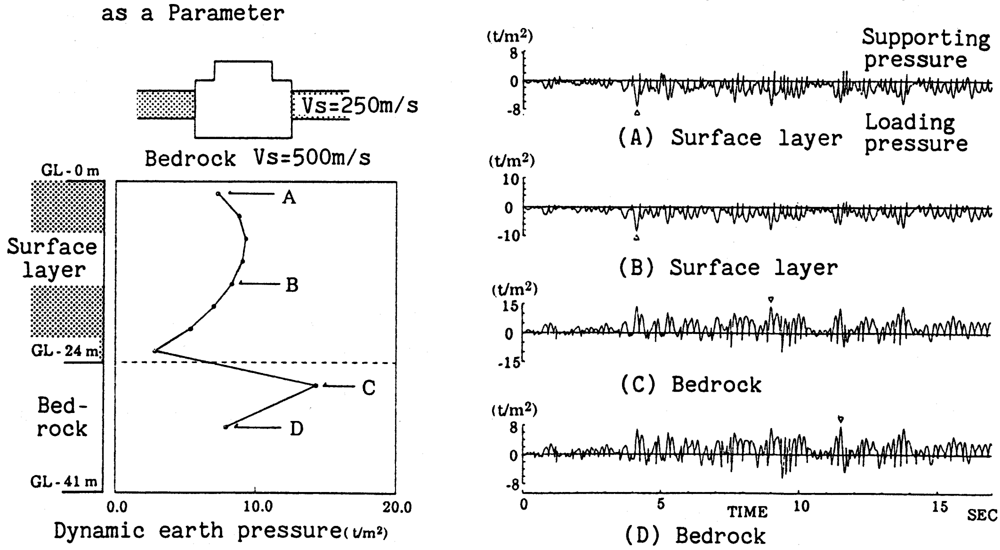
Tajimi, H. (1985). "Soil-Structure Dynamic Interaction", (in Japanese)

Lysmer, J. et al. (1975). "FLUSH", A Computer Program for Approximate 3-D Analysis of Soil-Structure Interaction Problems EERC 75-30



(a) Maximum dynamic earth pressure (b) Earth pressure behavior wave (Pc)

Fig.2 Dynamic Earth Pressure with Shear Wave Velocity of Surface Layer as a Parameter



(a) Maximum dynamic earth pressure (b) Earth pressure behavior wave (Pc)

Fig.3 Dynamic Earth Pressure for the Case of Reactor Building Embedded into the Bedrock

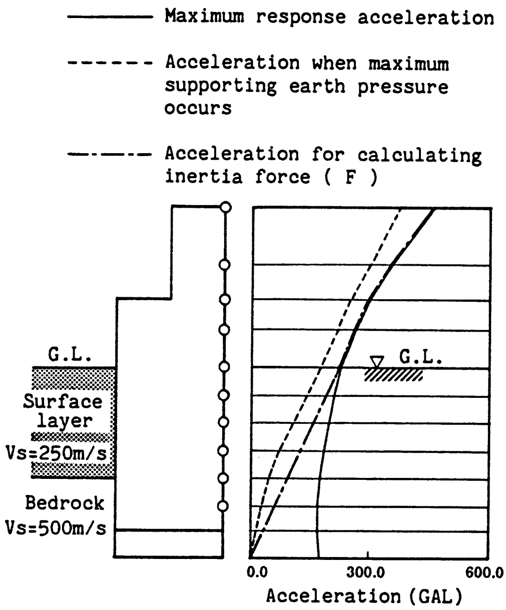


Fig.6
Comparison of Maximum Acceleration Distribution and Acceleration Distribution when Maximum Supporting Earth Pressure Occurs

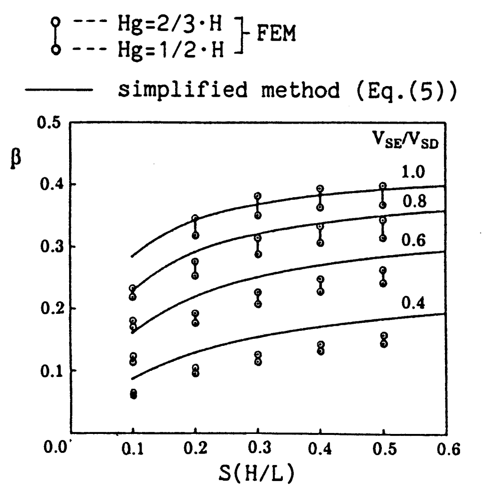
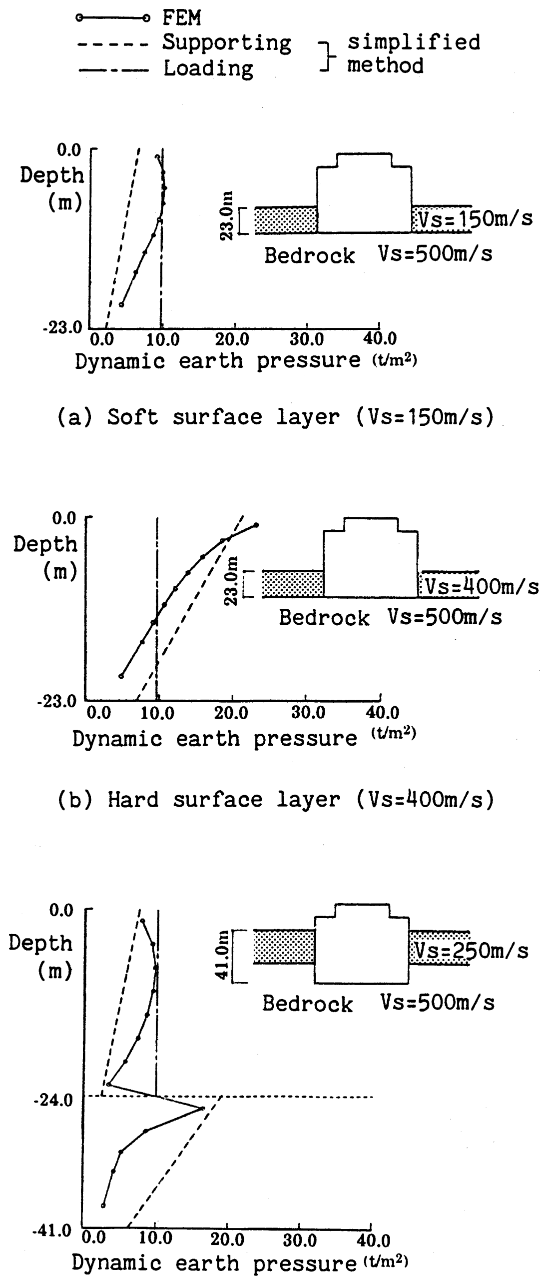


Fig.7 Comparison of Share Ratios Obtained from Simplified Method (Eq.(5)) and FEM Analyses



(a) Soft surface layer (Vs=150m/s)

(b) Hard surface layer (Vs=400m/s)

(c) Reactor building embedded into the bedrock

Fig.8 Comparison of Dynamic Earth Pressure between Simplified Method and Response Analysis