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DYNAMIC INTERACTION OF DEEPLY BURIED NUCLEAR POWER BUILDINGS

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SUMMARY

Three-dimensional (3D) dynamic analyses are performed to evaluate dynamic interaction between Turbine Building (T/B) with pile foundation and deeply buried Reactor Building (R/B) during strong earthquake. The results are compared with the two-dimensional (2D) dynamic analysis that is conventionally used in the design stage to evaluate its applicability as a design tool and to bring three-dimensional effects into relief. Three-dimensional R/B-T/B-soil dynamic interaction amplifies the section force of piles, the applied earth pressure to R/B and the relative displacement between R/B and T/B. It is concluded that three-dimensional R/B-T/B-soil interaction should be considered in the design stage of R/B, T/B and the main steam duct by which R/B is connected to T/B.

INTRODUCTION

In Japan, seismic load often dominates the design of structures. As a result, important structures such as nuclear power plants have to be directly supported on firm bedrock. However, considering recent requirements of siting restriction and cost reduction, a new structural system such as pile-supported structures and deeply embedded plants should be studied. For the requirements, smaller-scaled reactors with large capacity have been researched and developed at nuclear power plants for last few years in Japan. The limitation of site feasibility makes a Reactor Building (R/B) be deeply buried in the ground for direct support on bed rock and be close to a Turbine Building (T/B) with pile foundation as shown in Figure 1. It is required for establishment of the appropriate design framework for the plot plan to evaluate dynamic interaction between soil and structures (i.e. R/B and T/B) during strong earthquake.

The basic study on soil-structure interaction and R/B-T/B interaction has been already done through analyses and experiments (Togashi et al.[1], Kawamura et al.[2] and Ando et al.[3]). Togashi et al.[1] performed experiments using real sand which non-linearly behaves to evaluate dynamic interaction between deeply buried R/B and T/B with pile foundation. 2D numerical simulation of the experiments was also performed to find the applicability of 2D dynamic analysis. Kawamura et al.[2] carried out 2D dynamic analysis and 3D static analysis with equivalent seismic load for the R/B-T/B-soil system of the plot plan considering non-linear soil. Ando et al.[3] performed axi-symmetric dynamic analysis for the composite system of R/B, backfill and slurry wall with surrounding soil.

In this study, 3D dynamic analyses for the plot plan are performed to evaluate three-dimensional dynamic effects during strong earthquake in the R/B-T/B-soil system in comparison with the result of previous two-dimensional dynamic analysis.

OBJECTIVES AND APPROACHES

One of the main objectives is to develop the appropriate design frame work for this new system through assessing the dynamic interaction between deeply buried cylindrical R/B directly based on bed rock and

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rectangular T/B supported by pile foundation during strong earthquake. The following steps to above mentioned final goal are set:

-1st step ; 1/100 scale dynamic experiment to find the basic interaction between R/B and T/B (Togashi et al.[1]).

-2nd step ; Validation of 2D dynamic analysis based on comparison of the experiment with its numerical simulation (Togashi et al.[1]).

-3rd step ; Axi-symmetric dynamic analysis for the composite system of R/B, backfill and slurry wall with surrounding soil to evaluate the influence of backfill materials and slurry wall on the R/B (Ando et al.[3]).

-4th step ; 2D dynamic analysis and 3D static analysis for prototype to assess the real scale interaction (Kawamura et al.[2]).

-5th step ; 3D dynamic analysis to find the three-dimensional effect on R/B-T/B-soil interaction (current study).

-6th step ; Integration of the feasibility study to establish an appropriate design frame work.

CONDITION

As shown in Figure 1, R/B with 103m diameter are planed to be directly supported by the base rock located below 68m sediments. For construction of R/B, cylindrical slurry wall is planned for bearing the earth pressure and keeping water tightness due to excavation of inside soil. T/B with 126m× 110.5m rectangular shape supported by piles is planned. The distance between the slurry wall and the T/B is assumed to be 10m for consideration of cost performance.

Geological condition of the candidate site is assumed to consist of 68m quaternary sediments with 14m-soft sand, 12m-sandy gravel and 42m-silt which are non-linearly behaved with dynamic strain during earthquake.

Artificial design seismic wave, S2 for ultimate stage (maximum acceleration of 308.2gal at GL-378m), is used as input motion for the analyses. S2 horizontal input wave at GL-378m is shown in Figure 2. Though two input directions, that is parallel (x) and perpendicular (y) direction to the R/B-T/B direction, are considered. The former parallel case is discussed in this paper.

MODEL AND METHOD

Figure 3 shows the three-dimensional finite element mesh. Viscous boundary is applied for the lateral surfaces and the bottom of the model.

The R/B model which consists of solid elements, beam elements and rigid spring elements is equivalent to the prototype in terms of bending stiffness. The T/B is modeled by rigid solid elements for the base mat and beam elements for the upper structure with equivalent shear stiffness and bending stiffness to the prototype. The piles

are modeled by intensive beam elements with equivalent shear stiffness and bending stiffness to the prototype.

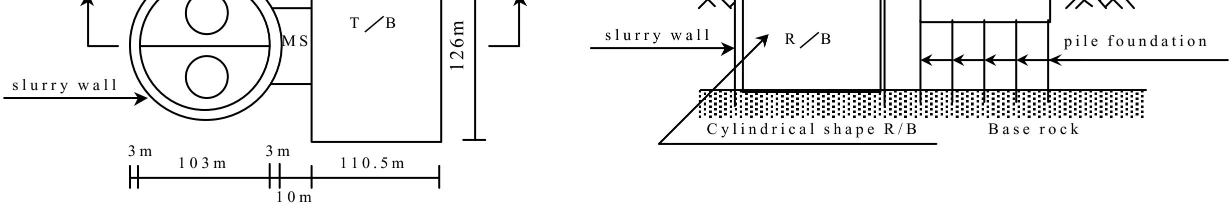


Figure 1: Plot plan

Number of piles is 357 in the prototype but is 35 in the model.

The equivalent linear analysis for the free field with assumed soil property in the candidate site (i.e. G-γ relation and h-γ relation, where G, h and γ denote shear stiffness, damping ratio and shear strain respectively) is performed by the program SHAKE to evaluate the soil property corresponding to dynamic shear strain (γ) during earthquake. Then, using the modified soil property, the 3D linear analyses are performed.

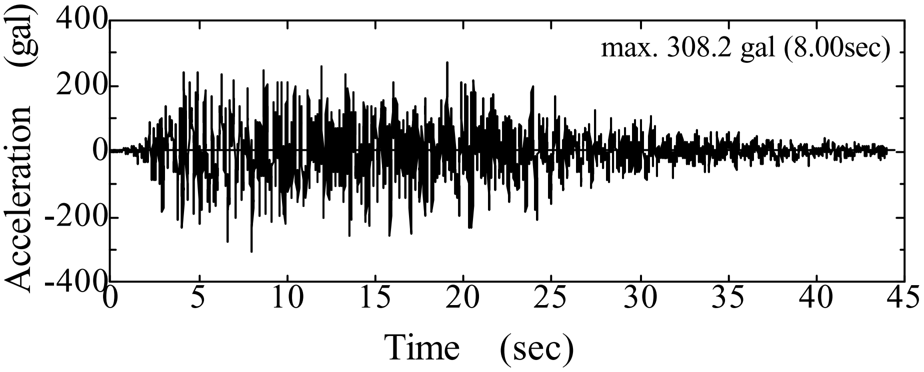


Figure 2: Input seismic wave at GL-378m

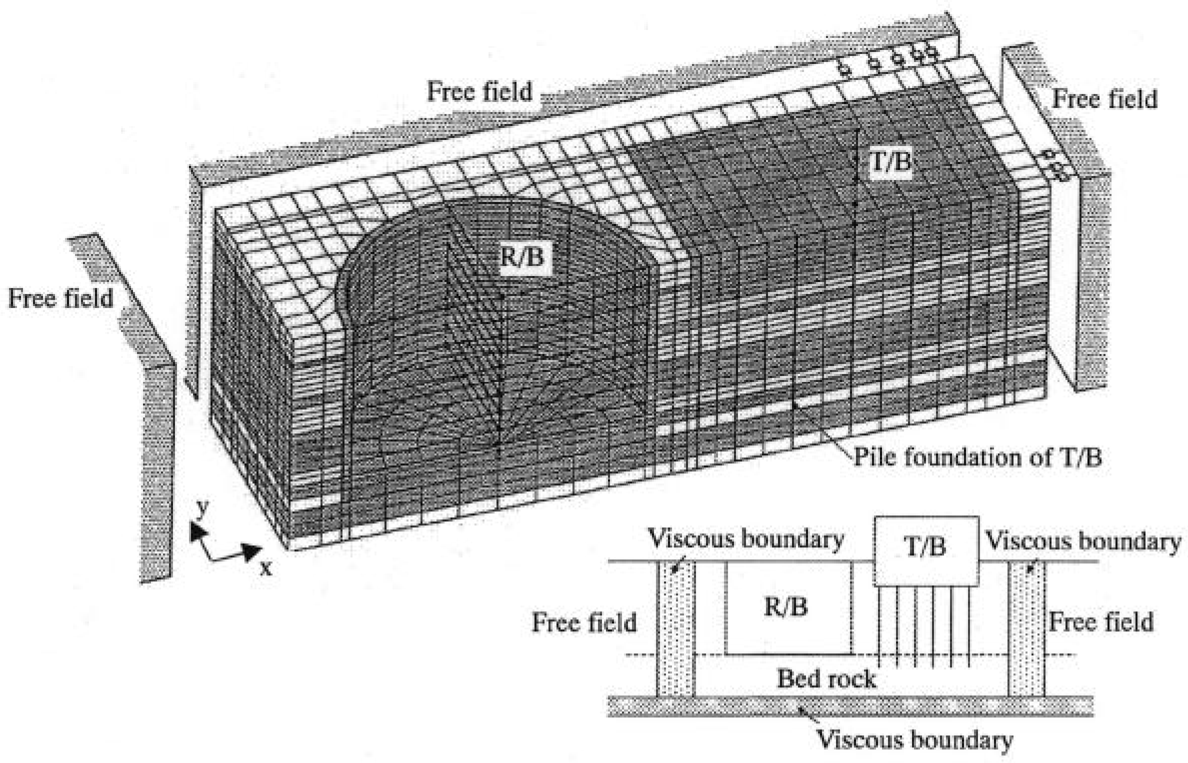


Figure 3: Finite element model for 3D dynamic analysis

RESULTS

5.1 Response Acceleration

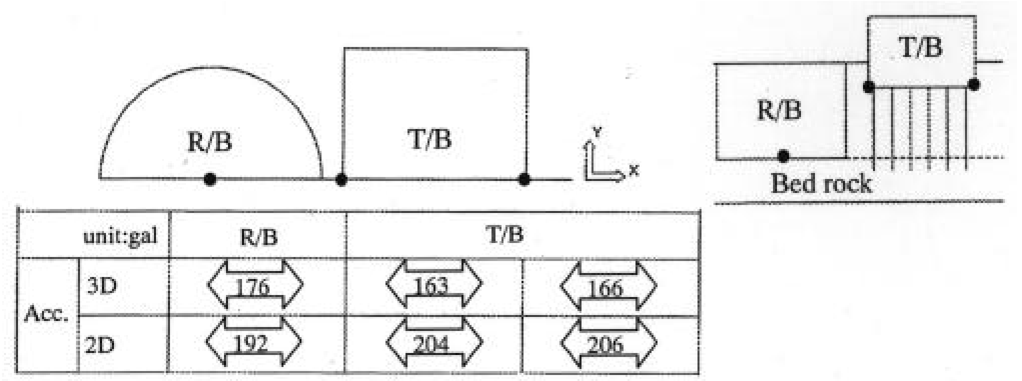
Figure 4 shows the maximum horizontal acceleration of the base mat of R/B and T/B. The following is found :

- There is no marked difference between the accelerations at R/B and two opposite points of T/B.
- The maximum acceleration of R/B and T/B obtained from 3D analysis is a little smaller than that from 2D analysis.

It is concluded from above mentioned facts that the interaction between R/B and T/B has no great influence on the maximum acceleration of R/B and T/B

5.2 Relative Displacement between R/B and T/B

Figure 5 shows time history of the relative horizontal displacements between R/B and T/B in comparison with the result of 2D analysis. The maximum relative displacement exceeds 5 cm from 3D analysis but is less than 1 cm from 2D analysis. The relative displacement between R/B and T/B is strongly influenced by three-dimensional interaction because of shape and stiffness of structures as well as surrounding soft soil



	unit:gal	R/B	T/B	
Acc.	3D	176	163	166
	2D	192	204	206

Figure 4: Maximum horizontal acceleration of base mat of R/B and T/B

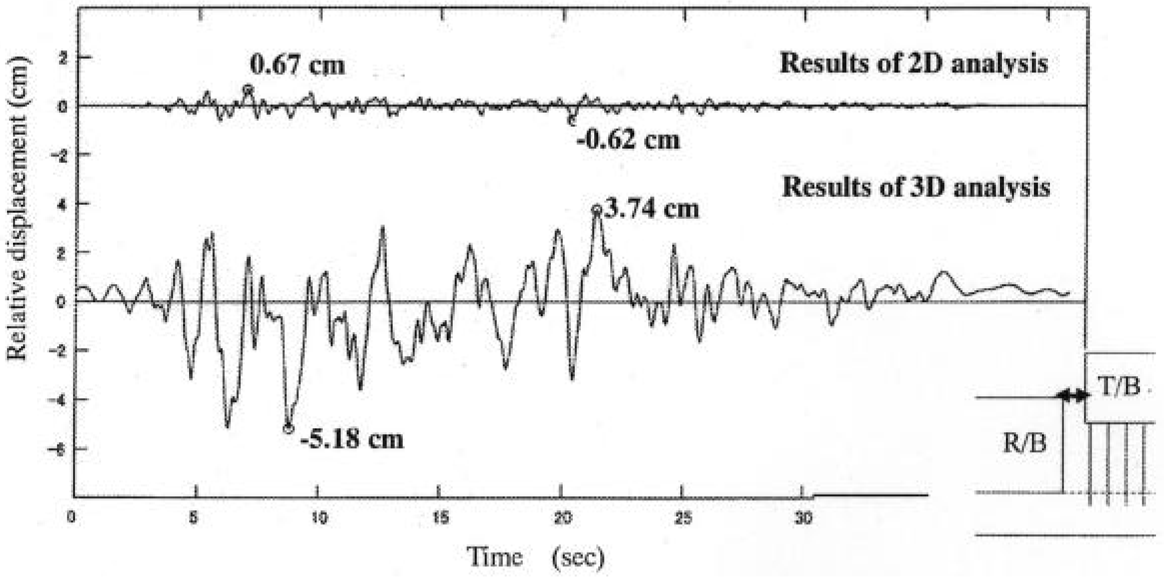


Figure 5: Relative displacement between R/B and T/B

5.3 Applied Earth Pressure to R/B

Distribution of the applied maximum earth pressure to R/B wall is shown in Figure 6. The following is found :

- The applied earth pressure to R/B wall in the closest side to T/B is about three times of that in the opposite free-field side.
- 3D analysis estimate markedly higher earth pressure than 2D analysis.
- The earth pressure is extremely high from EL-2.0m to EL-4.0m in which stiff gravelly sand layer lies.

In conclusion, the applied earth pressure to R/B wall during earthquake is strongly influenced by three-dimensional interaction between R/B and T/B and the condition of constitutive soil layer might play an important role in the interaction.

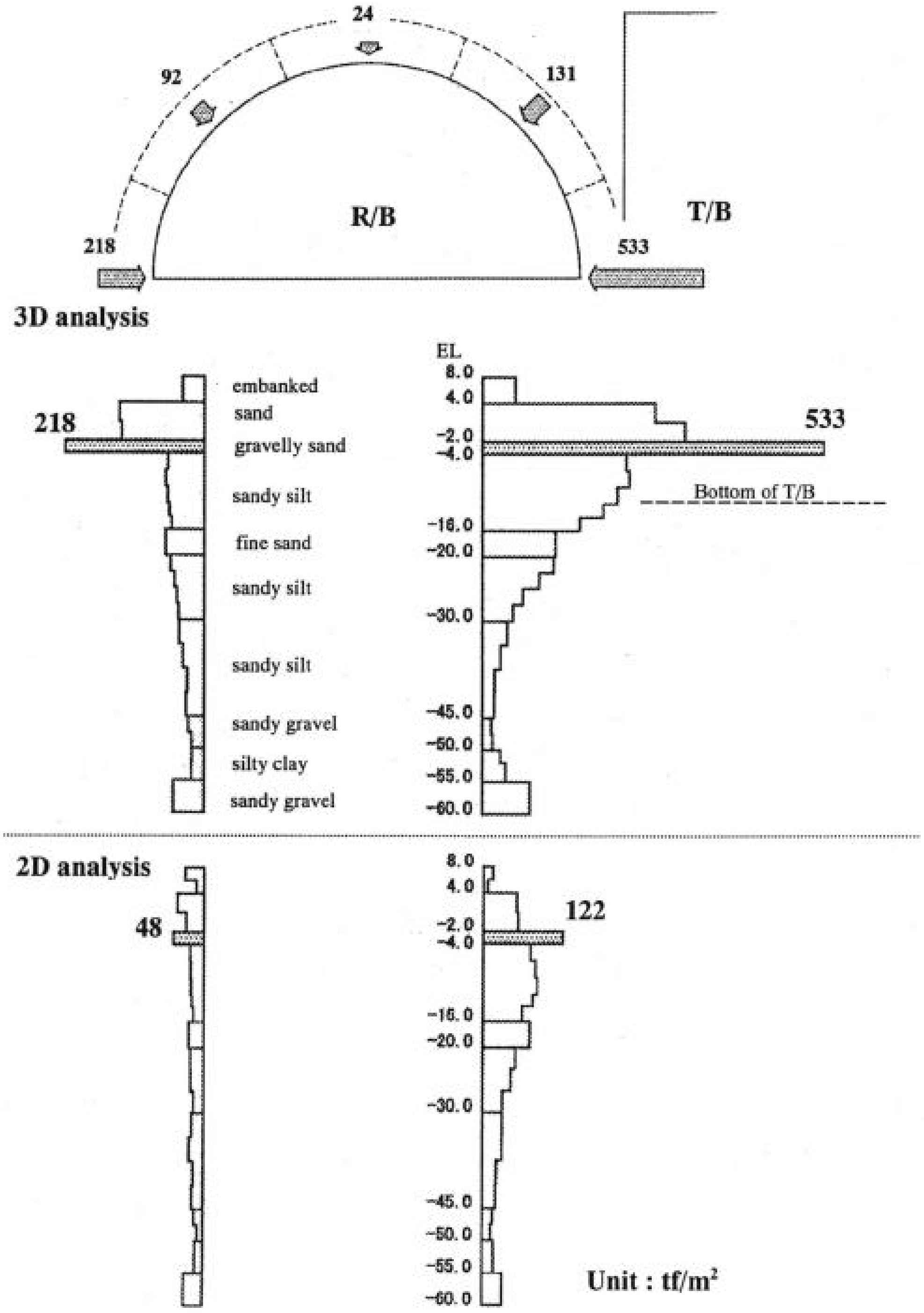


Figure 6: Distribution of the applied maximum earth pressure to R/B wall

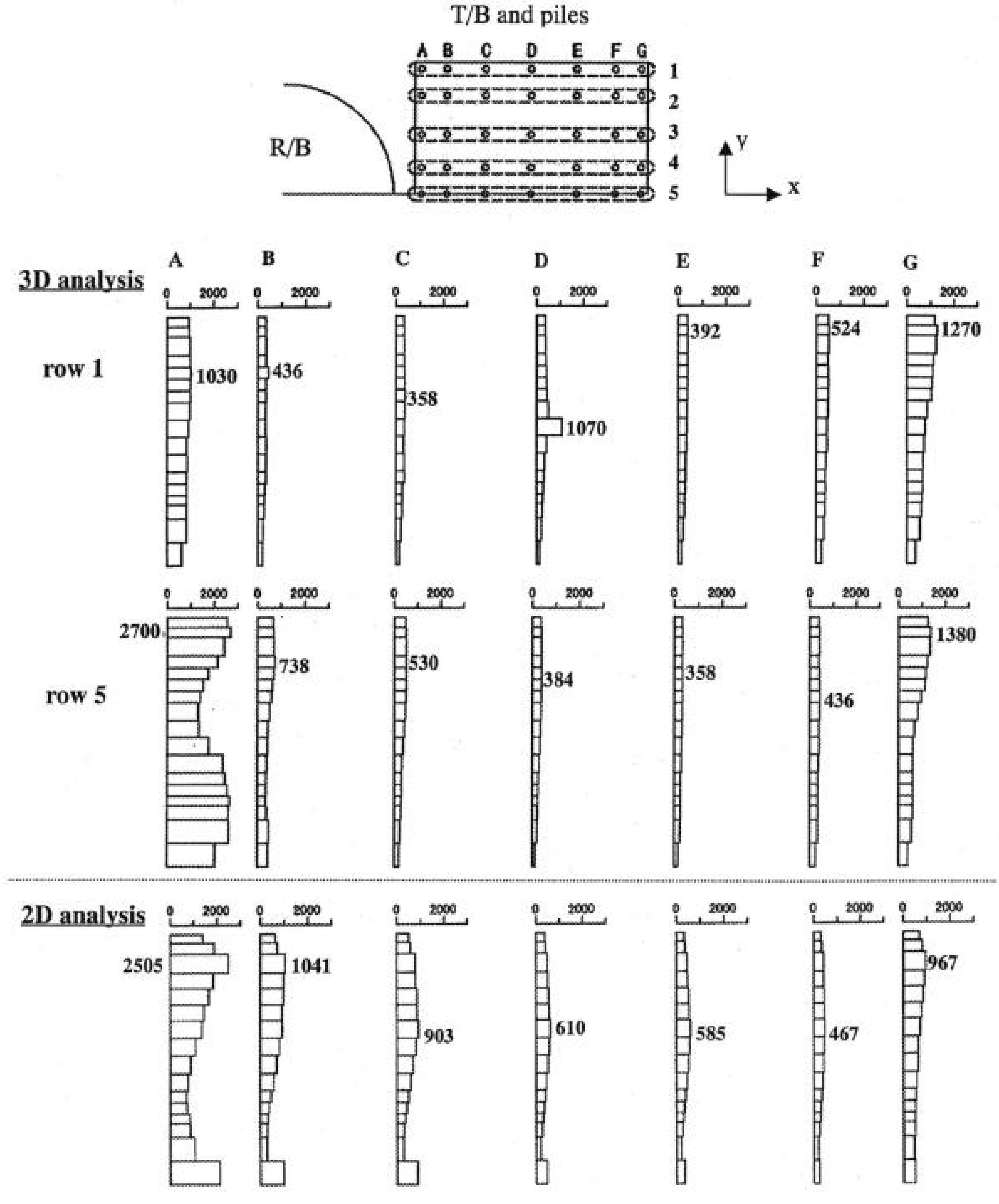


Figure 7: Distribution of maximum axial force of piles

5.4 Section Force of Piles

The distribution of maximum axial force and bending moment of the piles shows in Figure 7 and Figure 8 respectively. The shear force is omitted from figures. It is found that the section force, shear force included, closest to R/B is larger than that of other piles and 3D analysis estimate higher section forces than 2D analysis due to three-dimensional effect.

CONCLUSIONS

The major findings are summarized as follows:

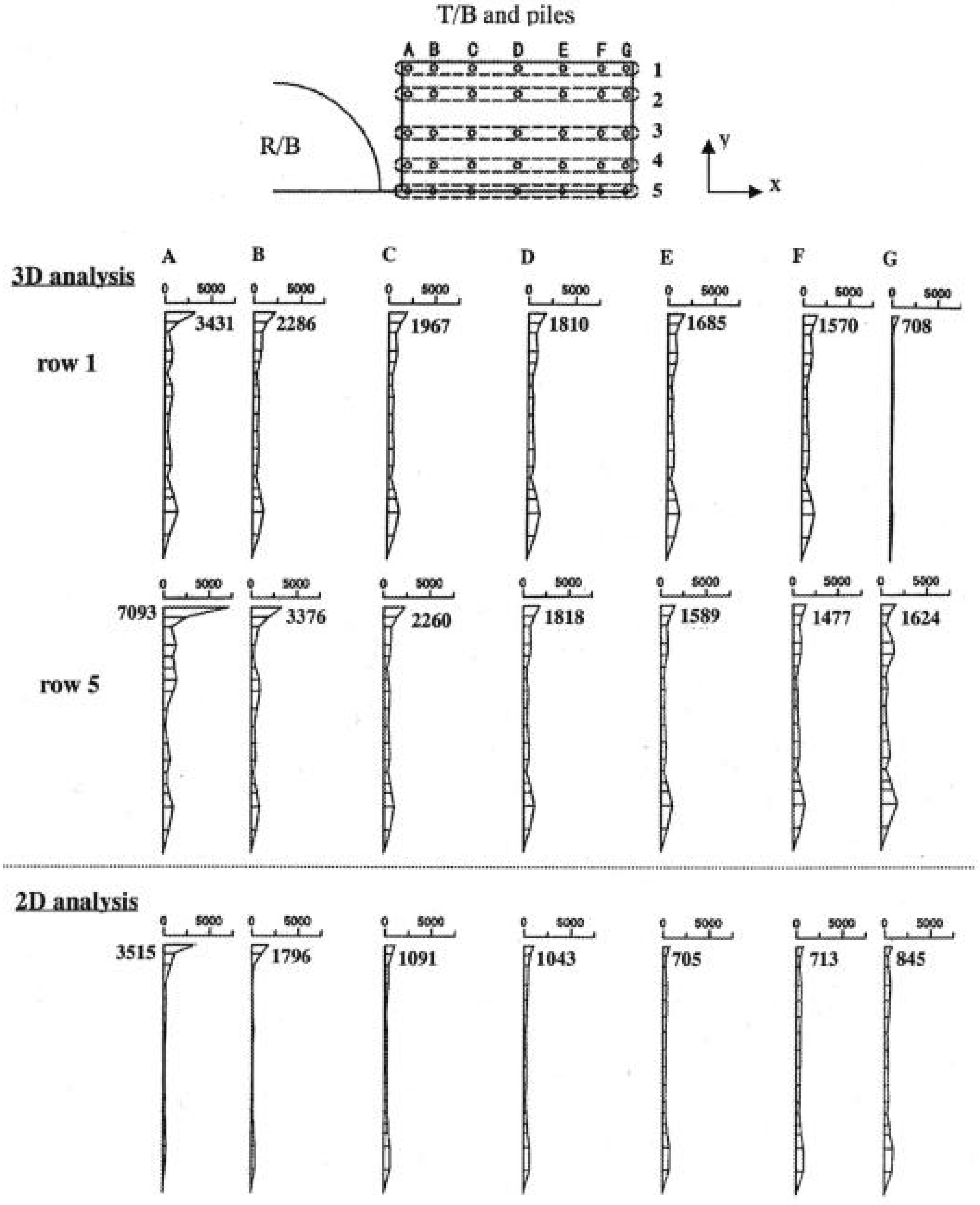


Figure 8: Distribution of maximum bending moment of piles

(1) The three-dimensional interaction between R/B and T/B has no great influence on the maximum acceleration of R/B and T/B

(2) The relative displacement between R/B and T/B is strongly influenced by three-dimensional interaction because of shape and stiffness of structures as well as surrounding soft soil.

(3) The applied incremental earth pressure to R/B wall during earthquake is strongly influenced by the three-dimensional interaction between R/B and T/B. The earth pressure to R/B wall in the closest side to T/B is about three times of that in the opposite free-field side.

(4) The interaction between R/B and T/B makes axial force, shear force and bending moment of the pile closest to R/B be larger than that of other piles.

Three-dimensional R/B-T/B-soil dynamic interaction amplifies the axial force, shear force and bending moment of piles, the applied earth pressure to R/B and the relative displacement between R/B and T/B. It is concluded that three-dimensional R/B-T/B-soil interaction should be considered in the design stage of R/B, T/B and the main steam duct by which R/B is connected to T/B. Especially, the behavior of pile foundation structure has to be evaluated with surrounding soft soil as well as influence of R/B, because pile foundation is flexible

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