Effect of Ground Improvement around Pile Foundation on Seismic Behavior of Pile Structure during Very Large Earthquake

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SUMMARY:
This paper presents the simulation analysis about the damaged structure supported by pile in Hyogo-ken Nanbu (Kobe) earthquake. The major findings obtained from analyses are summarized as follows;
1) The deformation of piles for FE analysis is a little larger than the observation. However, the deformation of pile which has low stiffness was largest in both the FE analysis and the observation.
2) The inertial force and the ground displacement applied to the pile at the same time and the ground doesn't resist the displacement of the pile. For this reason, the foundation subjected large displacement and the pile head may be damaged in Kobe Earthquake.
3) The seismic response of pile is able to reduce by the ground improvement, which led the increase of the lateral resistance of the surface layer and the decrease of the displacement of ground.

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1. INTRODUCTION

Many structures supported by pile were damaged seriously in Hyogo-ken Nanbu earthquake and the results of the investigation were summarized by Kinki Branch of AIJ (1996). However, the reasons of damage have not been cleared yet. The strong nonlinear behavior of pile-soil systems, which is the separation between the pile and the soil, slip in the soil or the yielding of the pile cap, will occur under the strong ground motions. The nonlinearity of soil-pile-structure dynamic interaction has a strong influence on the structural behavior during earthquake. It is considered that the 3D FEM is very effective in the evaluation of behavior of structure during earthquake with nonlinear soil-structure interaction.

On the other hand, the structure built on the improved ground suffered very little to minor damage, so the ground improvement has been applied to many structures after Hyogo-ken Nanbu earthquake. Therefore, we conducted the centrifugal model tests for the structure supported by piles in dry sand subjected large earthquake and the simulation analysis by elastic-plastic 3-D FEM (Hidekawa 2011). This paper presents the simulation analysis about the damaged structure supported by pile in Hyogo-ken Nanbu (Kobe) earthquake. In addition, the influence of the ground improvement on the behavior of soil-pile-structure system is discussed.

2. SECTION HEADING (11PT BOLD AND ALL CAPS)

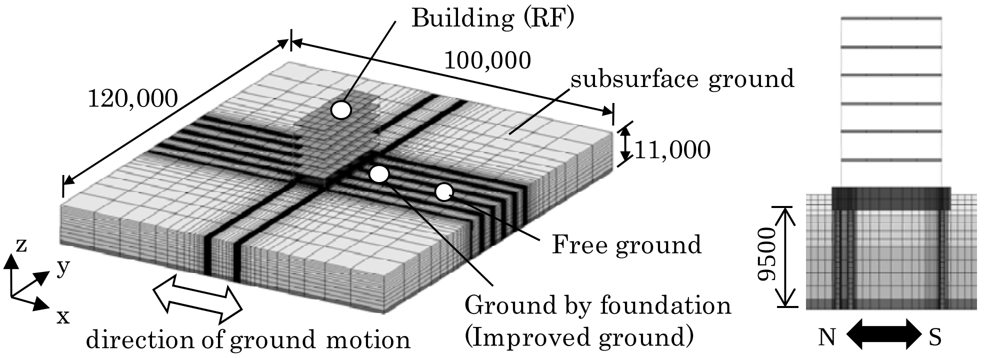
2.1. Description of model

The FE analysis was conducted about the collective housing which was a six story reinforced concrete structure and was supported by prestressed high strength concrete pile groups which consisted of two, three, or four piles (Kinki Branch 1996). The pile had 600mm outer diameter.

Figure 1 shows the finite element mesh for the structure supported by piles and subsurface layers. In this simulation analysis, only N-S direction which was short side direction of superstructure was considered because N-S component of seismic ground motion in this area might be dominant by considered tipping condition of gravestone. So, the superstructure assumed to be linear. For the superstructure, the slabs and base foundation models were used 8-node rectangular solid elements with reduced integration, and the column models were used 2-node beam elements. The properties of superstructure used in the analysis were summarized in Table 1. The slabs and base foundation were assumed to be rigid body with density ρ and contact property, and the columns assumed to be linearly elastic with elastic modules E and Poisson's ratio ν. The natural period of 1st mode under base fixed condition was 0.17 second. The pile models were used shell element, and assumed to have elastic-plastic bi-linear model with coefficient of strain hardening and yield stress. The elastic module E and the coefficient of strain hardening and the yield stress were determined as the moment-curvature relationship of pile by FE analysis simulated that of pile by fiber analysis, as shown Figure 2. The edges of piles were fixed in all rotated coordinate directions and vertical direction, and were free in horizontal direction. The pile caps were fixed to base foundation rigidly. The contact condition, which allowed the slip and the separation of the contacting surfaces, was applied between the pile and the soil.

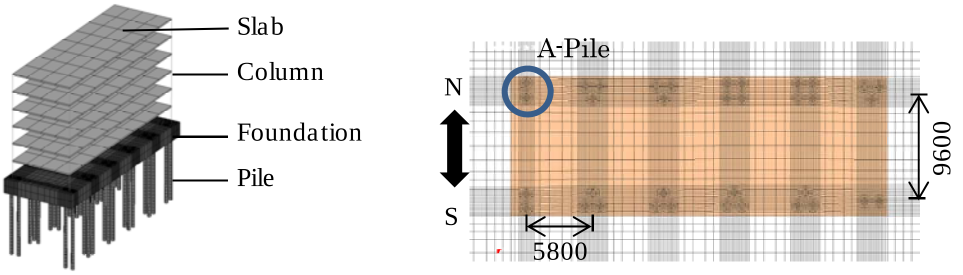
The properties of surface layers used in the analysis were summarized in Table 2. The surface layers model was assumed to consist four layer on the basis of the result of borehole survey, and bedrock model was used elastic solid element, where the shear wave velocity Vs=450(m/s). The soil of which the surface layers consist was assumed to be a Mohr-Coulomb elastic-plastic constitutive model with no associated flow rule. For the side boundaries, the nodes which were same depth were constrained in all three coordinate directions. For the bottom boundaries, the nodes were fixed without short side direction in the superstructure, and the model was shaken under a one-direction input motion, as shown Figure 3.

The input ground motion which was the bedrock motions at GL.-10m was evaluated by 2D FE Analysis using deep irregular underground model with vertical discontinuity, and the observation record at Motoyama elementary school. The input ground motion was acceleration record in N-S direction. Maximum acceleration value of the input motion is 8.23 m/s^2. As shown Figure 3 (b), the



(a) 3-D meshes for FEM

(b) Cross section view



(c) Analysis model of Structure

(d) Plan view of soil around piles

Fig.1 Layout of analysis model

(unit:mm)

input ground motion is far larger than the seismic acceleration of the Japanese code.
This superstructure suffered very little to minor damage and the pile caps suffered visible structural damage. Figure 4 shows the summary of damage investigation of pile cap at 1995 Hyogo-ken Nanbu (Kobe) earthquake. Pile caps which were suffered serious structural damage were 5 by visual check by Kinki Branch of AIJ and damaged piles were the member of pile groups which consisted of two or three piles.

2.2. Result of FE analysis

Figure 5 shows the calculated acceleration responses of the superstructure (RF) and the acceleration time history of input ground motion. The calculated results of superstructure are close to the input ground motion because the natural period of soil-pile-structure interaction system was shorter than the predominant period of input ground motion.

Figure 6 shows the time history of Q_b/W_{all}, where Q_b = sum of shear force on columns of 1st story, W_{all} =sum of the weight of slabs and columns over 1st story. The maximum value of Q_b/W_{all} is about 0.72, and this result indicates that the superstructure may not suffer structural damage under this input motion. This result is consistent with the investigation result by Kinki Branch.

Table1 Properties of structure

		Slab		Collumn (600×600)		
	GL (mm)	Width (mm)	Weight (t)	Hight (mm)	Weight (t)	Young's Module (N/mm^2)
RF	17000	210	357			
6F	14300	210	357	2500	31.4	5.39×10^{-5}
5F	11500	210	357	2500	31.4	9.66×10^{-5}
4F	8830	210	357	2500	31.4	12.4×10^{-5}
3F	6120	210	357	2500	31.4	15.2×10^{-5}
2F	3410	210	396	2500	31.4	20.7×10^{-5}
Foundation	700	2200	505	2500	31.4	6.73×10^{-5}

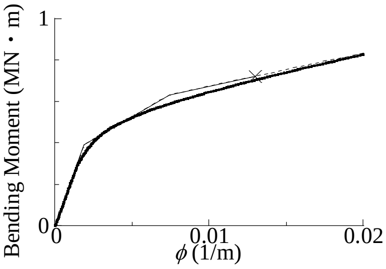
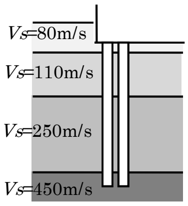
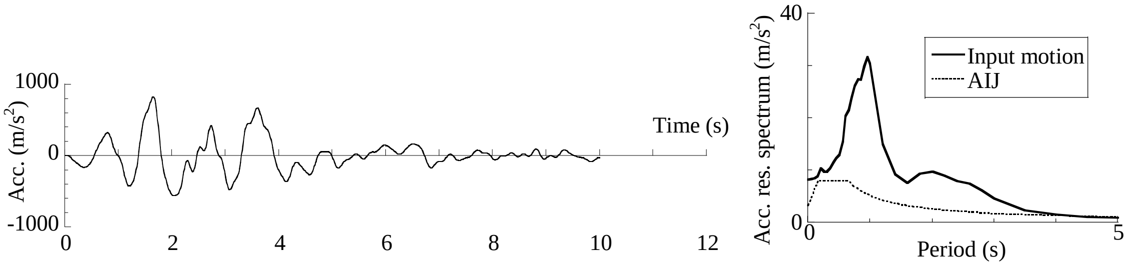


Fig.2 *M-ϕ* relationship of pile

Table2 Properties of surface layers

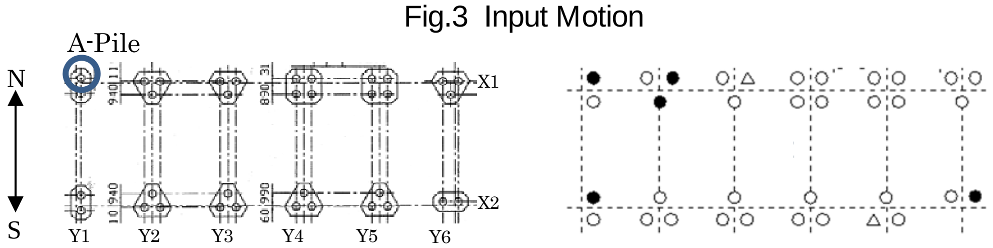
	GL (mm)	N Value	γ (t/m^3)	Vs (mm)	ν
0～-2.0m	2	10	1.8	80	0.4
-2.0～-5.0m	3	10	1.7	110	0.4
-5.0～-10.0m	5	18.2	1.8	250	0.4
-10.0m～		60	2	450	0.4





(a) Time history (b) Acceleration response spectrum

Fig.3 Input Motion



(a) Plan view of pile foundation (b) Summary of damage investigation by visual check （● : serious damage）

Fig.4 Summary of damage investigation of pile cap

Figure 7 shows the curvature of pile by seismic motion. Figure 7(a) shows the distribution of curvature at A-pile in Figure 3 at 1.83s, where ϕ_y = the curvature of yielding starting, ϕ_p = the curvature of full plasticity. Figure 7(b) shows the distribution of maximum curvature at the pile head of all piles. As shown Figure 7(a), the curvature at pile cap is greater than ϕ_p and the pile cap became full plastic state, whereas the other part of pile stayed in elastic state. As shown Figure 7(b), the curvature of the pile located in north is larger than that in south and all of the pile head are greater than ϕ_p and became full plastic state. Furthermore, curvature of the pile located in northwest is largest in all piles. As shown Figure 4, the pile head at the pile located in northwest suffered serious structural damage, whereas the others suffered no visible structural damage. Therefore, the evaluations for FE analysis were larger than the observation. However, the common trend is appeared between observation and analysis that the curvature of the pile located in northwest is larger.

Figure 8 shows the time histories of responses of soil-pile-structure system, Figure 8(a) shows the inertial force acting on the base foundation, Figure 8(b) shows the reaction force to inertial force at base foundation, Figure 8(c) shows displacement of ground and foundation, and Figure 8(d) shows the the curvature at pile cap at A-pile. As shown Figure 8(a), (c) and (d), the inertial force (shear force on column at 1st story and inertial force on foundation) and the displacement of the pile head peak at 1.83s and then the curvature of the pile head at A-pile peaks at the same time. Furthermore, as shown Figure 8(c), the displacement of the free ground, the ground by the foundation and the pile head (at the depth of -1.5m) are in agreement and this imply that the ground and foundation behaved in one by subjected the seismic motion shown Figure 3. On the other hand, as shown Figure 8(b), the shear force at the pile head, which is reaction force to inertial force on foundation, is nearly comparable to the subgrade reaction on the foundation.

Figure 9 shows the distribution of the bending moment and the subgrade reaction at A-pile at 1.83s, when the curvature of pile head at A-pile peaked. The subgrade reaction is calculated from bending moment. The subgrade reaction act by boundary of geological layer, and is small except for the boundary of geological layer.

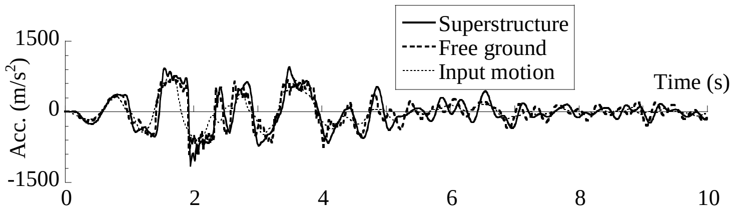


Fig.5 Time history of acceleration

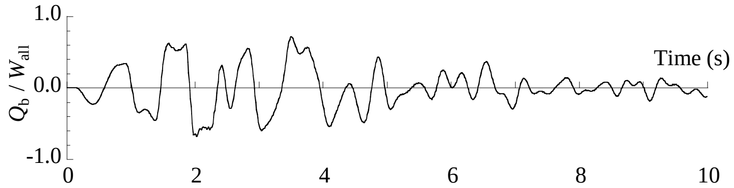
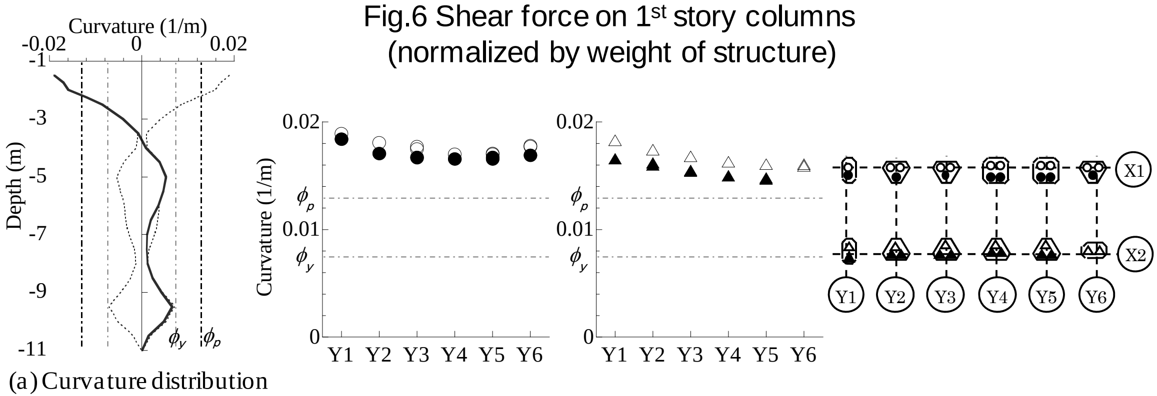


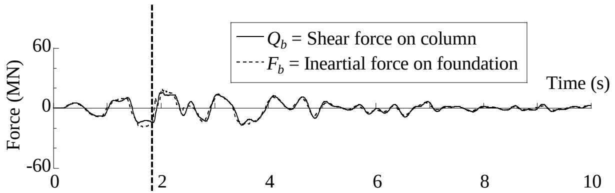
Fig.6 Shear force on 1st story columns (normalized by weight of structure)



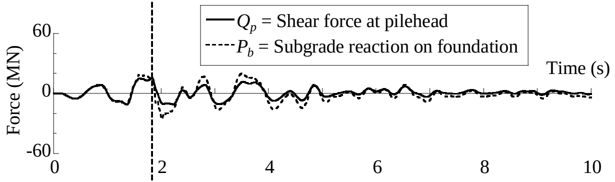
(a) Curvature distribution at A-Pile (A-pile, 1.83s)

(b) Maximum curvature at pile head

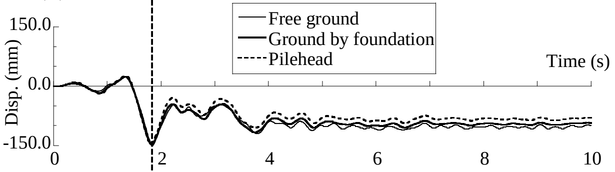
Fig.7 Curvature of piles caused by seismic motion



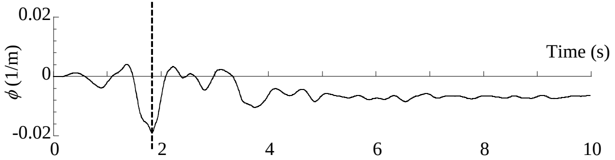
(a) Inertial force acting on foundation



(b) Reaction force to inertial force at base foundation



(c) Displacements of ground surface and foundation (G.L.-1.5m)



(d) Curvature at pile cap (A-Pile)

Fig.8 Time histories of responses of soil-pile-structure system

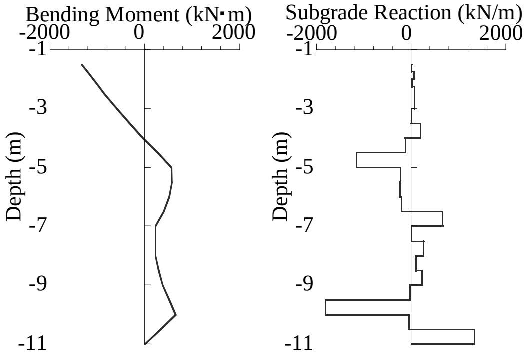


Fig.9 Distribution of bending moment and subgrade reaction at A-pile (1.83s)

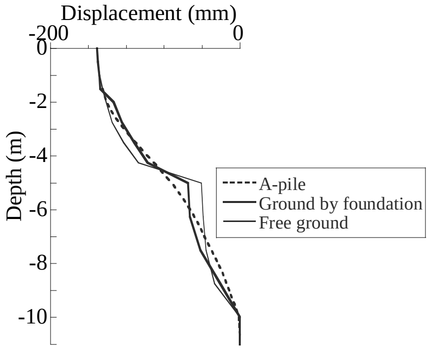


Fig.10 Distribution of displacement (1.83s)

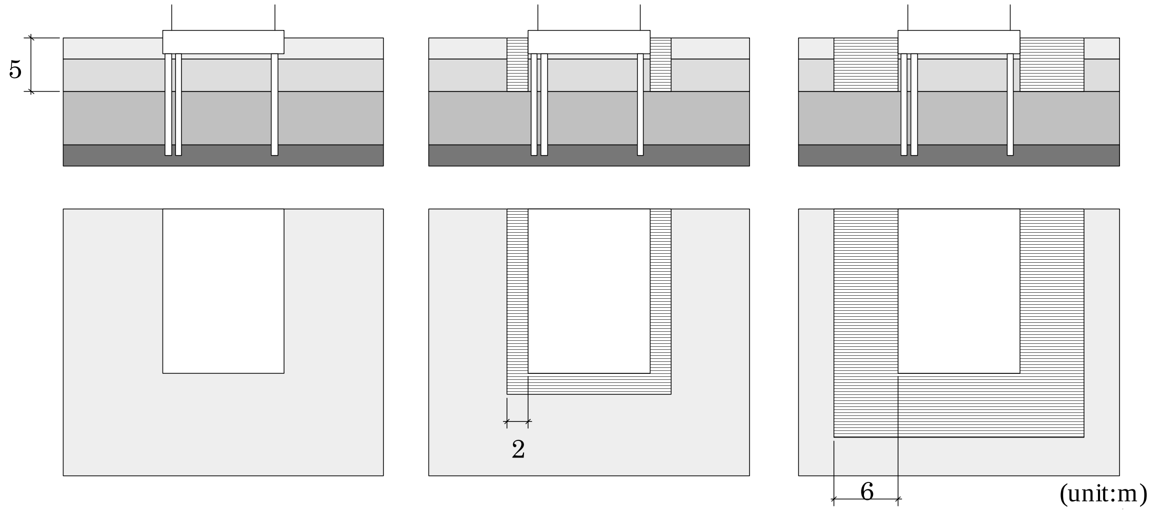
Figure 10 shows the distribution of displacement to the depth at the free ground, the ground by the foundation, and A-pile. The displacement of the free ground and the ground by the foundation is nearly comparable to the displacement of pile, so the ground doesn't resist the displacement of the pile. This may lead to the small subgrade reaction except for the boundary of geological layer and the large displacement and the large curvature at the pile head.

3. EFFECT OF RESPONSE REDUCTION BY GROUND IMPROVEMENT

3.1. Analysis model

Figure 11 shows the pattern of the ground improvement. Two analysis cases were conducted. In the case of 2m, the ground improvement was applied to the ground around the foundation; the dimensions are 2m in width and 5m in depth. In case of 6m, the ground improvement was applied to the ground around the foundation; the dimensions are 6m in width and 5m in depth.

Figure 12 shows shear stress τ – shear strain γ relationship of improved soil. The improved soil was assumed to be a Mohr-Coulomb elastic-plastic constitutive model as in the case with surface layer and the $\tau - \gamma$ curve was fitted to the result of the simple shear test. The improved soil model had the shear wave velocity Vs=140m/s, the friction angle ϕ=8.9dgree and the cohesion c=0.212N/mm^2. The maximum shear stress of improved soil was 2.5 times as large as that of the no improved soil at G.L.-5m, and 5times as large as at G.L.-2m



(a) No improvement (b) Improved ground 2m in width (c) Improved ground 6m in width

Fig.11 Pattern of ground improvement

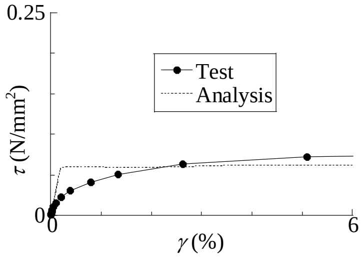


Fig.12 τ-γ curve of improved soil

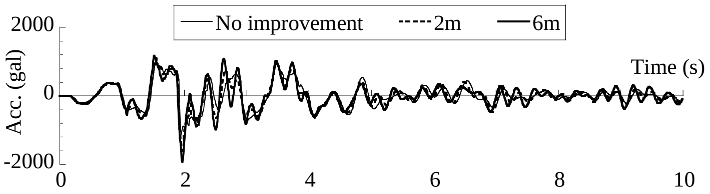


Fig.13 Effect of improved ground on acceleration at superstructure

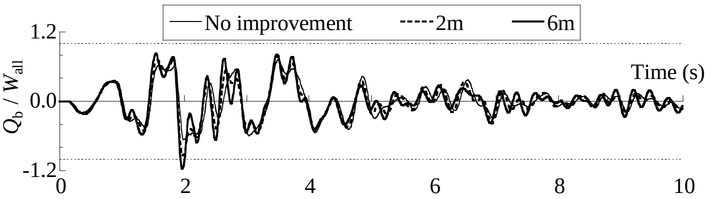
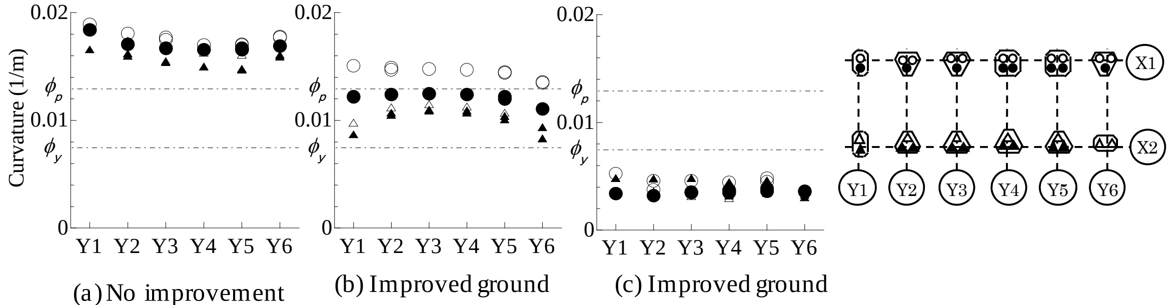


Fig.14 Effect of improved ground on shear force on 1st story columns



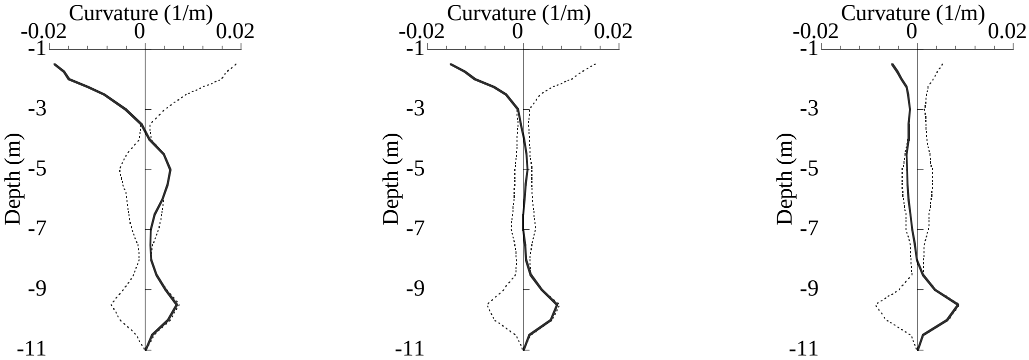
(a) No improvement (b) Improved ground 2m in width (c) Improved ground 6m in width

Fig.15 Effect of improved ground on curvature at pile head

3.2. Result of analysis

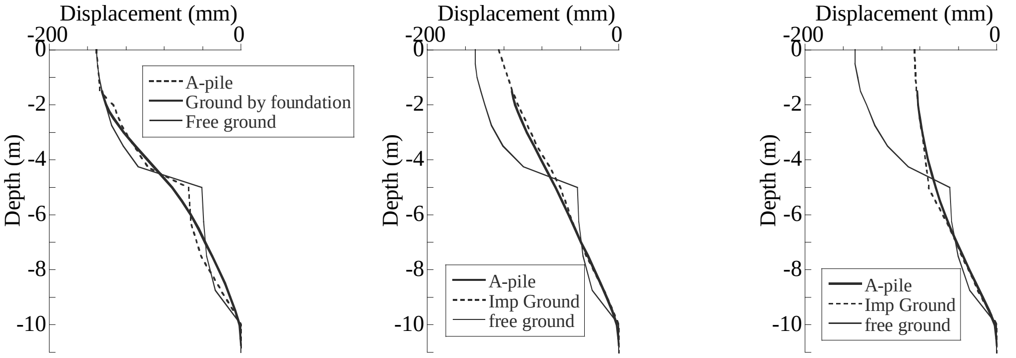
Figure 13 shows the time history of the acceleration at the roof of the superstructure. The accelerations in the cases with the ground improvement are larger than that in the case without the ground improvement. This trend is appeared remarkably at about 2.0s.

Figure 14 shows the time history of the time history of Q_b/W_{all}. The value of Q_b/W_{all} in the cases with the ground improvement are larger than that in the case without the ground improvement, and the



(a) No improvement (b) Improved ground 2m in width (c) Improved ground 6m in width

Fig.16 Effect of improved ground on curvature distribution



(a) No improvement (b) Improved ground 2m in width (c) Improved ground 6m in width

Fig.17 Effect of improved ground on displacement distribution

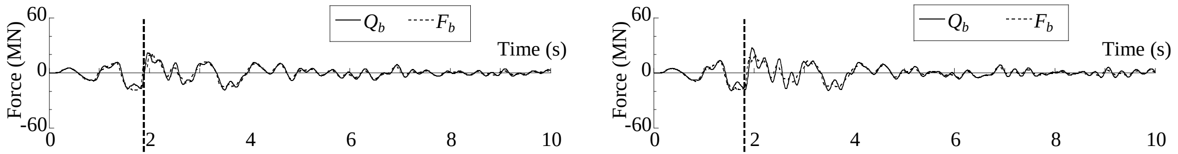
maximum value of Q_b/W_{all} in the case with the ground improvement 6m is over 1.0 which is the base shear coefficient at Japan Level 2 Design Earthquake, and this result indicates that the superstructure may suffer some structural damage under this input motion in the case with the ground improvement.

Figure 15 shows the effect of the improved ground on the distribution of maximum curvature at the pile head of all piles. The curvature at the pile head in the case with the ground improvement is smaller than that in the case without the ground improvement. Especially, in the case with the ground improvement 6m in width, the curvature at the pile head is smaller than ϕ_y in all piles.

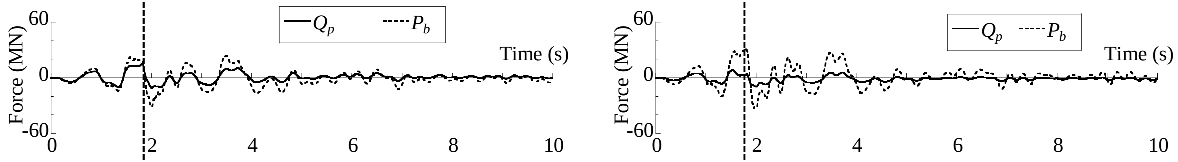
Figure 16 shows the comparison of the curvature distribution for A-pile at 1.83s. In these cases, the curvature at the pile head peaks at the same time, which is 1.83s. In the case with the ground improvement, the curvature decreases in the depth of G.L. to -5m.

Figure 17 shows the comparison of the displacement distribution for A-pile, the improved ground (the ground by foundation) and the free ground at 1.83s. The values of displacement of the free ground in three cases are close. And, the displacement of the ground by the foundation or the improved ground is nearly comparable to the displacement of A-pile. In the case with the ground improvement, the displacement of A-pile and the improved ground is smaller than the displacement of the free ground in the depth of G.L. to -5m. This result indicates that the improved ground resist the displacement of the free ground.

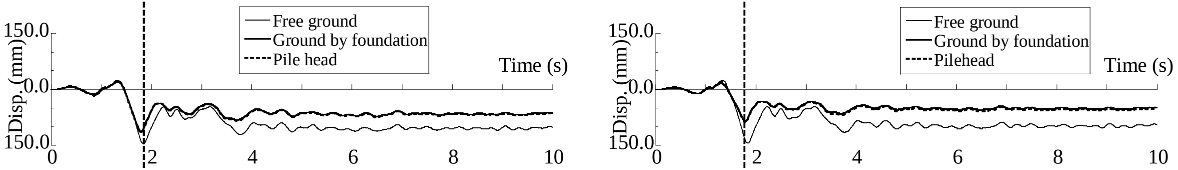
Figure 18 shows the effect of improved ground on responses of soil-pile-structure system, Figure 18(a) shows the inertial force acting on the base foundation, Figure 18(b) shows the reaction force to inertial force at base foundation, Figure 18(c) shows displacement of ground and foundation, and Figure 18(d) shows the the curvature at pile cap at A-pile. As shown Figure 18(a), (c), (d), and Figure 8, the inertial force (shear force on column at 1st story and inertial force on foundation) and the displacement of the pile head peak at 1.83s and then the curvature of the pile head at A-pile peaks at the same time. This trend is appeared in all cases. However, compared to Figure 8(c) and Figure 18(c), the values of displacement of the improved ground and the pile head in the case with the ground improvement are



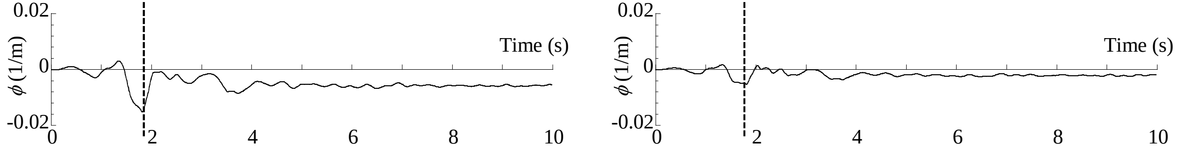
(a) Inernal force acting on foundation



(b) Reaction force to inertial force at base foundation



(c) Displacements of ground surface and foundation



(d) Curvature at pile cap (A-Pile)

(1) Improved ground 2m (2) Improved ground 6m

Fig.18 Effect of improved ground on responses of soil-pile-structure system

smaller than the displacement of the free ground and decrease in comparison with the case without the ground improvement. This decrease in the displacement of the pile head results in the decrease in the curvature. On the other hand, as shown Figure 18(b), the subgrade reaction on the foundation in the case with the ground improvement is larger than the shear force at the pile head. In the case with the ground improvement, the ground improvement dominantly resists the displacement of foundation.

Thus, the seismic response of pile is able to reduce by the ground improvement, which led the increase of the lateral resistance of the surface layer and the decrease of the displacement of ground. However, it may be noted that the seismic response of superstructure is increased by the ground improvement.

4. CONCLUSION

The major findings obtained from analyses are summarized as follows;

1) The deformation of piles for FE analysis is a little larger than the observation. However, the deformation of pile which has low stiffness was largest in both the FE analysis and the observation.

2) The inertial force and the ground displacement applied to the pile at the same time and the ground doesn't resist the displacement of the pile. For this reason, the foundation subjected large displacement and the pile head may be damaged in Kobe Earthquake.

3) The seismic response of pile is able to reduce by the ground improvement, which led the increase of the lateral resistance of the surface layer and the decrease of the displacement of ground. However, it may be noted that the seismic response of superstructure is increased by the ground improvement.

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