SEISMIC EVALUATION OF GROUP PILE FOUNDATION WITH M1 AND M2 MODEL

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In this paper, a series of numerical analyses using dynamic finite element method on simplified model and full model are conducted to investigate the seismic behaviors of group-pile foundation. In the analyses, a beam theory proposed for RC material, in which the axial-force dependency in the nonlinear moment-curvature relation can be considered properly, is used. Two kinds of models for a ground-pile foundation-superstructure system are used. One is called as simplified model, in which, the interaction between piles and ground is represented by springs and the ground-pile foundation-superstructure system is simplified to a frame-spring model (M1 model). Another model is call as full model, in which, the system is modeled with three-dimensional finite elements without simplification (M2 model). The purpose of the research is to verify the applicability of the dynamic analysis with M1 model that can be commonly used in daily seismic design without much difficult. The analyses with M1 and M2 models on a highway bridge with a 9-pile foundation are conducted to check the accuracy of the analysis with simplified model.

***Key words**:* *Group pile, Foundation, Dynamic, FEM, Plasticity*

1. INTRODUCTION

It is known that during a strong earthquake, the dynamic behavior of a group-pile foundation is not only related to the inertial force come from the superstructures but also to the deformation of the surrounding ground. During the Hyogoken-Nambu earthquake, it is found from field observations (Horikoshi et al., 1996) that even in the absence of a superstructure, piles failed because of the deformation of the surrounding ground. The moments developed due to the deformation of ground are usually referred to as kinematic moments.

On the other hand, dealing with a full system, which consists of superstructures, a foundation and a ground, in a numerical dynamic analysis in time domain is usually thought to be effective and executable nowadays when the nonlinearity of the superstructure, the piles and the soils is considered. In daily seismic design, however, dynamic analysis with M2 model is still a little bit of difficulty for engineers. The commonly used model is usually a frame-spring model (M1 model). Many simplified assumptions, however, have been included in the M1 model and therefore it is necessary to verify the accuracy of the analysis with M2 model.

In a common analysis, a very important fact, that is, the influence of axial force on the stiffness and the bending strength of RC piles that greatly affects the nonlinearity of piles, is neglected. The reason why the influence of axial force was not considered is that it is difficult to model the influence under cyclic loading condition within the framework of common beam theory. For this reason, by introducing a new weak form of the equilibrium equation for beams (Zhang & Kimura, 2002), the interaction between the bending moment and the axial force can be properly evaluated under generalized loading conditions.

As to the nonlinearity of soil, a kinematic hardening elastoplastic constitutive model using the concept of

subloading, known as tij subloading model (Chowdhury et al., 1999), is adopted for soils in the 3-D dynamic analysis conducted in this paper.
One of the purposes of the paper is to provide an accurate numerical method of evaluating the dynamic behavior of a group-pile foundation based on 3-D finite element analysis for a superstructure -foundation-ground system, in which the nonlinearity of a pile is described by the axial-force dependent model and soils are described with the tij subloading model. Another purpose of the paper is to check the accuracy of the analysis with M1 model, based on the condition that the dynamic analysis on M2 model is an accurate method in seismic design of group-pile foundation. In the paper, all the numerical analyses are conducted in the same program named DGPILE-3D (Zhang et al., 2000).

2. SEISMIC RESPONSES OF GROUND-PILE FOUNDATION USING M1 AND M2 MODELS

In order to avoid meaningless comparison, the calculations with M1 and M2 models are conducted with the same program name as DGPILE-3D.
In the calculation, an elevated highway bridge with a group-pile foundation made of 3×3 cast-in-place reinforced concrete piles, in which the center-to-center distance of the group piles is 2.5D, is considered. **Table 1** shows the physical and geometrical properties of the piles. The ground is composed of six layers of sandy soils and clayed soils. **Table 2** lists the material parameters of the soils.

Table 1 Physical and geometrical properties of pile

Diameter	Length	Yield strength	Young's modulus (Reinforcement)	Young's modulus (Concrete)	Sectional moment
D (m)	L (m)	σ_y (MPa)	E_S (kPa)	E_C (kPa)	I (m^4)
1.2	15.0	295	2.000E+08	2.500E+07	1.018E-01

Table 2 Material parameters of soils

Layer	Thickness (m)	Density (g/cm^3)	Poisson's Ratio	Void ratio	Stress ratio at failure	Compression index	Swelling index
	H	ρ	ν	e_0	R_f	C_t	C_e
A_{S1}	2.2	1.7	0.30	0.93	4.5	0.0234	0.0140
A_{C1}	2.6	1.7	0.40	0.88	3.5	0.0191	0.0124
A_{S2}	4.0	1.7	0.30	0.93	4.6	0.0124	0.0092
A_{C2}	3.5	1.7	0.40	0.88	3.5	0.0168	0.0097
A_{S3}	3.5	1.9	0.30	0.87	4.7	0.0084	0.0060
D_S	1.4	1.9	0.30	0.65	---	---	---

For simplicity, earthquake wave is input in one direction so that the domain can be reduced to half volume because of the symmetric conditions of both geometrical and loading condition.
In M1 model, three piles in each row are combined to one so that the simplified model can be used in two-dimensional analysis. The springs representing the interaction between pile and surrounding ground in horizontal and vertical directions, the interaction between footing and the surrounding ground, and the shear spring representing the connection of free ground slices, are evaluated according to the Design Codes of Foundations and Earth-Retaining Structures of Japan Railway (Japan Ministry of Transportation, 1997). Detailed description about the evaluation of these equivalent springs can be referred to corresponding references, e.g., Mori, 1997 and Noda, 2003. **Figure 1** shows the simplified M1 model.
In M2 model, due to the above-mentioned symmetrical conditions, only six piles are considered as shown in **Figure 2**. In order to make the comparison between the analyses using M1 and M2 models more easily, the first row of piles are call as Pile1, and so on. The boundary condition of M2 model is that: (a) the bottom of the ground is fixed; (b) the vertical boundaries parallel to the XOZ plane are roll boundaries; (c) an equal-displacement-boundary condition is used between the two other side boundaries The boundary condition of the piles is that the head of the pile is fixed with the footing and the toe of the pile is free.

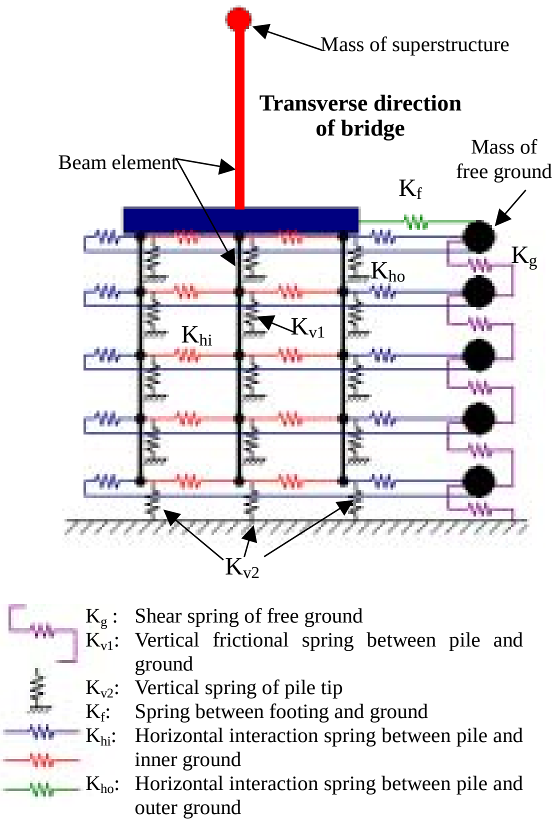


Figure 1 Simplified model of ground-pile foundation-superstructure system (M1 model)

2.1 Comparison of seismic responses of free ground using M1 and M2 models under elastic condition

Before conducting the comparison between the analyses of group-pile foundation, the seismic responses of the free ground with M1 and M2 models under elastic condition is investigated. In M1 model, the free ground is simply modeled with a column of masses and springs as shown in the right side of **Figure 1**. In M2 model, the ground is modeled with a three-dimensional finite element mesh without piles and column as shown in **Figure 2**. **Figure 3** shows the input wave of earthquake.

A direct integration method of Newmark-β is adopted in the dynamic analysis. A Rayleigh type of damping is adopted and the damping factors of the structures and the ground are assumed as 2%, in the dynamic analysis of a full system. Although the stiffness of the ground, the piles, and the column may change because of the nonlinearity of these materials, the viscous matrix calculated from the Rayleigh type of damping is assumed to be constant irrespective of the changes in the stiffness matrix. In calculating the viscous matrix, an eigenvalue analysis for the full system is conducted to evaluate the first two eigenvalues. The eigenvalue analysis is conducted with a hybrid of Jacobian and subspace methods. In the dynamic analysis, the time interval of the integration is 0.01 sec. In the calculation, 20 seconds of the main vibration of the input wave is calculated.

Figure 4 shows the comparisons of response acceleration and displacement at the surface of the free ground. It can be seen from the figure that under elastic condition, the results from M1 and M2 models are totally the same, implying that the simplification involved in M1 model is completely acceptable in seismic evaluation of ground under elastic condition.

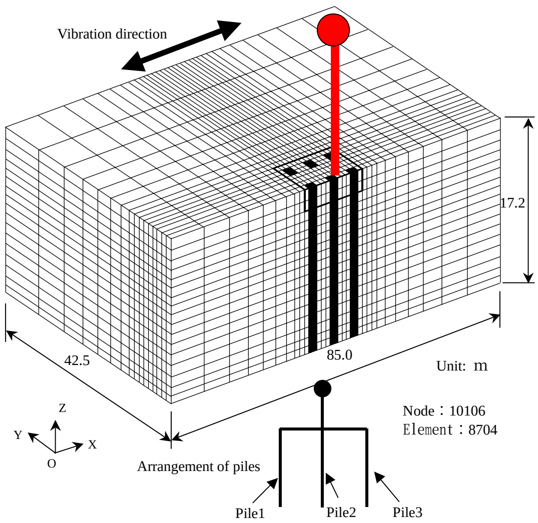


Figure 2 Finite element mesh (M2 model)

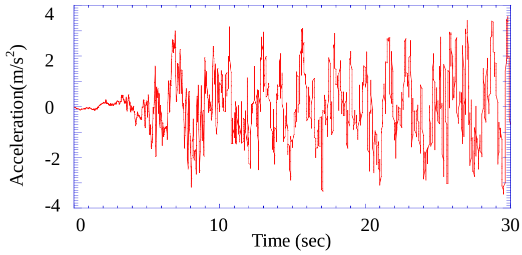
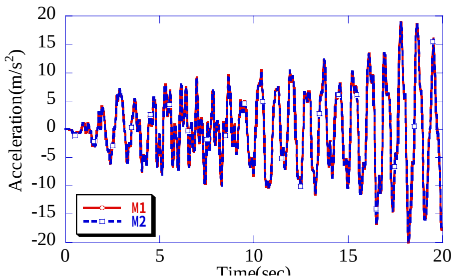
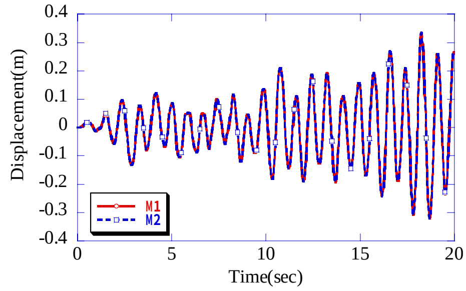


Figure 3 Input wave



(a) Acceleration at the surface of ground



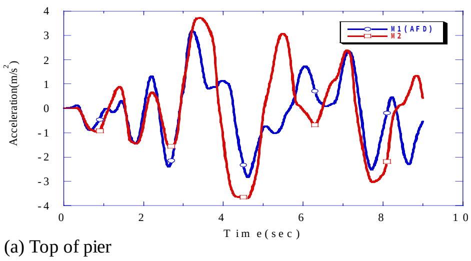
(b) Displacement at the surface of ground

Figure 4 Comparison of seismic responses of free ground using M1 and M2 models under elastic condition

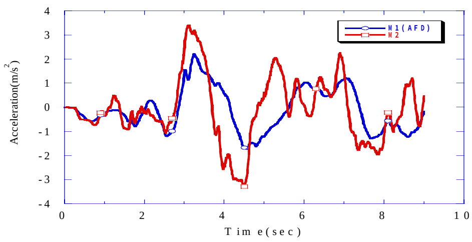
2.2 Comparison of seismic responses of full system using M1 and M2 models

In the dynamic analyses of the ground-pile foundation-superstructure system using M1 and M2 models, the nonlinearity of the ground, the piles and the superstructure is fully considered. In M1 model, all the equivalent springs are modeled with tri-linear model considering the hysteresis of loading and unloading. The nonlinearity of pile is simulated by two kinds of models; one is tri-linear model that cannot take into consideration the axial-force dependency (Briefly, M1-Tri), another is AFD model (Briefly M1-AFD). In M2 model, the soils are simulated with tij subloading clay model and original tij sand model. The pile is simulated with AFD model. The superstructure, or column, is simulated by tri-linear model in both M1 and M2 models.

Figure 5 shows the comparison of response accelerations at the top of column and the bottom of column. It is found that the maximum accelerations at the top of column from M1 and M2 models are in the same order. While at the bottom, the response

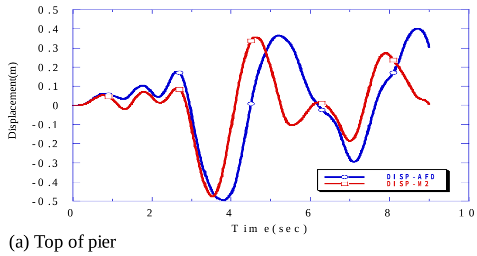


(a) Top of pier

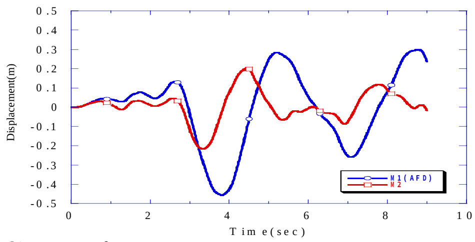


(b) Bottom of pier

Figure 5 Comparison of response accelerations using M1 -AFD and M2 models

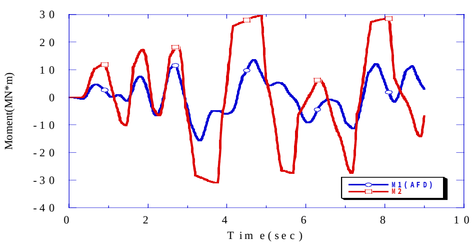


(a) Top of pier

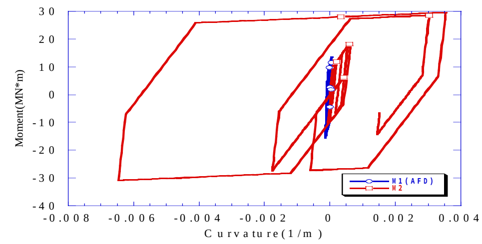


(b) Bottom of pier

Figure 6 Comparison of response displacements using M1 -AFD and M2 models



(a) Time history of bending moment at the bottom of column



(b) M-ϕ relation at the bottom of column

Figure 7 Comparison of moment-curvature relation using M1-AFD and M2 models

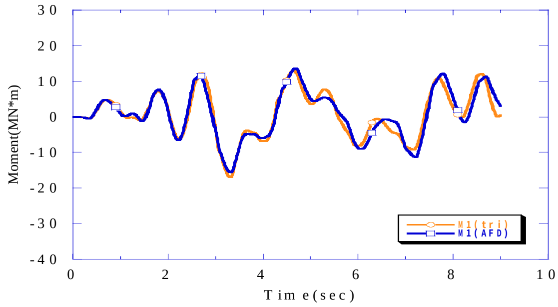
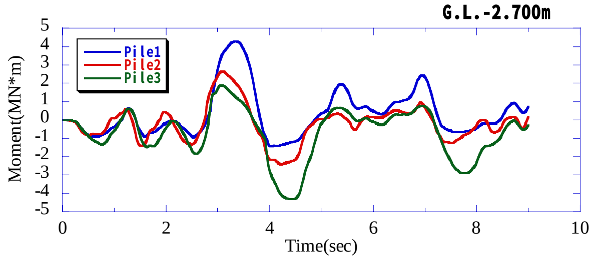
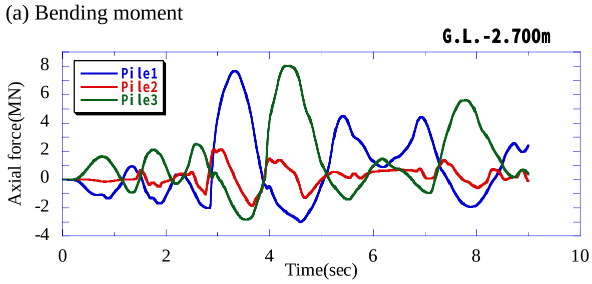


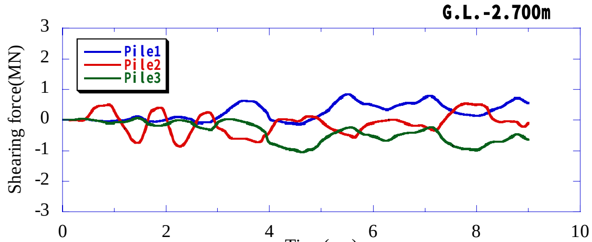
Figure 8 Comparison of time history of bending moment at the bottom of column using M1-AFD and M1-Tri models



(a) Bending moment



(b) Axial force

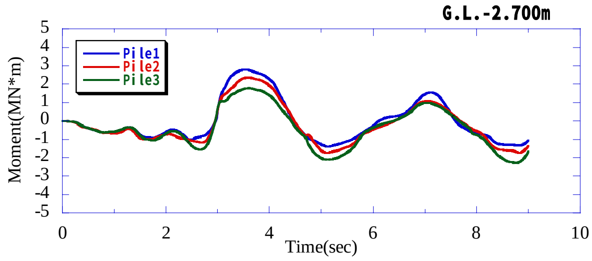


(c) Shear force

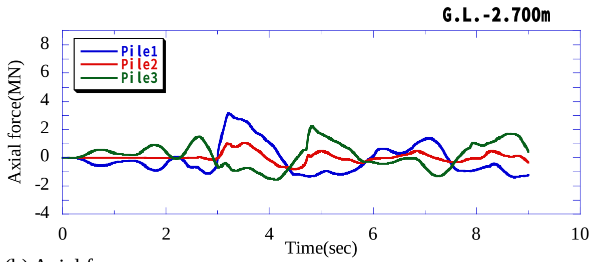
Figure 9 Time histories of sectional forces at pile head using M2 model

accelerations are quite different. The same tendency can be observed in the response displacements from M1 and M2 models, as shown in **Figure 6**. The displacement evaluated with M1 model is much larger than that of M2 model while the acceleration evaluated with M1 model is much smaller than that of M2 model. This is thought to be the reason that in M1 model, the stiffness of ground will decrease dramatically when the stress overpass the yielding point due to the adoption of tri-linear model. As the results of the difference between the response accelerations and displacements, the bending moments and the moment-curvature relations at the bottom of column, are also quite different, as shown in **Figure 7**.

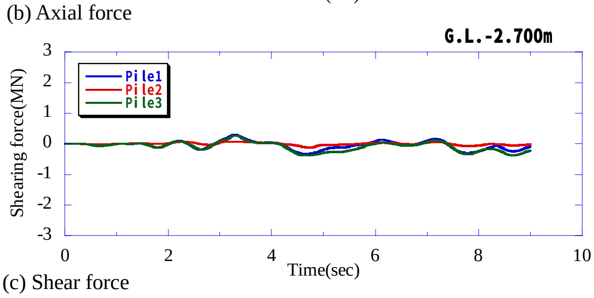
Figure 8 shows the comparison of time history of bending moment at the bottom of column from M1-



(a) Bending moment

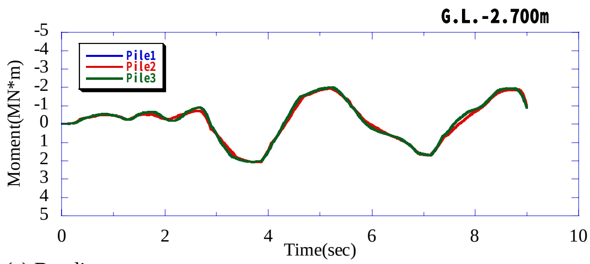


(b) Axial force

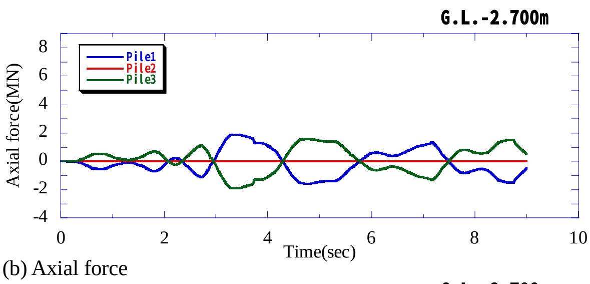


(c) Shear force

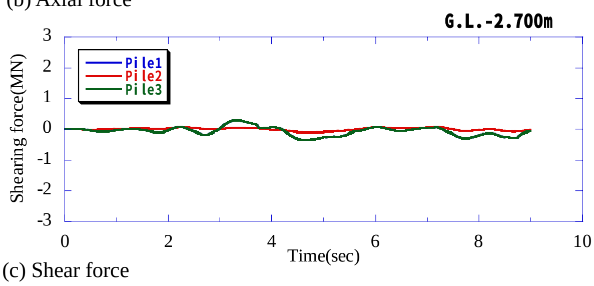
Figure 10 Time histories of sectional forces at pile head using M1 (AFD) model



(a) Bending moment



(b) Axial force



(c) Shear force

Figure 11 Time histories of sectional forces at pile head using M1 (Tri) model

AFD and M1-Tri models. It is found that the difference of the nonlinear model used for piles in M1 model has little influence on the responding moment at the bottom of column (superstructure), though it may greatly affect the response of sectional forces of piles as can be seen in **Figures 9-11**.

Figures 9-11 show the time histories of sectional forces at pile head using different models. In the analysis with M2 model, the difference of sectional forces between different piles is clearly described. In M1-AFD model, due to the adoption of AFD model for piles, the difference of sectional forces between different piles can also be described to some extent. In M1-Tri model, however, the difference cannot be described at all. The above results indicate that it is very important to introduce a proper model for piles both in M1 and M2 models.

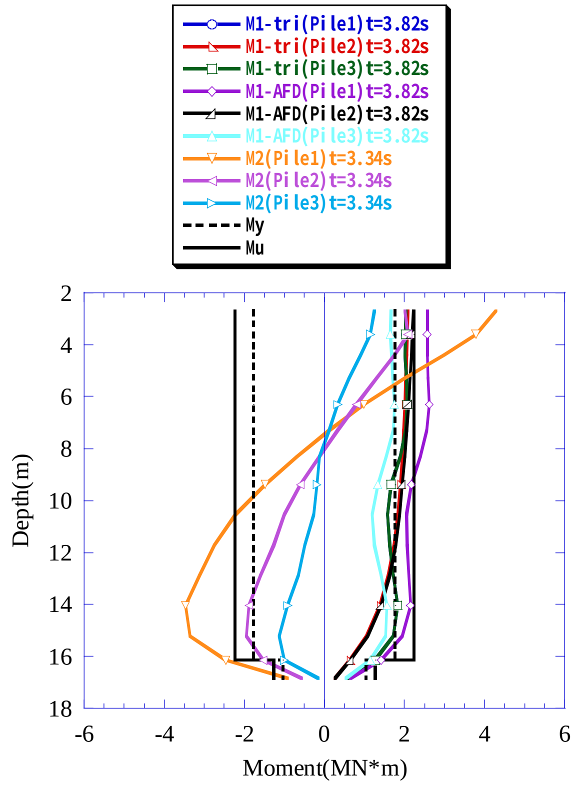


Figure 12 Comparison of the distributions in the maximum bending moment of piles using M1 and M2 models

Figure 12 shows the comparison of the distributions in the maximum bending moment of piles obtained from different analyses with M1 and M2 models. It is found that the bending moment from M2 model is, on the whole, much larger than that from M1 model. It is also known that the distribution of the bending moment from M2 model changed its direction along the depth, which is thought to be usual in group-pile foundations. The results from M1 models, however, did not change along the depth. This is thought to be the reason that the interactions between the piles and ground are underestimated in the analyses with M1 models. For this reason, it should be pointed out that the seismic evaluation using M1 model has the risk of underestimation of sectional forces due to earthquake vibration.

3. CONCLUSIONS

Under elastic condition, the seismic behavior of free ground from M1 and M2 models are totally the same. Therefore, the simplification involved in M1 model is completely acceptable in seismic evaluation of free ground under elastic condition.

Under elasto-plastic condition, however, there is big difference between the analyses using M1 and M2 models.

The displacements at the top and bottom of column evaluated with M1 model are much larger than that of M2 model while the accelerations evaluated with M1 model is much smaller than that of M2 model.

The bending moment from M2 model is, on the whole, much larger than that from M1 model. The distribution of the bending moment from M2 model changed its direction along the depth, while the results from M1 models did not change along the depth. These differences are found to be caused by the difference of the deformation of the ground evaluated by different models. The seismic evaluation using M1 model has the risk of underestimation of sectional forces due to earthquake vibration. Therefore, further research should be made to improve the modeling of M1 model in its application.

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(Received June 28, 2003)