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STUDY ON STABILITY AGAINST SLIDING OF DEEP EMBEDDED NUCLEAR POWER BUILDING

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SUMMARY

This paper has been prepared to explain stability evaluation against sliding of Nuclear Reactor Building(R/B) during earthquake. Although R/B is supported directly on bedrock, dynamic earth pressure acting on R/B cannot be ignored in case of deeply embedded nuclear power buildings. Primarily, studies on R/B-surrounding soil interactions and effects of adjoining Turbine Building(T/B) were carried out using static design force derived from Japanese regulations[1][2]. Secondly, studies on adaptability of static design force were carried out by 3-dimensional dynamic analysis using artificial design seismic wave. From these studies, it can be concluded that 3-dimensional R/B-surrounding soil interactions affects strongly on earth pressure. And analyses using static design force were conservative

INTRODUCTION

In Japan, important structures such as Reactor Buildings(R/B) of nuclear power plants must be directly supported on stable rock. Before construction, it is obligated to certify the stability of support rock. Most of the sites of nuclear power plants have shallow bedrock. However, because of lack of the potential rock sites, it is necessary to study another conditions, for example deep bedrock sites.

Traditionally, the stability of support rock has been estimated by the safety against sliding at the base of R/B, based on the stress state in support rock obtained by FEM.

Sliding force is obtained as a sum of R/B inertia force and earth pressure acting on R/B. In the case of shallow bedrock sites, R/B inertia force is much larger than earth pressure, hence, detailed discussion about earth pressure has not been carried out. However, in the case of deep embedded R/B, it will be important to estimate earth pressure exactly as well as inertia force.

In this paper, following three studies were carried out, taking earth pressure acting on R/B into account.

(a) Interactions between deep embedded R/B and surrounding soil.
(b) Interactions of R/B and adjoining Turbine Building(T/B).
(c) Adaptability of static design force through comparison of dynamic analysis and static analysis.

CONDITIONS

(1)Geological conditions

It is assumed that the surrounding soil is about 70m alternative Quaternary layers which is consisted by sandy soil and silty soil. Bedrock is located below the Quaternary layers. These layers show non-linear behavior with dynamic strain.

The non-linearity can be estimated conservatively on evaluation R/B sliding force using the equivalent stiffness of one-dimensional seismic analysis(code name: SHAKE), in advance. Therefore, in this paper, the equivalent stiffness were used.

(2)Structural conditions

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The size of R/B is assumed to be 103.0m diameter and to be directly supported on the bedrock. The size of T/B is assumed to be 126.0m×110.5m rectangular shape and to be supported by pile foundation. The distance between R/B and T/B is assumed to be 10m.(See Fig.1)

(3)Seismic Forces

Seismic forces are assumed based on artificial design seismic wave S2 (308Gal at outcrop surface) according to Japanese regulations.

The studies (a) and (b) were carried out using static design force that is equivalent to this seismic wave. The study(c) was carried out using this seismic wave.

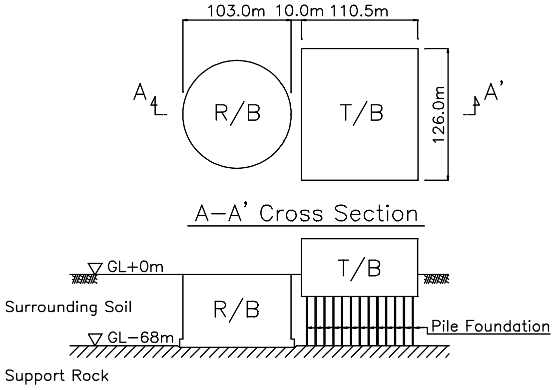


Fig.1 Basic Plot Plan

R/B-SURROUNDING SOIL INTERACTIONS

Generally, stability of shallow support rock is evaluated by FEM using plane strain model which has the central vertical cross section of R/B. In this section, the applicability of this model for deeply embedded R/B was investigated through comparison with an axisymmetric model which can estimate 3-dimensional interaction of R/B and surrounding soil exactly.

Fig.2 shows plane strain model. Symmetric axis of the axisymmetric model is assumed to be R/B center of the plain strain model.

Fig.3 shows horizontal displacement contours of a horizontal section on axisymmetric model. It can be verified that R/B restricts displacements of surrounding soil, which results in the dynamic earth pressure acting on R/B. And the area, where R/B restricts surrounding soil displacements, is larger at load direction than at the right angle to load direction. This is characteristic point of 3-dimensional R/B-soil interactions.

Fig.4 shows R/B story shearing forces by incremental earth pressure during earthquake. Story shearing force is defined as the cumulative total of shear forces acting from top story to given story of R/B.

From this figure, the earth pressure, which is examined using plane strain model, is less than 75% of the result obtained by axisymmetric model. The decrement of 25% is due to the effects of surrounding soil from outside of plane, which plane strain model cannot exactly represent.

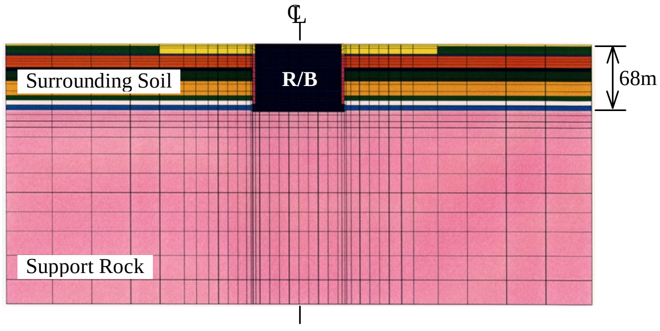


Fig.2 Plane Strain Model

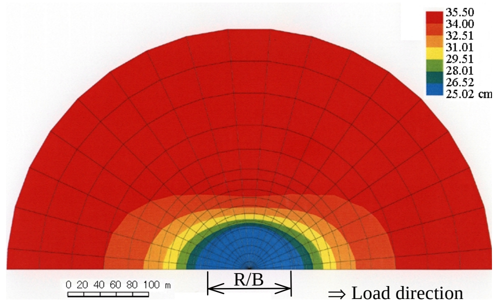


Fig.3 Horizontal displacement contour

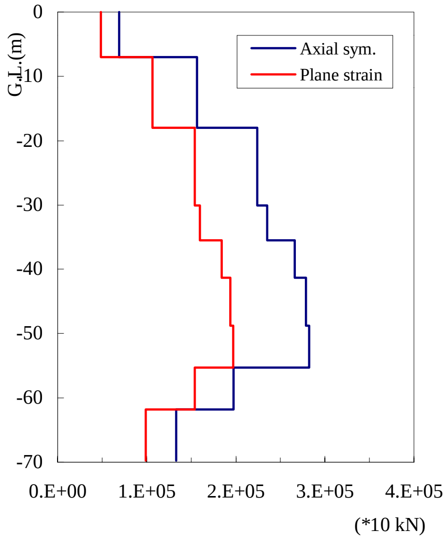


Fig.4 Comparison of earth pressure

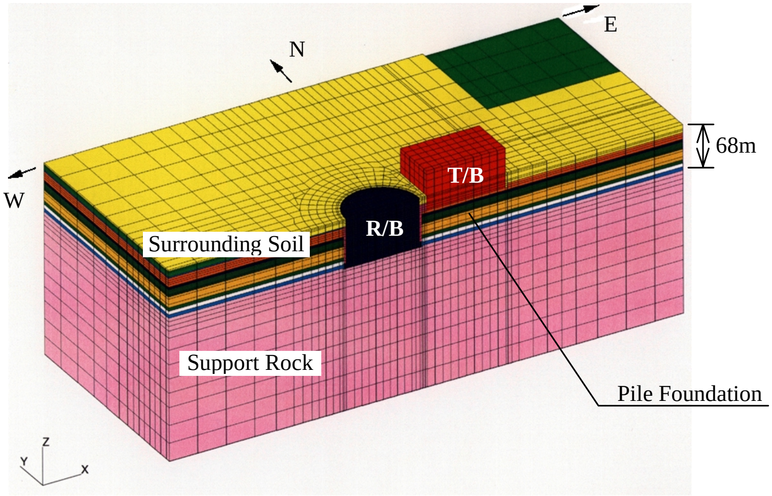


Fig.5 3-Dimensional Model

ADJOINING T/B EFFECTS

In the previous section, only R/B was modeled. In this section, in order to evaluate influences of T/B on earth pressure of R/B, 3-dimensional static FEM, in which R/B and T/B were modeled, was carried out.

Fig.5 shows 3-dimensional model. This model is half model which is symmetrical about West-East cross line of R/B center.

Load directions were assumed to be X-direction(West-East) and Y-direction(North-South) respectively.

Fig.6 shows deformation of X-direction load case. R/B shows rocking mode due to deformation of support rock. T/B shows sway mode due to bending deformations of pile foundation. And the deformation of T/B pile foundation follows surrounding soil.

Fig.7 shows distributions of incremental earth pressures acting on R/B of X-direction load case. Fig.7(1)~(3) show X-direction incremental earth stresses (σ_X,τ_{XY}) at west side, north side and east side of R/B. Fig.7(4) shows story shearing force by integrated earth stresses acting on R/B.

From these figures, there are a slight difference between 3-dimensional analysis and axisymmetric analysis at west side and north side of R/B. Whereas, at east side of R/B, the earth pressures of 3-dimensional analysis are two or three times larger than those of axisymmetric analysis, and the differences are maximum at T/B base level.

The influences of T/B affect distribution of story shearing forces strongly. The total of earth pressure acting on R/B, which is story shearing force by earth pressure at R/B base level, examining 3-dimensional analysis increase 25% from that of axisymmetric analysis.

In Fig.8, deformation of Y-direction load case is shown. The deformations of R/B and T/B show the similar tendency to X-direction load case. In Fig.9, distributions of incremental earth pressure of Y-direction load case are shown. The comparison of earth pressure distributions shows a slight difference at each side, and the influences of T/B on earth pressure acting on R/B are negligible small.

Relationship between T/B location and the interaction area of R/B-surrounding soil (see Fig.3.) explains the difference between X-direction load case and Y-direction load case.

Fig.10 shows that the overlapping region between T/B and the interaction area of R/B-surrounding soil. On X-direction load case, the region is large, and R/B restricts displacement of T/B which follows surrounding soil deformations. In other words, the region, in which R/B restricts displacements of surrounding soil, is larger than that of axisymmetric analysis. Therefore, earth pressure acts on T/B, and that is transmitted to R/B.

Whereas, the overlapping region of Y-direction load case is small, and earth pressure acting on T/B, which is transmitted to R/B, is small.

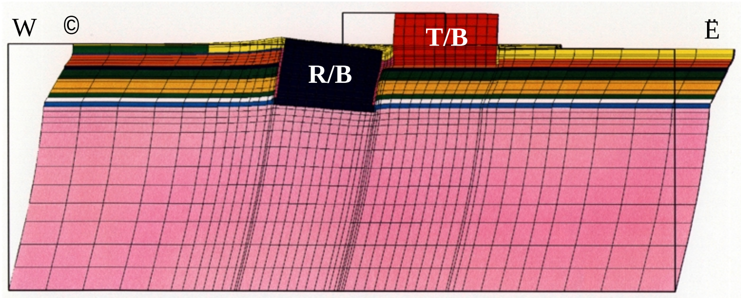
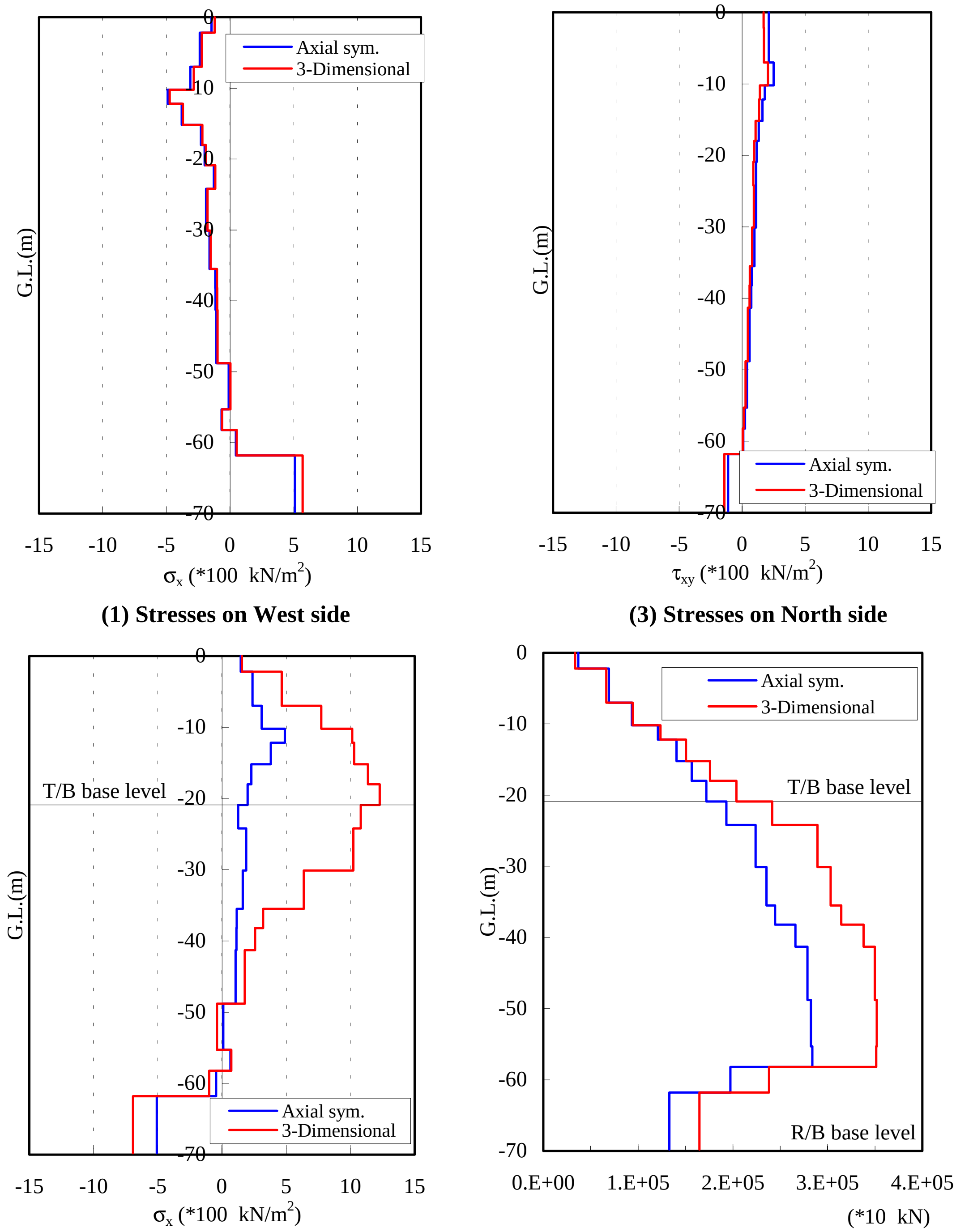


Fig.6 Deformation of X-direction load case



(1) Stresses on West side **(3) Stresses on North side**

(2) Stresses on East side **(4) Story shearing forces**

Fig.7 Distributions of incremental earth pressure (X-direction load case)

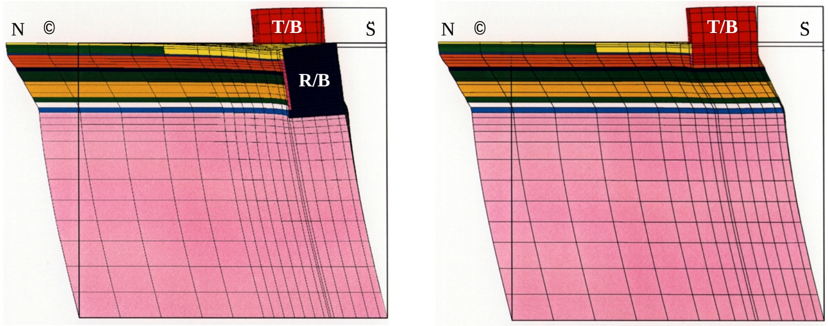
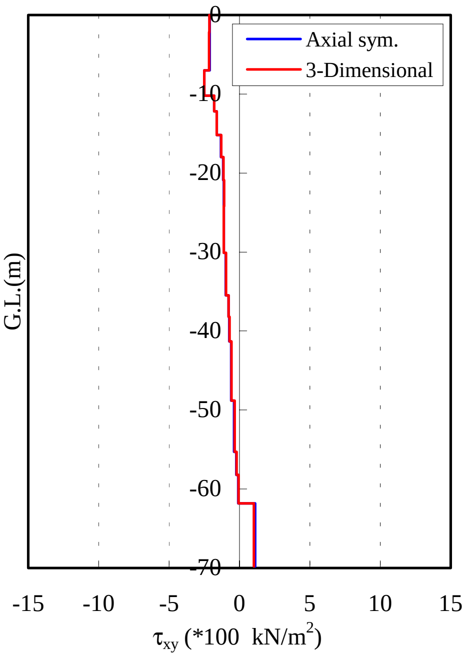
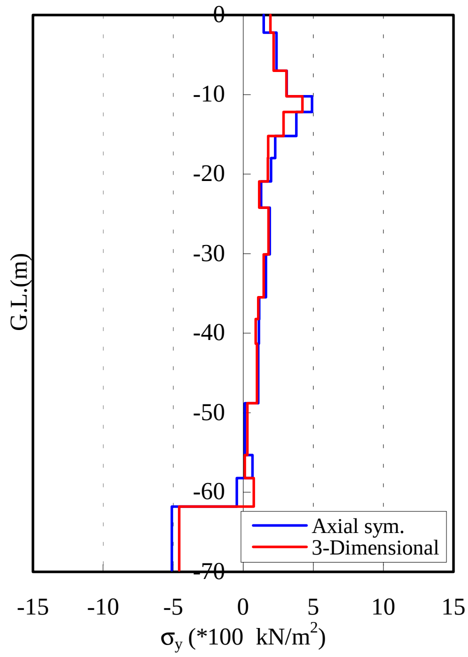


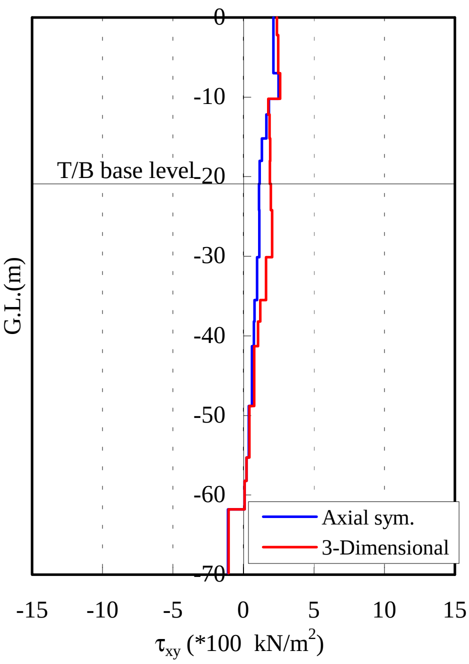
Fig.8 Deformation of Y-direction load case



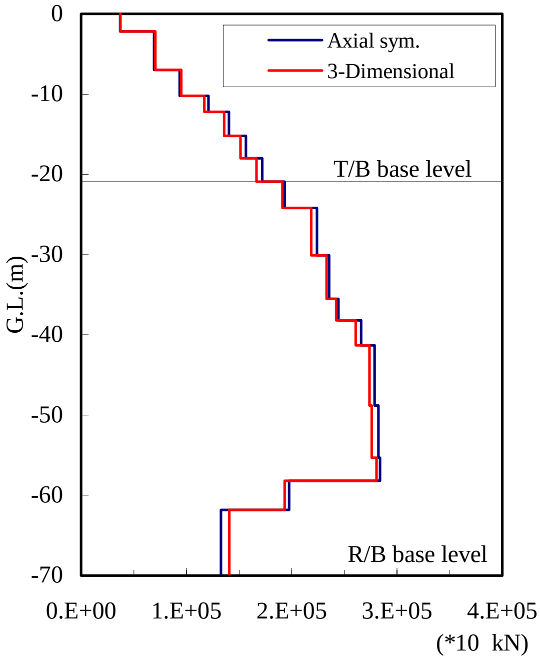
(1) Stresses on West side



(3) Stresses on North side

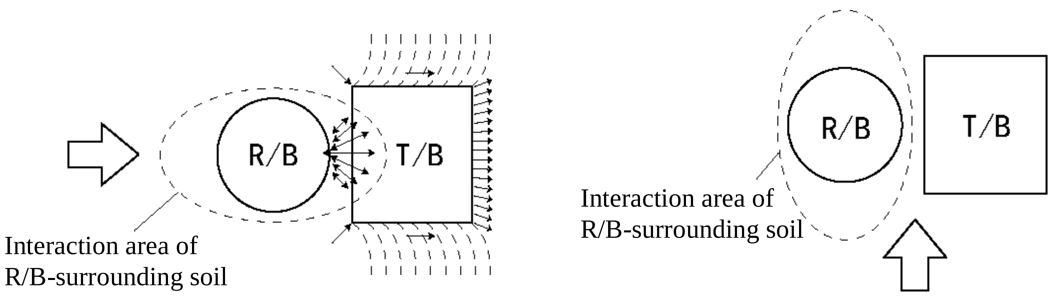


(2) Stresses on East side



(4) Story shearing forces

Fig.9 Distributions of incremental earth pressure (Y-direction load case)



(1) X-direction load case **(2) Y-direction load case**

Fig.10 Relationship T/B and interaction area of R/B-surrounding soil

ADAPTABILITY OF STATIC DESIGN FORCE

In previous sections, the studies were examined using static design force derived from Japanese regulations as following:

Buildings: The static design force representing the maximum story shearing force distribution due to buildings inertia forces.

Soil and Rock: The static design force representing the maximum horizontal shear stresses distributions of free field.

In this section, the results of dynamic analysis using 3-dimensional model, shown in Fig.5, were compared with those of static analysis, in order to evaluate adaptability of static design force for deep embedded plants.
Fig.11 shows the story shearing forces by inertia forces and incremental earth pressures in case of static analysis and dynamic analysis respectively. The results of dynamic analysis are the maximum values during earthquake.
There is a slight difference on comparison of inertia forces. Whereas earth pressure of static analysis is larger than that of dynamic analysis. Actual causes of the difference come from the fact that static analysis cannot evaluate phase difference between the responses of R/B and surrounding soil. In this regard, some evidences derived from this study are shown below:

- Horizontal cross sections

Fig.12 shows resonance modes of ground surface at 0.5Hz and 1.2Hz. This figures show horizontal shear stress(τ_{xy}) as well.
In the case of 0.5Hz, in which phase difference between responses of R/B and free field is small, surrounding soil shows uniform deformation in the same way as static analysis. Whereas, in the case of 1.2Hz, the wave motions due to phase difference between responses of R/B and free field, are found in surrounding soils.
Fig.13 shows comparison between deformations of static analysis and dynamic analysis. The deformation of dynamic analysis is stop motion at the time when sliding force of R/B is maximum. On the results of static analysis, it is clear that R/B restricts uniform deformations of surrounding soil. On the other hand, the results of dynamic analysis shows uneven deformations of surrounding soil, since deformations of dynamic analysis are influenced by interaction waves due to phase differences. Therefore, earth pressure acting on R/B examined by dynamic analysis is less than that of static analysis.

- Vertical cross sections

Static design force of surrounding soil gives each layer shear strain which represents the maximum shear strain during earthquake. Actually, shear stresses are propagated as shear wave, hence, each layer does not have maximum shear strain at the same time. Earth pressure acting on R/B is obtained as a product of relative displacements, which are differences between displacements of R/B and surrounding soil, by stiffness of surrounding soil. Therefore, static design force, which does not reflect phase differences on vertical cross sections, overestimates earth pressure acting on R/B .
Fig.14 explains this overestimation. The figure shows distributions of relative displacements, i.e. difference between displacements of surrounding soil and bedrock surface at free field. Line A in Fig.14 stands for relative displacements examined by static design force. Line B stands for relative displacements which are differentiated on maximum values distribution during earthquake, those are integrated displacements of surrounding soil at free field from ground surface to given depth.
If the stiffness of surrounding soil is invariable, and R/B has the same displacement of bedrock surface, distribution of maximum earth pressure acting on R/B is obtained as a product of Line B by stiffness of

surrounding soil. In other words, Line B corresponds the displacements distribution, which is obtained as maximum story shearing forces distribution by earth pressure acting on R/B. In this case, Line A is 1.1 times larger than Line B at top level of R/B.
Since R/B shows rocking mode behavior, above results are not always applicable. However, static design force overestimate earth pressure acting on R/B.

Static analyses were frequently applied on design works, because static analyses are easier than dynamic analyses. From this study, it is seen clearly that analyses using static design force are conservative for deep embedded R/B to estimate earth pressure acting on R/B. However, there is room for further study that phase difference has to be considered in evaluating suitable static design forces.

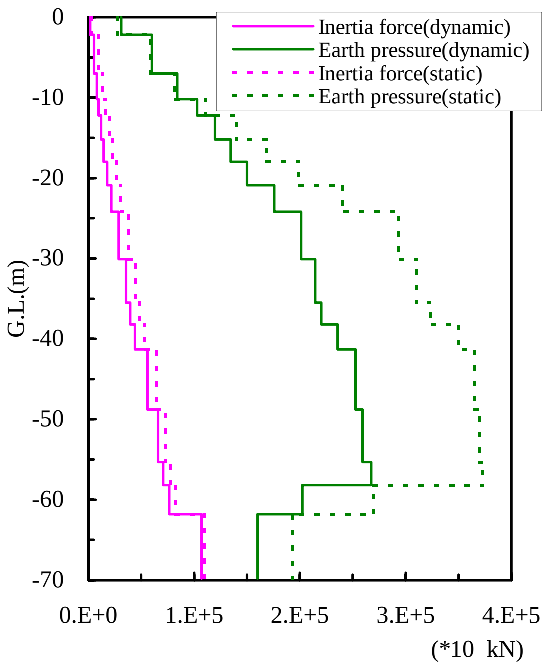


Fig.11 Comparison o story shearing forces

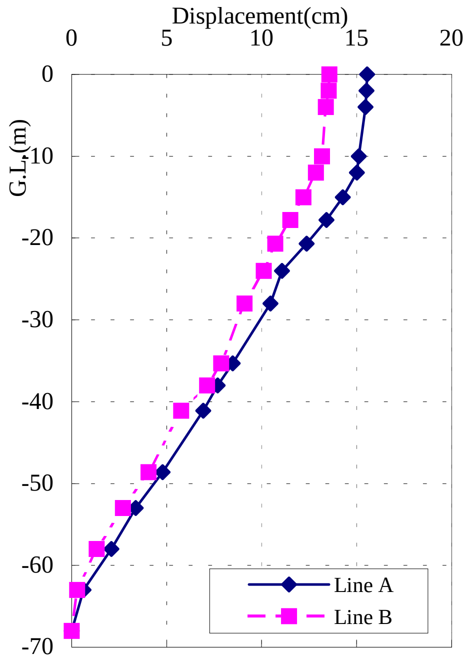


Fig.14 Comparison of relative displacement

CONCLUSIONS

The followings are concluded as results of investigations.
(a)The earth pressure acting on R/B is strongly influenced by 3-dimensional interaction, and plane strain models have a specific tendency to underestimate earth pressure acting on R/B than axisymmetric models.
(b) Adjoining T/B affects on the earth pressure acting on R/B, and it can be mentioned that the influences of T/B depend upon relationship of T/B location and the interaction area of R/B-surrounding soil.
(c)The earth pressure estimated by static design force, derived from Japanese regulations, is conservative in comparison with the earth pressure estimated by dynamic analyses. Static design force can be still more rationalized.

REFERENCES

1. Japan Nuclear Safety Commission (1981), “Regulatory guide for aseismic design of nuclear power reactor facilities”
2. Japan Electric Association (1987), “Aseismic design technical guideline for nuclear Power Plant”, JEAG 4601-1987