SOIL IMPROVEMENT OF SOFT GROUND AROUND PILE FOUNDATION IN EARTHQUAKE-RESISTANT DESIGN

T. Ohtsuka[1], G. Aramaki[2] and K. Koga[3]

ABSTRACT: When a pile foundation structure is designed in soft ground with Japanese road bridge design specifications, there are many cases in which the cross section, the amount of steel reinforcement, and the number of piles are decided according to the displacement limiting value. In such soft ground, it is possible to expect that displacement magnitude of the base structure is suppressed by improving the soft ground around the piles. This study clarified that there was a depression effect by improving the peripheral ground of piles, for both the displacement of the base structure and the bending moment in piles. The calculation was carried out variously, by change of improvement depth and improvement width around the pile. Additionally, the effect of soil improvement for nonlinear response of the bridge pier was also examined. In a series of calculations, a two-dimensional finite element analysis program (FLUSH) often used in earthquake-resistant design was used.

Key Words: Earthquake-resistant design, pile foundation, soil improvement

INTRODUCTION

We conducted ground-structure integrated analysis considering the effect of ground displacement on seismic design of the foundation with piles at the Saga plain where very soft Ariake clay is deeply deposited. Specifically, it was shown that the pile foundation experienced a profound effect of ground movement and had a very large bending moment when shear velocity of elastic wave Vs became 100m/s or less (Aramaki et al., 2001, and Mahmudur et al., 2001, 2002).

When a pile foundation is designed with road bridge design specifications in soft ground, there are many cases in which the pile structural system is decided by the limiting value of the displacement rather than by the bearing capacity and strength of piles (Japan Road Association, 2002). The pile foundation structural system of the abutment is almost always decided according to the limiting value of the pile top displacement, because under these conditions the restriction of horizontal displacement is not eased. In Saga plain deeply deposited Ariake clay, it is expected that the number of piles can be decreased by improving the ground around the pile foundation and by reducing the displacement of the pile foundation.

Ogata et al. (2001) carried out research on the static analysis of pile foundation acting the inertia force of the superstructure as the external force and the loading test on the improved pile foundation. This research is only a static analysis; the ground movement, which has an important effect in soft ground in the event of an earthquake, is not considered. Though it can be easily imagined that the static displacement is reduced by improving the ground around the pile, it is unclear what kind of displacement control effect can be expected in dynamic earthquake load conditions. In pile foundation earthquake-resistant design in soft ground, it is necessary to consider not only the effect of inertia force of the superstructure but also the effect of ground movement.

Takemiya et al. (2003) carried out nonlinear dynamic analysis considering the effect of ground movement on the improved pile foundation of a bridge pier. However, what kind of effect the change of the soil improvement range around the pile give for the control of displacement in earthquake, is not described. Further, bending moment and displacement control effect in the pile foundation of

[1] Doctoral student, Department of Civil Engineering, Saga University, Saga 840, JAPAN
[2] Professor, Department of Civil Engineering, Saga University, Saga 840, JAPAN
[3] Lecturer, Department of Civil Engineering, Saga University, Saga 840, JAPAN
Note: Discussion on this paper is open until December 2004

the abutment that earth pressure was exerted only from one side, are not mentioned either.

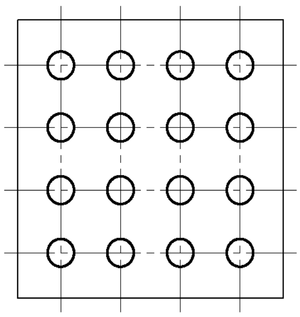
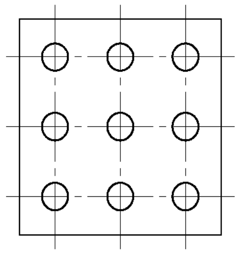
This study discussed the effects of soil improvement around a pile foundation for two models, the pier model and the abutment model. In this analysis, the FLUSH (Lysmer et al., 1975) program, often used for nonlinear analysis of soil-structure interaction in the design field, was used. The effects of various earthquake accelerations on the response of the bridge pier column base with an improved foundation are discussed. The shear wave velocity of an elastic medium and the strain dependence properties shown dynamical property of the soil were used as a physical properties, used as parameters of the soil improvement effect.

DESIGN REQUIREMENTS AND CONSTRUCTION METHOD OF SOIL IMPROVEMENT

The horizontal displacement of the pile for the stationary load and the earthquake vibration with a high possibility of being encountered during the life of the structure should be obtained by elastic analysis. It has been required that the displacements be under the constant permission value irrespective of the hardness of the ground. Permission displacement magnitude of the pile foundation has been set at 1% or less of the pile diameter or at a constant value (15mm) irrespective of the ground conditions as a range of the elastic behavior in the Japan Bridge Code (Japan Road Association, 2002). Though limiting the displacement value as described above is for the pile foundation, the displacement problem of the superstructure in an earthquake is also important. The collision between the girder of the superstructure and the parapet becomes productive when the displacement during the earthquake increases, and damage to the expansion device is considered. When the natural period of soft ground coincides with the natural period of the bridge, it is important to avoid resonance between the structure and the ground by increasing the rigidity of the foundation.

Construction costs increase when a pile foundation in soft ground is designed because the limiting value of the displacement must be satisfied. A comparison of construction costs for the case in which the limiting value of horizontal displacement of pile foundation and the case in which the limiting value was disregarded is shown in Table 1.

Table.1 Horizontal displacement of the pile

Design Condition	Limited of the horizontal displacement	Unlimited of the horizontal displacement
Configuration of the pile		
Displacement of the pile	13.9mm ＜ 15.0mm	23.2mm ＞ 15.0mm
Dimension of the pile	Cast-in-place pile ϕ 1000×30m n=16	Cast-in-place pile ϕ 1000×30m n=9
Ratio the cost	Not receiving soil improvement	
	1.65	1.00
	Receiving soil improvement	
	1.19	1.00

The construction cost of the pile foundation in the case considering the limiting value of horizontal displacement became 1.65 times that for the case in which the limiting value of horizontal displacement was disregarded.

For soil stabilization, there are two methods: the surface layer improvement method and the deep mixing stabilization method. The former method improves the surface layer 2m～3m, and involves the use of backhoes. The deep mixing stabilization method is used for soil improvement more than 3m deep. In the Ariake clay ground, DJM (Dry Jet Mixing method), a machine mixing method, has mainly been used. On the other hand, the method involving use of backhoes as the base machine would be used to improve the soil to a depth between 3m～8m.

An example of soil improvement around the pile by liquefaction prevention and temporary supplementary construction near the top of the pile is shown in Figure 1. Figure 2 shows a medium-pressure injection method called MITS used for soil stabilization.

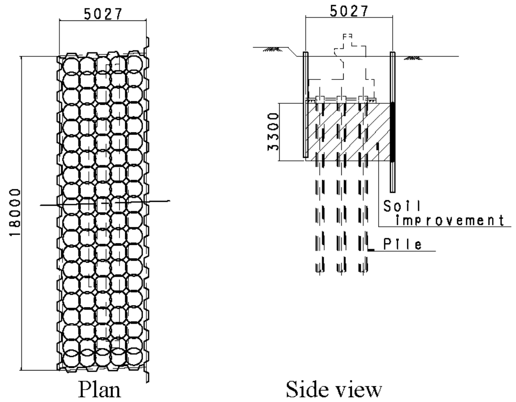


Fig.1 Combined examination of pile foundation and soil improvement

Fig.2 Construction of the MITS method

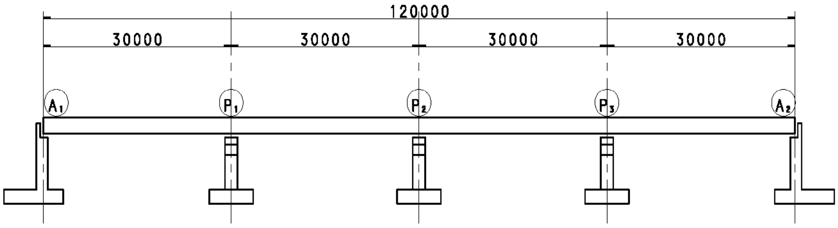
INVESTIGATION OF THE EFFECTS OF GOUND IMPROVEMENT AROUND THE PILE FOUNDATION

Analysis Program

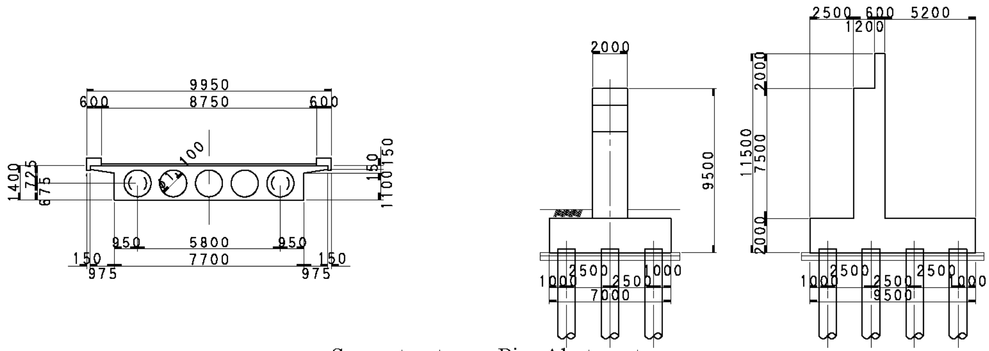
In the analysis of the dynamic interaction of the ground-structure system, the two-dimensional finite element program D-FLUSH using the equivalent linear analysis for soil nonlinearity is used. D-FLUSH is a revised version of the original program FLUSH to which an equivalent linearity beam element function based on the bending moment-curvature relational expression was added. It is possible to treat the nonlinear analysis for the bridge pier and pile by the equivalent linear analysis. The nonlinearity of the bridge pier and the pile is considered by giving the bending moment-curvature relational expression (crack, initial yielding, and ultimate state) in constant axial force by the tri-linear model and carrying out the suspected nonlinear analysis as well as analysis of the nonlinearity of the ground. The energy transfer boundary is used for the side boundary, and the viscous boundary for the bottom in D-FLUSH as same as that in the original program.

Analytical Model

In the calculation, two models, the bridge pier model and the abutment model, were used with the pile foundation. As ground composition and physical properties, the values obtained near Saga Prefecture's Rokkaku River were used. The analytical model of the bridge as an object for calculation is shown in Figure 3. These bridges were designed experimentally using the road bridge specifications for the Ariake ground. The pile foundation is diameter 1.0m cast-in-place pile. The cross section performance of the bridge pier and the pile was given in the tri-linear model of the bending moment M-curvature ϕ relational expression (crack time Mc- ϕ c, first yield time My- ϕ y, ultimate time Mu- ϕ u), as shown in Figure 4. A drawing of the reinforcing bar arrangement of the bridge pier and the pile required by trial design is shown in Figures 5,6. The numerical value of the bending moment M-curvature ϕ relational expression of the bridge pier and the pile is shown in Tables 2,3.



Side view



Superstructure Pier Abutment

Fig.3 Sample Bridge

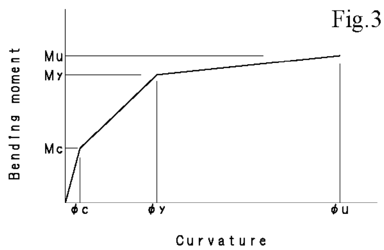


Fig.4 Cross-sectional property of pier and pile

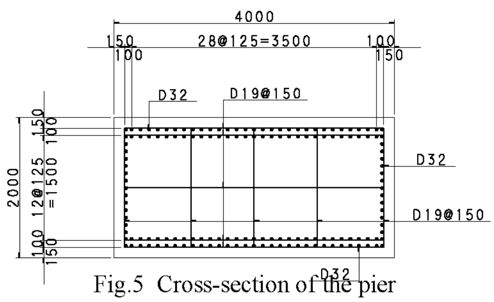


Fig.5 Cross-section of the pier

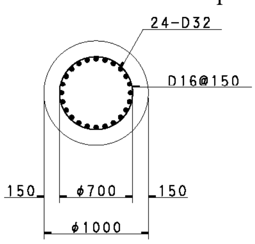


Fig.6 Cross-section of the pile

Table.2 Cross-sectional property of the pier

	Bending moment (kN・m)	Curvature (1/m)
Cracking	8796.44	0.1170×10^{-3}
Yield	24990.63	1.3745×10^{-3}
Ulitmate	27439.86	17.2150×10^{-3}

Table.3 Cross-sectional property of the pile

	Bending moment (kN・m)	Curvature (1/m)
Cracking	234.56	0.1531×10^{-3}
Yield	1587.97	3.1569×10^{-3}
Ulitmate	2428.00	32.9654×10^{-3}

Soil condition

The ground was modeled in 4 kinds of soil with the soil properties shown in Figure 7 and Table 4. Vs shows the shear wave velocity of the ground. Soil 1 and soil 2 show Ariake clay. As a physical property of improved ground, the values obtained used the DJM (Dry Jet Mixing Method) were used. Here, the shear wave velocity of soil 1 ～ 2 and improved ground are also measured values. The dynamic deformation properties (the strain dependence of elastic shear modulus and damping constant) of each ground are added. This program was used with test values obtained by vibrational tri-axial test and hollow torsional shearing test (Figure 8).

Input Earthquake Acceleration

In this analysis, the seismic wave of a level 2 earthquake, type I and Ⅲ of ground (on the Middle Japan Sea Earthquake's Tsugaru Long Bridge peripheral ground in 1983) reported in the road bridge specifications V as a sample seismic wave, was used as earthquake acceleration on ground level. The seismic wave given on the ground surface level was converted into the base acceleration using linear analysis technique of the earthquake response analysis program SHAKE (Schnabel et al., 1972). The waveform of the rock surface acceleration is shown in Figure 9.

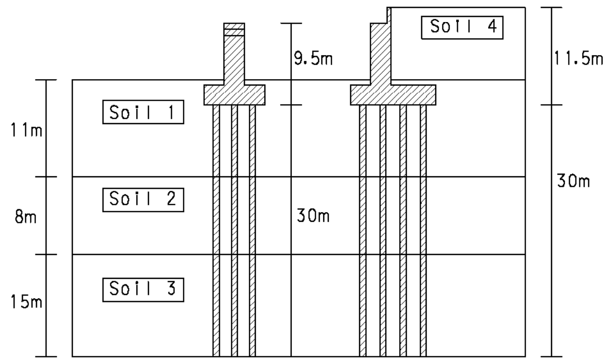


Fig .7 Analytical Model

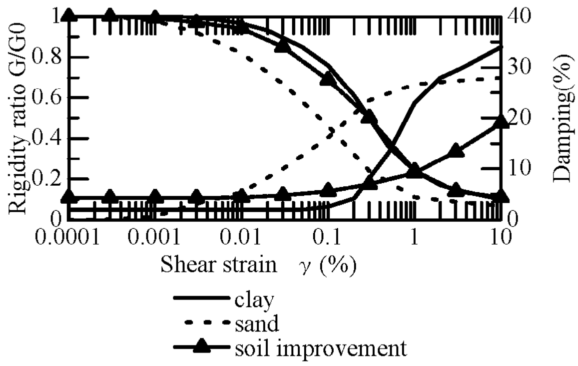


Fig.8 Strain dependence of rigidity ratio and damping

Table.4 Soil properties

	Description	Layer Thickness (m)	Density γ (kN/m^3)	Shear wave velocity Vs(m/s)
Soil 1	Clay	11.0	14.5	70
Soil 2	Clay	8.0	14.5	130
Soil 3	Sand	15.0	18.0	300
Soil 4	Sand	7.5	18.0	250
Soil improvement	Clay	2.0 ～ 16.0	14.5	250

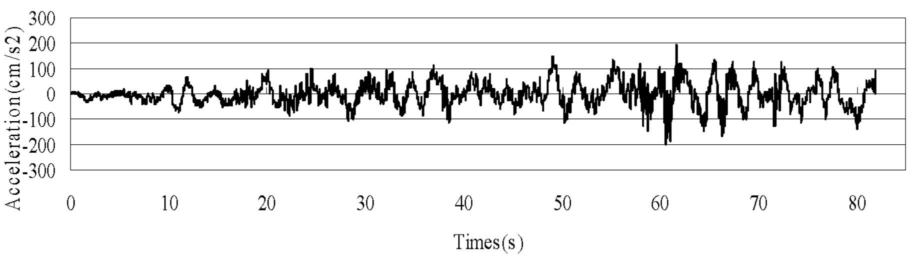


Fig.9 Seismic waveform of the basis wave

Analysis Case

The analytical model of the bridge pier is shown in Figure 10 and the analytical model of the abutment is shown in Figure 11. Though the displacement control effect of the pile foundation appears to grow larger as the soil improvement range increases, it is important from a cost-effective perspective to consider the effective soil improvement range for displacement control. The depth of the soil improvement is dependent on the shear wave velocity Vs of the ground when the ground movement is considered. The particular effect the soil improvement range gives in terms of the earthquake response of the structure was examined, and analysis was carried using the depth and width of the soil improvement area around the pile as parameters.

To examine the soil improvement range, the sum total of 8 cases, 4 cases of depth direction and 4 cases of cross-direction, were analyzed for the model of bridge pier and that of abutment. Taking soil improvement depths of soil 1 as 2m, 4m, and 8m, respectively, for the depth direction, soil improvement depth of soil 2 was set at 16m. For the soil improvement depth of 8m, for which the soil improvement depth was effective, the depth was changed to 1m, 2m, 3m, and 4m from the pile front in a cross-direction. Calculation cases for the bridge pier model and the abutment model are shown in Figures 12,13 and Figures 14, 15.

Case 1 shows the calculation for original ground, Cases 2 to 5 the calculations in soil subjected to improvement in the depth direction, and Cases 6 to 9 the calculations in soil subjected to improvement in the cross-direction. Soil improvement depth from the ground level and soil improvement width from the pile front in each CASE are shown in Table 5. Analysis and consideration of the control of the displacement of the base structure and decreasing effect of bending moment in pile foundation by soil improvement range are carried out.

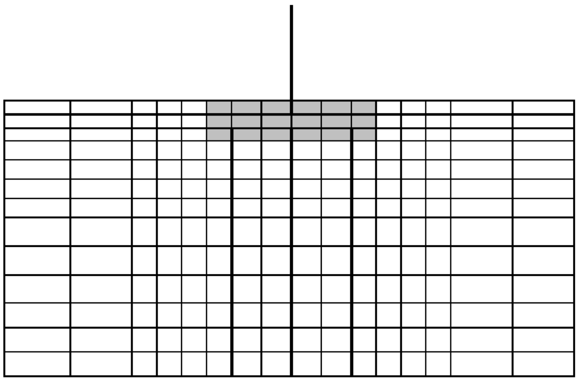


Fig.10 Pier frame model

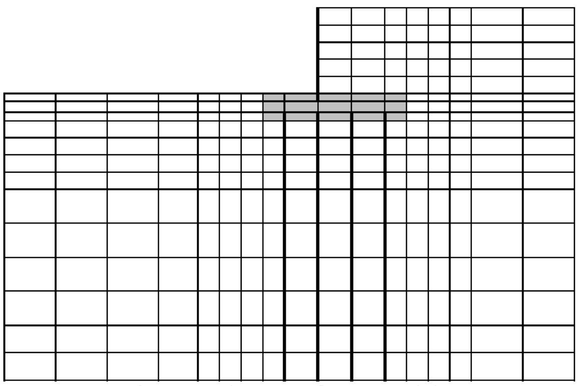


Fig.11 Abutment frame model

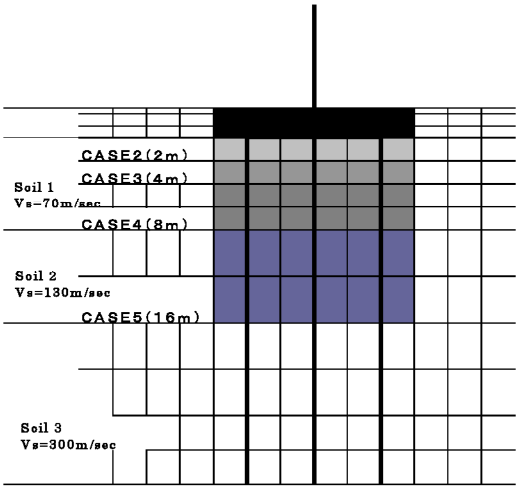


Fig.12 Pier model
(Depth-direction change)

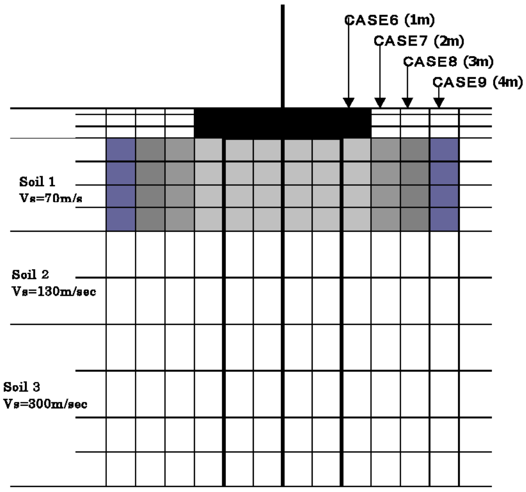


Fig . 13 Pier model
(Cross-direction change)

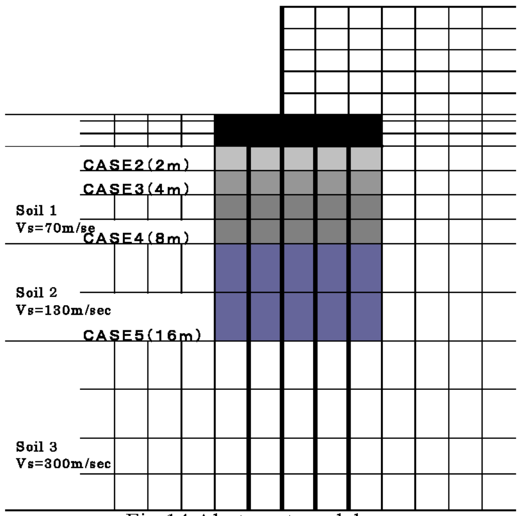


Fig.14 Abutment model
(Depth-direction change)

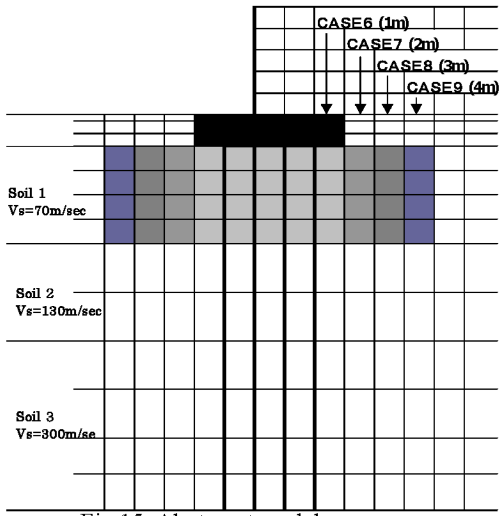


Fig.15 Abutment model
(Cross-direction change)

Table.5 Case Analysis

	H:depth (m)	B:cross (m)
CASE 1	0	1
CASE 2	2	1
CASE 3	4	1
CASE 4	8	1
CASE 5	16	1
CASE 6	8	1
CASE 7	8	2
CASE 8	8	3
CASE 9	8	4

RESULTS AND DISCUSSION

The largest displacement and largest bending moment distributions in the pile were used in order to verify the soil improvement effect around the pile. The vertical broken line as shown in Figure 17 is the largest bending moment diagram, shows the yield bending moment of the pile.

Soil improvement effect in depth of bridge pier

The largest displacement distribution in the pile as the soil improvement depth changes is shown in Figure 16. The data suggests that the pile foundation displacement is greatly suppressed by soil improvement in the depth direction. More specifically, the effect of soil improvement in soft ground is very large near the surface layer. The displacement at the top of the pile in the case improved to 8m depth decreases to about 1/3 in comparison with the case of original soil deposit. However, the displacement control effect does not increase even if soil improvement is carried out to the second layer (16m). The displacement wave profile at the top of the pile without the soil improvement (Case1) is shown in Figure 18, and the pile top displacement wave profile of Case 4, in which the soil improvement effect is large, is shown in Figure 18. The wave profile shows the same shape, and the displacement response in the case of soil improvement relatively decreases.

In the bridge pier model, the largest bending moment distribution of the pile as the soil improvement depth around the pile foundation changes is shown in Figure 17. In Case 1, a large bending moment is shown at the pile top and the boundary where shear elastic constant changes. The largest bending moment of the pile top occurs by inertia force of the superstructure and bridge pier, and the largest bending moment is caused at the layer boundary of the stratum by the ground movement. The largest bending moment distribution in the pile is greatly different relative to the depth of the soil improvement, largely because improved ground has a restraint effect. Though in Case 2 and Case 3 the ground surface was improved and the bending moment near the pile top greatly decreases, there is no change for the bending moment distribution of the pile under the soil improvement region. It should be noticed that there is a case in which the generation position of the largest bending moment in the pile becomes the stratum boundary surface. It is necessary to use the calculation method considering the ground deformation in the design of pile foundation, because the large bending moment arising at the stratum boundary surface cannot be obtained in the calculation disregarding ground movement.

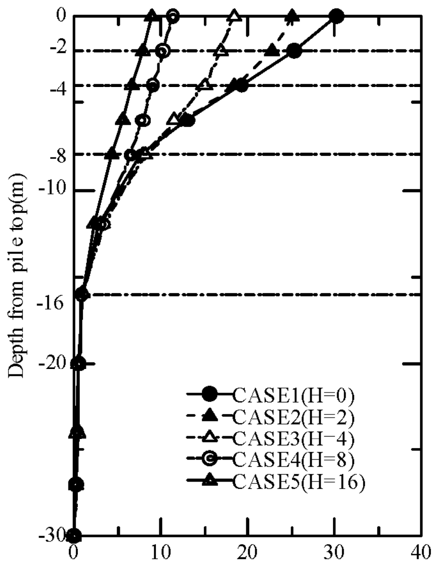


Fig.16 Displacement pier of pile
(Depth-direction change)

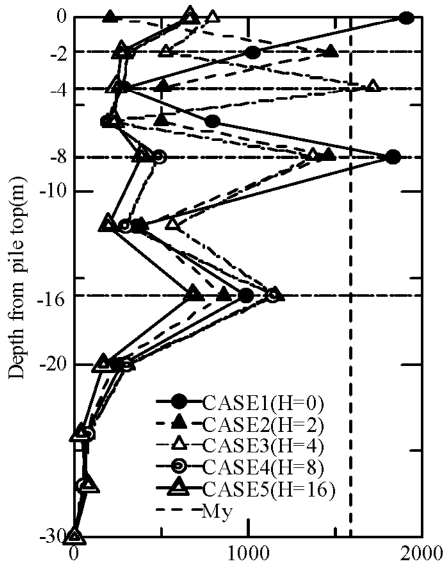


Fig.17 Bending moment pier of pile
(Depth-direction change)

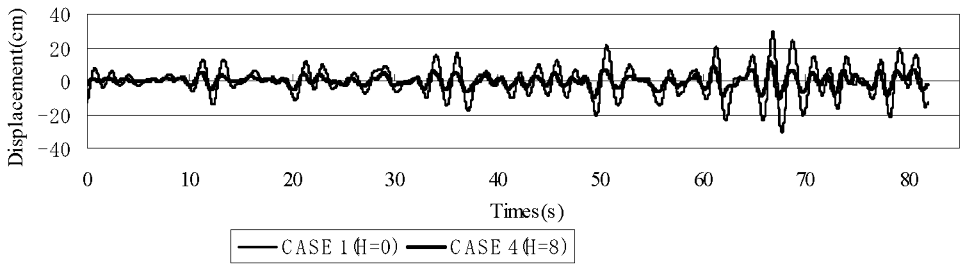


Fig.18 Displacement of the pile top

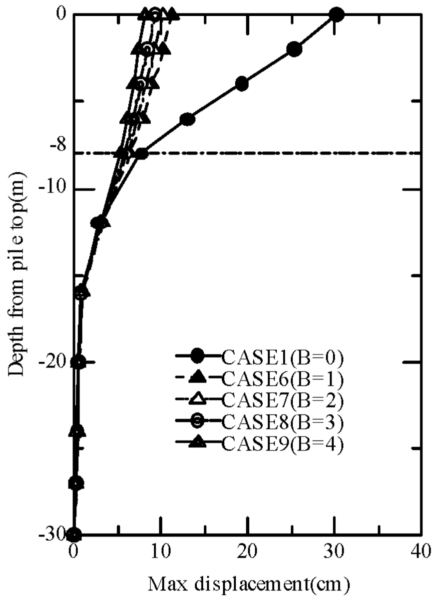


Fig.19 Displacement pier of pile
(Cross-direction change)

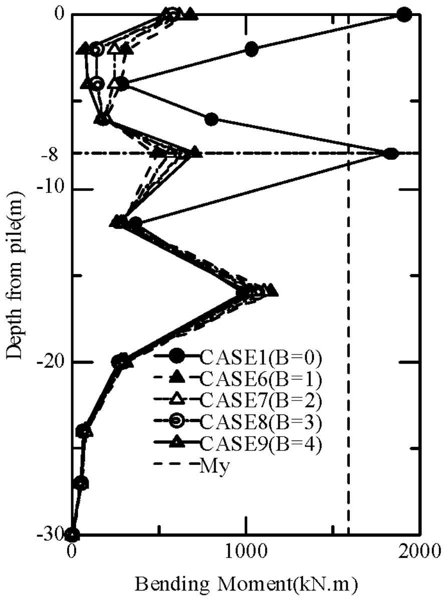


Fig.20 Bending moment pier of pile
(Cross-direction change)

The soil improvement depth is dependent on the characteristic value β of the pile in the case in which only inertia force of the superstructure is considered, as it is in the static analysis, but the soil improvement depth must be determined considering the stratum boundary surface in the dynamic analysis. Takemiya et al. (2003) have only noticed at two places of the pile top and the boundary between improved ground and original ground as the points to occur the maximum bending moment. When the ground composition is more complicated, it is necessary to also notice the boundary layers in the ground.

Soil improvement effect in width of bridge pier

On the basis of the case in which the soil improvement was done to an 8m depth, the effect is discussed for the case in which the improvement range changes in a cross-direction. Even if the soil improvement width around the pile increases, the displacement control effect or the bending moment reducing effect of the pile cannot be expected, as illustrated in Figure 19 and Figure 20. Because the analysis is two-dimensional, the resistance area of the soil improvement body does not change. It seems to be effective to extend the width of improved area in depth direction, as loading area of the soil improvement body increases.

Soil improvement effect in depth in bridge abutment

The largest displacement distribution of the pile as the depth of soil improvement of the bridge abutment model changes is shown in Figure 21. As it was in the case for the bridge pier model, the soil improvement in the depth direction is effective for reducing the pile foundation displacement. The displacement in the case of ground improved to an 8m depth decreases to about half that of soil without improvement. The displacement reducing effect does not increase, even if soil improvement is carried out to the second layer (16m). The displacement reducing effect by soil improvement in abutment is large than the pier.

The largest bending moment distribution in each case is shown in Figure 22. Because the earth pressure is acting from the back of the abutment, the movement of the abutment is not symmetrical, unlike the case of the bridge pier. Therefore, the largest displacement and the largest bending moment show a positive or negative value at every depth. The position and the size at which the largest bending moment arises are greatly different relative to the depth of the soil improvement. As it was the case for the bridge pier, the position at which the largest bending moment arises and the magnitude are greatly different relative to the depth of soil improvement, due to the fact that the improved ground has a restraint effect. The effect of the inertia force of the superstructure decreases very much near the pile top in Case 4. The effect of the inertia force near the pile top does not change, even if the soil improvement depth deepens past that in Case 4.

Soil improvement effect in width under the bridge abutment

The largest displacement distribution of the pile foundation in expanding the soil improvement region cross-direction on the basis of Case 4 in which the soil was improved to layer (8m) of Soil 1 is shown in Figure 23. Though the displacement gradually decreases as the improvement width is widened, the effective is not remarkable.

The largest bending moment distribution in each case is shown in Figure 24. This finding is similar to the calculation result for the bridge pier.

Relation of ground movement of the free ground and displacement of the pile

The comparison of ground movement of the free ground without the structure and displacement of the pile in the bridge pier model is examined. The largest response displacement distribution of the free ground and the displacement distributions of the pile in Case 1 and Case 4 are respectively shown in Figure 25. Case 0 shows the ground movement in the free ground without the structure. In Case 1, the pile displacement is bigger than the ground movement. Findings prove that the pile shakes much more than the ground does.

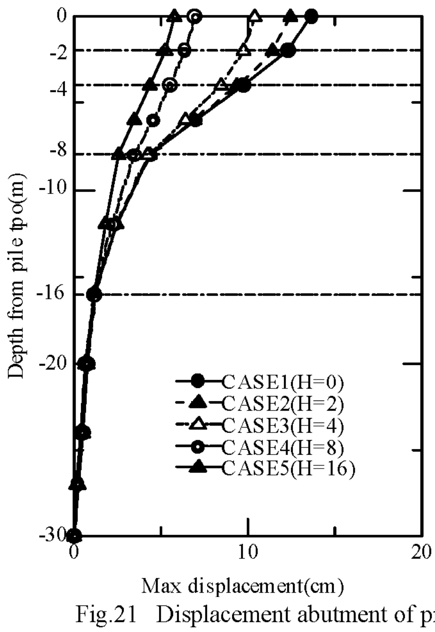


Fig.21 Displacement abutment of pile
(Depth-direction change)

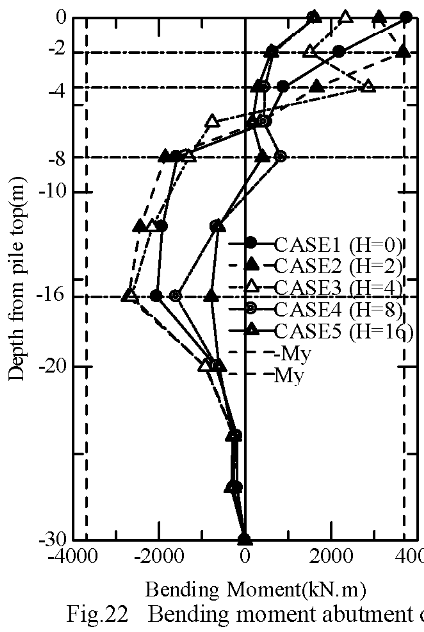


Fig.22 Bending moment abutment of pile
(Depth-direction change)

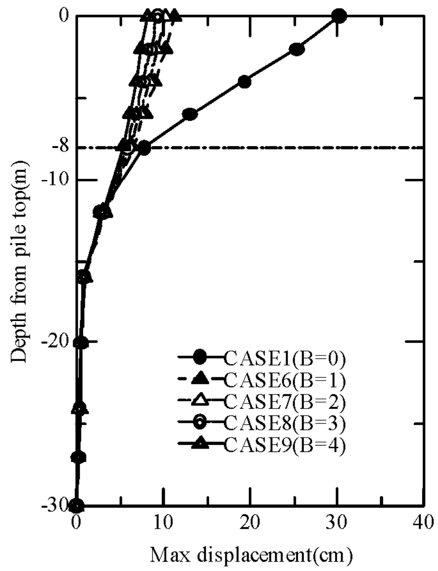


Fig.23 Displacement abutment of the pile (Cross-direction change)

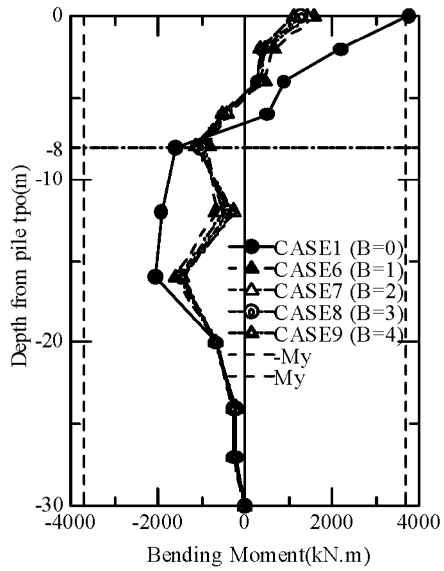


Fig.24 Bending moment abutment of the pile (Cross-direction change)

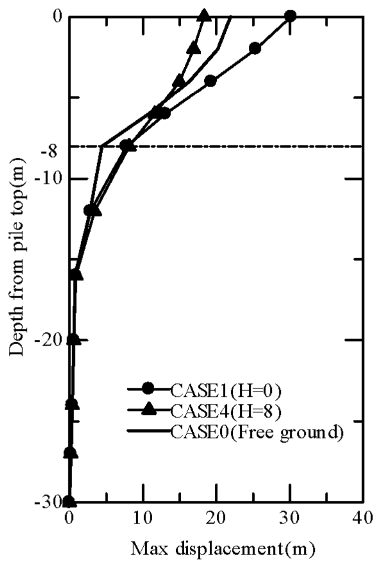


Fig.25 Ground movement in the pile position

Effect of soil improvement on the bridge pier

It was proven that the displacement control effect after carrying out soil improvement around the pile was large. Because input acceleration of the seismic wave to the superstructure changes by soil improvement, the effect was examined in the following. Figures 26, 27 show the acceleration response spectrum (damping ratio 5%) at the footing. Figure 26 shows that the acceleration response spectrum of the seismic wave at the bottom of the foundation decreases relative to changing the depth of the soil improvement. It is shown that the effect of reducing the inertia force of the super structure can be expected by improving the soil around the pile', because the acceleration response spectrum decreases when the soil improvement depth is increased. However, the effect is dependent on the natural period of the structure. The acceleration response spectrum of cases 4 greatly decreased near 1(sec) of the natural period of structure, and a remarkable effect of soil improvement depth appeared.

Figure 27 shows the effect of the width of the soil improvement area on the acceleration response spectrum. The change of the soil improvement width does not have a large effect on the acceleration response spectrum, though there is an acceleration response spectrum of decrease near natural period 1(sec) in Case 4 and 9.

Figure 28 shows the largest response bending moment and the largest curvature of the bridge pier base by change in soil improvement depth. Those values are near the ultimate state in Case 1 but are near the initial yielding point in Cases 2 5 in which the ground was improved around the piles. This finding indicates that soil improvement around the piles also contributes to decreasing the bending moment in the bridge pier base. Figure 29 shows the largest response bending moment and the largest curvature of the bridge pier base by change in the soil improvement width. The largest response bending moment of the bridge pier base reversely increases when the soil improvement width widens. This finding proves that that largest response bending moment of the bridge pier base decreases is possible by adjusting the depth and width of the soil improvement.

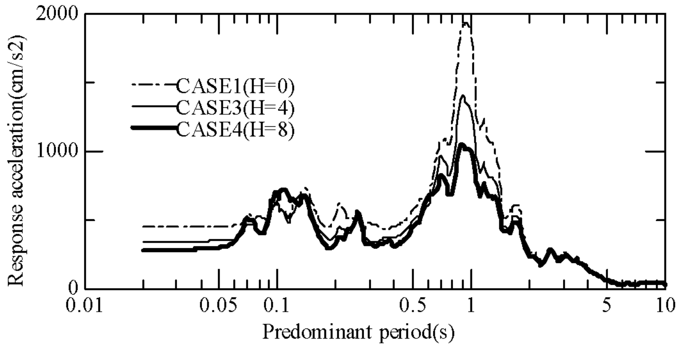


Fig.26 Acceleration response spectrum in the footing lower end (Comparison of soil improvement depth direction)

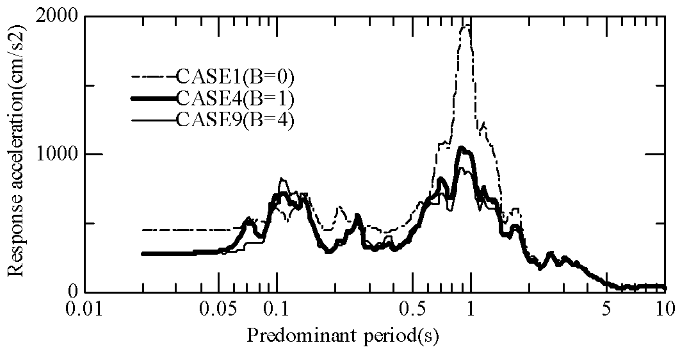


Fig.27 Acceleration response spectrum in the footing lower end (Comparison in which the soil is improvement in the cross-direction)

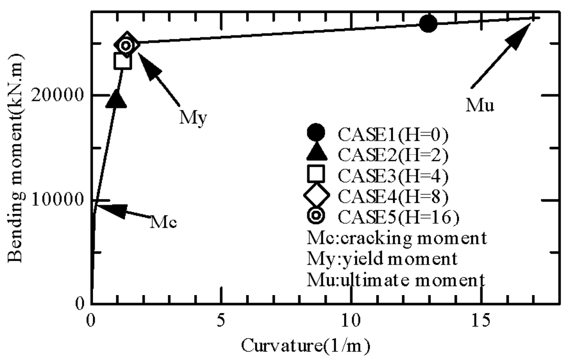


Fig.28 Bending moment and curvature of the bridge pier base (CASE2-CASE5)

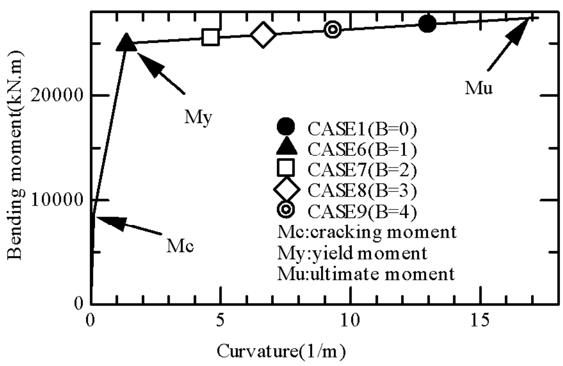


Fig.29 Bending moment and curvature of the bridge pier base (CASE6-CASE9)

CONCLUSION

Analytical results clarified the following effects of soil improvement around pile foundation.

1. It is possible to reduce the largest response displacement of the pile foundation by improving the ground around the pile in both cases of bridge pier and abutment.
2. In a determining the largest bending moment in the pile foundation, the pile top and the boundary of soil improvement and the stratum boundary must be considered.
3. Soil improvement in terms of the width direction is not so effective for reduction of the largest bending moment and the largest response displacement.
4. In order to confirm the soil improvement effect, it is important to consider the dynamic interaction of the superstructure, pile foundation, soil improvement and ground, and integrated analysis is necessary.
5. By carrying out soil improvement, the acceleration response spectrum of seismic wave input into the structure decreases. Therefore, soil improvement is effective for strengthening existing bridge piers against earthquake, given that the response of the columns of the bridge pier can be reduced.

REFERENCES

Aramaki, G., Imamura, K., Matsuo, Y., Ohtsuka, T. and Mahmudur. R. (2001). Earthquake-resistant design of bridges with pile foundation considering the ground displacement. Proceedings of the First Asian-Pacific Congress on Computational Mechanics, Sydney, N.S.W., Australia. 2(2):1573-1578.

Japan Road Association (2002). The Code for Road Bridge V Earthquake-Resistant Design Edition and Explanation (in Japanese). JSCE, Japan.

Lysmer, J., Udaka, T., Tsai, C.F., and Seed, H.B. (1975). FLUSH: A Computer Program for Approximate 3-D Analysis of Soil-Structure Interaction Problems, Report. No. EERC 75.30, Univ. of California, Berkeley.

Mahmudur, R., Izuka, K., Koga, K., Ohtsuka, T. and Aramaki, G. (2001). Effect of soil stiffness and ground displacement in earthquake response of bridges with pile foundation. Lowland Technology International 3(2): 74-85.

Mahmudur, R., Aramaki, G., Koga, K., Ohtsuka, T. (2002). Seismic analysis system of bridge pier with pile foundation in Ariake soft clay region. Lowland Technology International 4(2): 27-42.

Ogata, T., Jho, K., Sakate, M. (2001). Design Model of a New Composite Foundation of Steel Pile with Improvement, Tsuchi-to-kiso, The Japanese Geotechnical Society, May: 7-9.

Schnabel, P.B., Lysmer, J. and Seed, B.H. (1972). SHAKE: A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites , Report. No. EERC 72.12, Univ. of California, Berkeley.

Shimabuku, J., Takemiya, H. (2002). Inelastic seismic response of bridge piles: Effects of superstructure properties and soil layering. Structural Eng. Earthquake Eng. JSCE,19,1: 11-20.

Takemiya, H. (2003). Geotechnical and Structural Seismic Design Considerations in View of Ground Motions, Tsuchi-to-kiso, The Japanese Geotechnical Society, March: 1-3.