DYNAMIC-RESPONSE CHARACTARISTICS OF STRUCTURES WITH MICROPILE FOUNDATION SYSTEM

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SUMMARY

Piled raft foundation and PHC nodular piles, which less depends on point bearing, are increasingly used in Japan. The reason is that low degree damages of such foundation type as soil improvement of landfill and friction piles is reported after Kobe Earthquake. Therefore, researchers and foundation engineers have studied the pile systems without point bearing, recently.

Authors have studied Micropile system, friction type pile, by 2D FEM analysis. Micropile is “drilled and grouted pile” with steel pipes which diameters is less than 300mm and driven by boring machine, featuring small diameter with thick wall and mechanical joints with couplers not welding.

INTRODUCTION

In recent years, an increasing number of pile foundations not dependent on load bearing at the points of piles have been used in Japan such as piled raft foundations and friction piles. It was reported that at the time of the Kobe Earthquake, structures that stood on improved soil in landfills or those that were supported by friction piles suffered relatively minor damage. Foundations supported by other means than bearing piles are now catching attention. The authors have been studying micropiles that support structures by friction with the earth surrounding the points of the piles. Micropiles have a diameter of 300 mm or less and are drilled with small boring machines. Drilling of micropiles involves little sound and vibration, can be carried out in small spaces and as such is favorable in terms of environmental protection and ease of construction.

In order to study dynamic response of structures supported by small-diameter piles (micropiles) and dynamic effectiveness of small-diameter piles, the authors have made an analysis of micropiles in comparison with cast-in-situ piles and pre-cast piles, by nonlinear response analysis. This paper describes the results of the analysis.

OUTLINE OF HIGH-CAPACITY MICROPILES

The micropile is a general term meaning a cast-in-situ pile or bored pile with a diameter of 300 mm or less. It is called by different names all over the world including the micropile, root pile, minipile, pin pile and needle pile.

Micropiles are constructed by creating a small-diameter hole in the ground with a boring machine

(Photo 1), inserting reinforcing materials such as deformed reinforcing bars and steel pipes and injecting cement grout into the surrounding space.

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Photo 1 Boring Machine

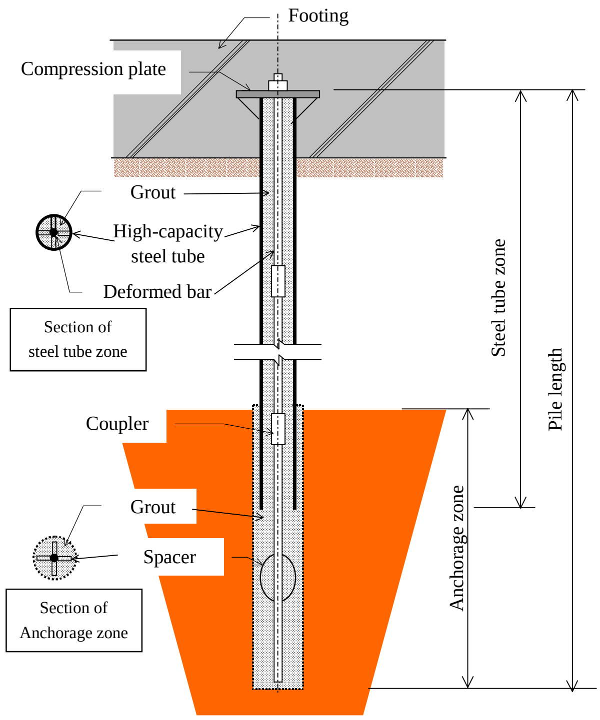


Fig. 1 Outline of the high-capacity micropiles

The high-capacity micropile method incorporates drilling and pressured grout injection techniques used in ground anchor methods into micropile-related techniques, and uses steel pipes as reinforcers in addition to deformed reinforcement to construct high-capacity piles with great bearing capacity. Pile diameter typically ranges from 150 to 300 mm. The standard pile length is 5 to 30 m. A compressive strength of 1,000 kN or larger is made available. The micropile method is outlined in the following figure.

1) Characteristics of high-capacity micropile design

Micropiles have the following design characteristics.

- Despite their small thickness, micropiles provide large bearing capacity. When used as foundation piles, therefore, micropiles require only a small area of footing.
- Bearing capacity of micropiles provides both axial and pull-out resistances. Pull-out resistance can, therefore, be used effectively when micropiles are used for seismic retrofit, slope stabilization and reinforcement of retaining walls.
- Micropiles can be used both individually as bearing piles and in groups for soil strengthening.

2) Characteristics of high-capacity micropile construction

Micropiles have the following construction characteristics.

- Micropiles are drilled with boring machines with little sound or vibration being caused during construction.
- The small diameter of 300 mm or less results in little influence on buried obstructions and existing structures.
- Use of small construction equipment enables construction wherever at least 3.5-m overhead clearance is available.
- Since the diameter of a micropile is small, only small volume of earth needs to be excavated.
- Raking piles can be constructed easily.

In the analysis below, studies are also made for models using raking piles mentioned above.

OUTLINE OF ANALYSIS

A combined earthquake response analysis for soil, pile and foundation was made using two-dimensional finite element methods. Figure 2 shows a typical grid used in the analysis. As shown in the figure, soil was modeled to have two layers, an upper 25-m layer and a lower 5-m layer. In a linear analysis, three models with varying shear wave velocities in the upper layer were examined. Table 1 shows the soil conditions and analytical models. Analysis was made for the pile foundation model in four cases where precast piles (Case 1), cast-in-situ piles (Case 2), high-capacity micropiles (Case 3) and high-capacity micropiles for raking piles were used (Case 4). Table 2 lists dimensions for the pile models. The analysis used two types of input earthquake motions, those of El Centro 1940 and Kobe earthquake 1995. Figures 3 and 4 show the input earthquake motions.

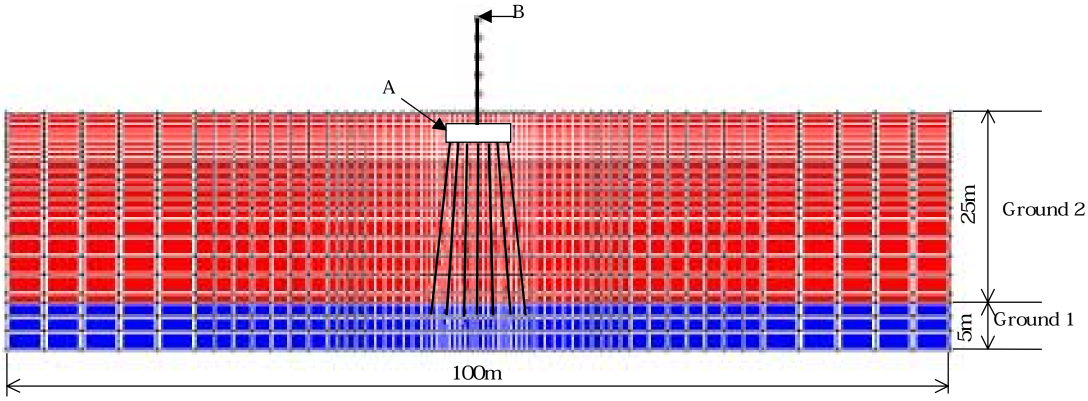


Fig. 2 Typical grid used in the analysis

Table 1 Soil conditions

	Shear Wave Velocities (m/s)	
	Ground 1	Ground 2
Model1	300	100
Model2	300	175
Model3	300	250

Table 2 Dimensions for the pile models

	Sectional Area	Principal Moment of Inertia	Elastic Modulus
	A (m^2)	I (m^4)	E (kN/m^2)
Case 1	0.18096	5.10000E-03	3.80E+07
Case 2	1.13180	1.15296E-01	2.50E+07
Case 3	0.01104	2.68132E-05	2.00E+08
Case 4			

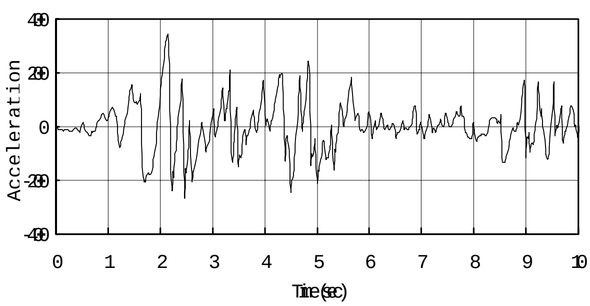


Fig. 3 The input earthquake motions (El Cent)

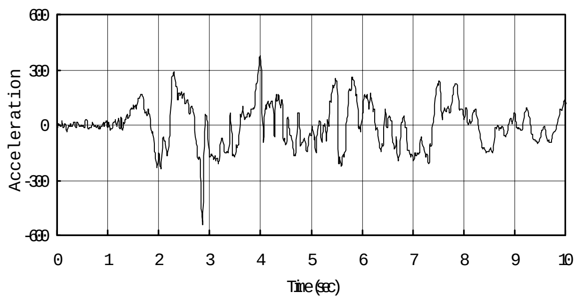


Fig. 4 The input earthquake motions (K.P -83)

RESULTS OF LINEAR ANALYSIS

In the linear analysis, effects of soil and pile foundation conditions on response values were studied by comparisons between footing and structure in terms of maximum response, displacement and acceleration response.

Maximum response

Maximum values of acceleration and displacement response at the leftmost end of the footing (point A in Figure 2) and at the top edge of the structure (point B in Figure 2) are shown in Tables 3 and 4. Tables 3 and 4 show the results of analysis with the El Centro and Kobe earthquake motions, respectively. The tables show the minimum values for respective pile types in boldfaced letters. Responses at the leftmost end of footing presented no outstanding variances although slight variances were found in response according to the soil model or pile type. This means that the major cause of response of the footing in the soil was the response of the soil. The value of response at the top edge of structure was small for model 1 in soft soil in case 4 where high-capacity raking micropiles were assumed, and for model 3 in hard soil in case 2 where cast-in-situ piles were used. The linear analysis shows that the response of upper part of structure is influenced by the interaction between the soil stiffness and the stiffness of pile foundations.

Table 3 Results of maximum response (El cent)

Ground Models	Case of Piles	Left end of the footing				Top of the structure	
		Displacement(m)		Acceleration(m/s^2)		Displacement(m)	Acceleration(m/s^2)
		Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
Model1	Case1	-0.2184	0.0133	-11.4731	1.5162	-0.2657	-14.8886
	Case2	**-0.2021**	-0.0124	**10.9223**	1.6579	-0.2411	13.4384
	Case3	-0.2192	-0.0202	-11.4327	2.3430	-0.2882	16.6725
	Case4	-0.2106	**0.0037**	12.0790	**-1.4460**	**-0.2103**	**11.0315**
Model2	Case1	-0.0778	0.0103	-11.2900	-2.2130	0.1159	-19.8100
	Case2	**-0.0733**	**0.0084**	-11.3900	**-1.9660**	**0.1030**	-18.4100
	Case3	-0.0794	0.0146	**-10.7800**	-2.8360	0.1301	-21.1500
	Case4	-0.0750	0.0097	-10.7600	-2.0570	0.1093	**-17.9200**
Model3	Case1	0.0312	-0.0053	-7.6790	2.5980	0.0475	16.0700
	Case2	0.0307	**-0.0037**	7.7420	**1.8260**	**-0.0448**	**13.0300**
	Case3	**0.0307**	0.0074	-7.6090	3.2920	0.0600	-17.3700
	Case4	0.0308	0.0063	**-7.5790**	2.9640	0.0550	-16.0900

Table 4 Results of maximum response (Kobe earthquake)

Ground Models	Case of Piles	Left end of the footing				Top of the structure	
		Displacement(m)		Acceleration(m/s^2)		Displacement(m)	Acceleration(m/s^2)
		Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
Model1	Case1	0.2249	0.0145	-11.7500	-1.2870	0.2783	11.5200
	Case2	**0.2104**	0.0142	**-11.3400**	-1.4590	0.2562	10.4700
	Case3	0.2308	0.0204	-12.0800	-1.5410	0.3053	13.1600
	Case4	0.2163	**0.0033**	-12.5700	**0.8022**	**0.2181**	**9.8550**
Model2	Case1	-0.0595	-0.0087	9.4290	1.8940	-0.0938	16.8800
	Case2	-0.0598	**-0.0063**	9.6200	**-1.5380**	**-0.0824**	13.9900
	Case3	**-0.0567**	-0.0136	**8.6130**	3.0070	-0.1090	19.9700
	Case4	-0.0584	-0.0098	9.1150	2.2590	-0.0966	**17.5400**
Model3	Case1	-0.0451	-0.0069	11.5500	2.0680	-0.0747	20.3700
	Case2	-0.0446	**-0.0048**	11.5300	**-1.8390**	**-0.0636**	**16.4300**
	Case3	-0.0439	-0.0100	**10.9600**	-3.0230	-0.0848	23.2100
	Case4	**-0.0438**	-0.0086	11.1000	-2.6650	-0.0799	22.0900

Time history response

The results of analysis with the El Centro and Kobe ground motions are shown in Figures 5 and 6, respectively. The figures show from above the horizontal displacement response at the leftmost end of the footing, vertical displacement response at the leftmost end of the footing , and horizontal displacement response of the structure. The thick lines in the figures represent the results in case 4. As seen from the figures, no variances were found in horizontal response of the footing among different soil conditions or pile types although there were slight variances in the response value. With respect to horizontal response of the structure, on the other hand, the softer the soil, the more the response and the frequency fluctuated. This is because there were variances in vertical response at the leftmost end of the footing according to the pile type. The variances were larger for softer soil. In case 4 using raking piles in particular, vertical variances were small and the response was out of phase with that for other pile types. This may be because the raking pile in the forefront in a group of piles in the direction of horizontal deformation prevented the collapse of the footing but pushed up the footing.

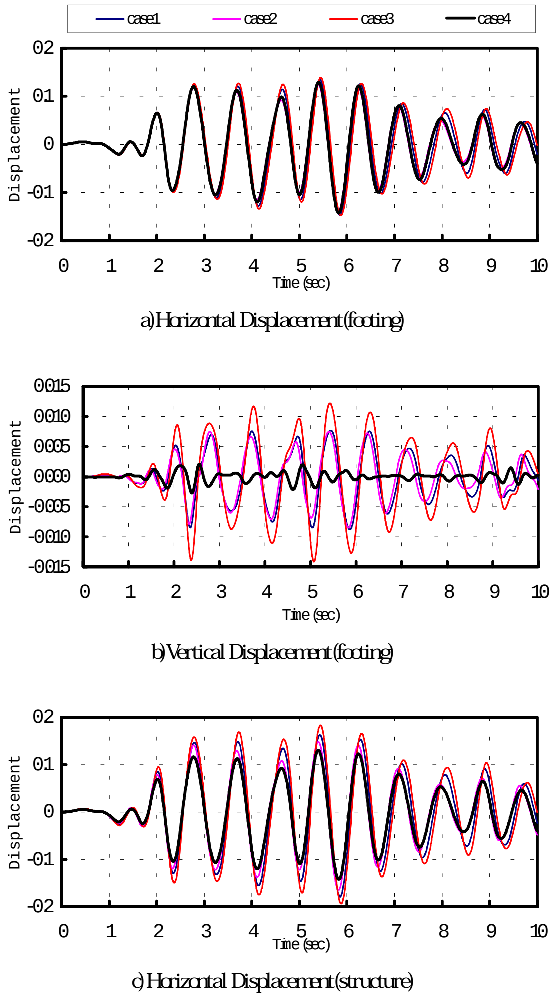


Fig. 5 Results of time history (El cent)

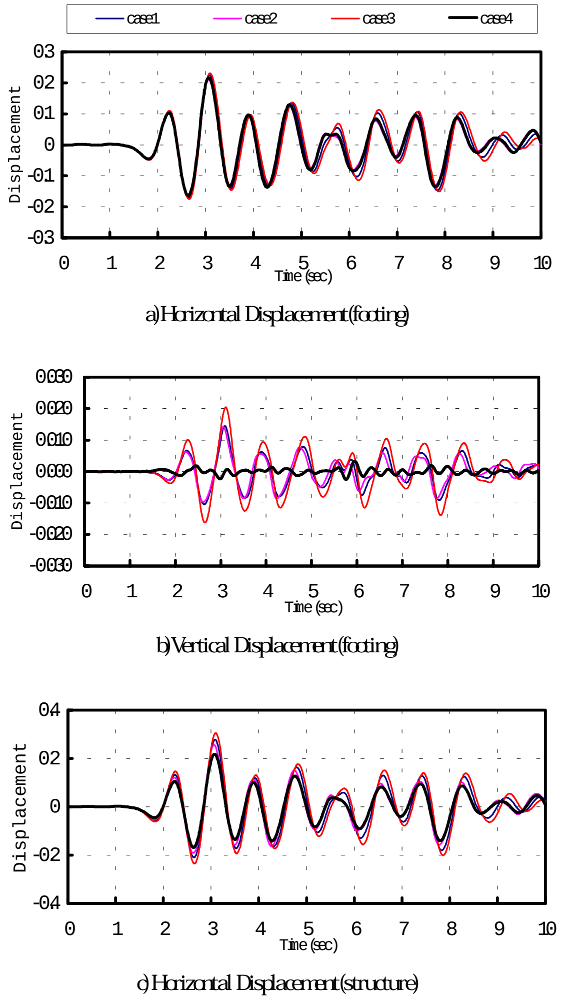


Fig. 6 Results of time history (Kobe earthquake)

RESULTS OF NONLINEAR ANALYSIS

Piles are generally used for structures founded on soft soils. In a nonlinear analysis, therefore, a study was made only for the model in the softest soil. For respective members, various models were used to represent non-linearity. A modified Ramberg-Osgood Model was used for soil, a tri-linear model for cast-in-situ pile, a modified Takeda model for pre-cast pile and a bilinear model for high-capacity micropile. The values for respective pile elements used for nonlinear analysis were those at the time when the axial force was 0 kN .

Maximum response

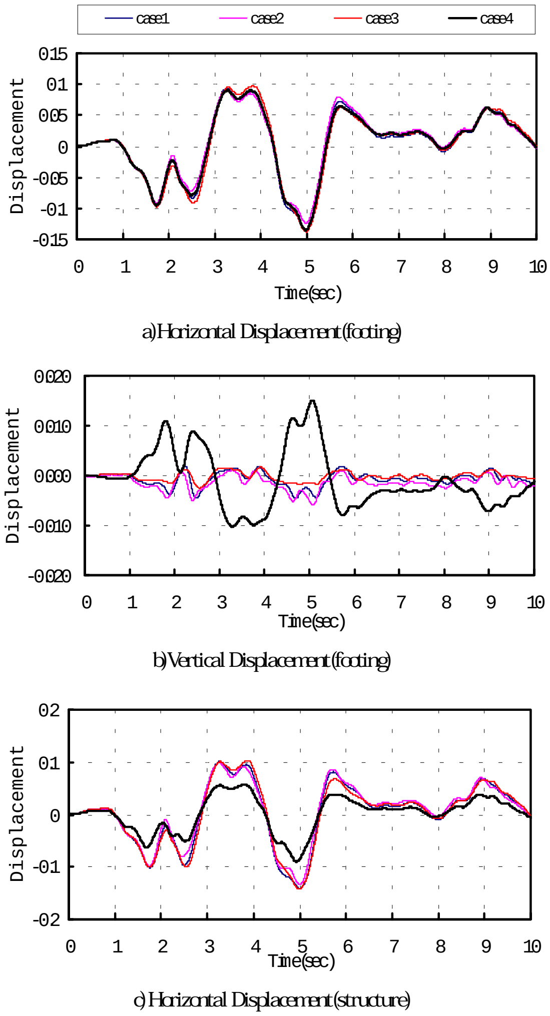
Table 5 shows maximum responses. As shown in the table, with the high-capacity micropile, the value was smallest for all responses except for horizontal response of the footing. The value of horizontal response in the upper part of the structure in particular was approximately half the values for other types of piles. Thus the nonlinear analysis also confirmed the effectiveness of high-capacity micropiles.

Table 5 Results of maximum response

	Case of Piles	Left end of the footing				Top of the structure	
		Displacement(m)		Acceleration(m/s^2)		Displacement(m)	Acceleration(m/s^2)
		Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
ElCentro	Case1	-0.1342	-0.0046	1.1940	-0.4918	-0.1409	1.9980
	Case2	**-0.1238**	-0.0058	1.0860	-0.7126	-0.1340	2.2630
	Case3	-0.1372	**-0.0025**	**0.7750**	**-0.2321**	-0.1416	**1.1690**
	Case4	-0.1349	0.0150	0.8539	0.5386	**-0.0898**	1.5440
Kobe Earthquake	Case1	0.4518	-0.0062	-1.4150	0.5347	0.4732	-1.6980
	Case2	**0.4441**	-0.0075	-1.4430	0.6341	0.4655	2.2070
	Case3	0.4663	**-0.0031**	**-1.0660**	**-0.2642**	0.4794	**-1.1730**
	Case4	0.4542	-0.0536	-1.1120	-0.5394	**0.2728**	-1.2830

Time history response

Figure 7 shows time history of displacement responses. As is obvious from the figure, no variances were observed in horizontal response at the leftmost end of footing as shown by the linear analysis. This means that the horizontal response of footing was affected by horizontal response of soil rather than by the type of pile. Horizontal response of upper part of structure supported by vertical piles (cases 1 through 3), like the behavior of

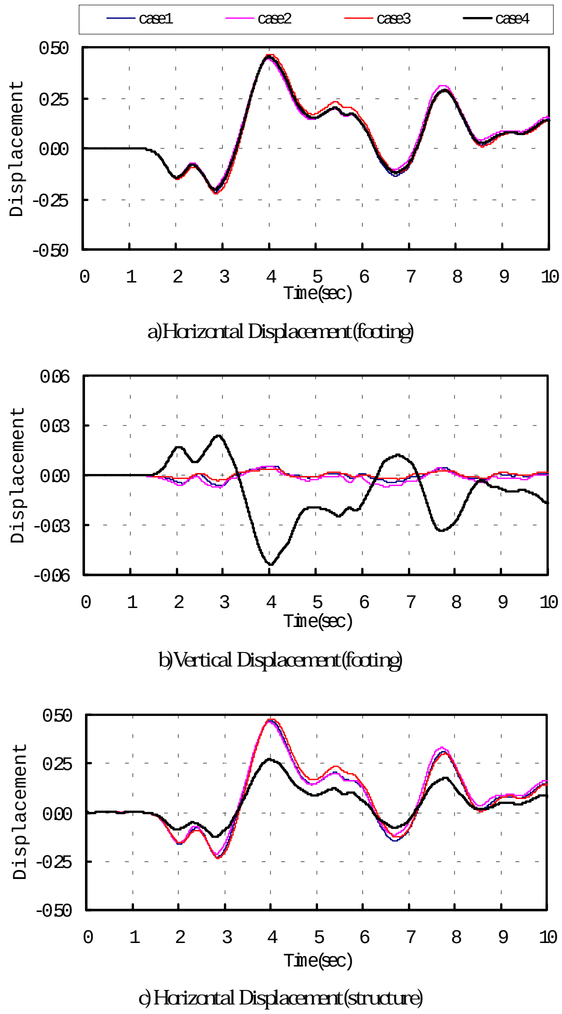


a) Horizontal Displacement (footing)

b) Vertical Displacement (footing)

c) Horizontal Displacement (structure)

Fig. 7 Results of time history (El cent)



a) Horizontal Displacement (footing)

b) Vertical Displacement (footing)

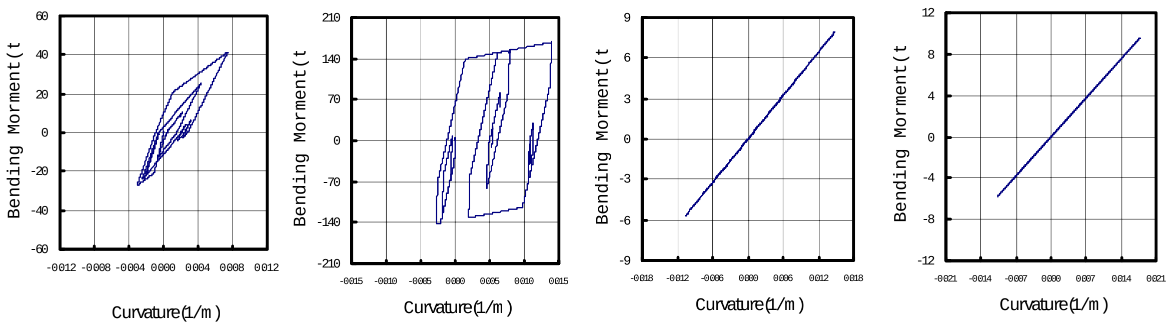
c) Horizontal Displacement (structure)

Fig. 8 Results of time history (Kobe earthquake)

footing, was not greatly affected by the type of pile. In case 4, however, where high-capacity micropiles were used as raking piles, response was smaller than for vertical piles. The response in the upper part of the structure was small because the response of footing to vertical motions was out of phase with the response to horizontal motions. Similar tendency was also found in the linear analysis. With the increase of non-linearity of soil, the tendency seems to have become more apparent.

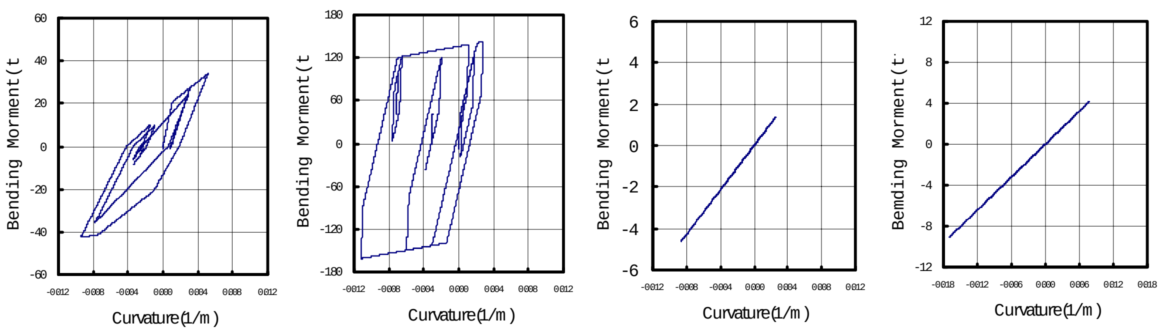
Non-linearity of piles

Figures 9 and 10 show the relationship between bending moment and curvature when the ground motion of the Kobe Earthquake was input. Figure 9 shows the results at the top of the pile and Figure 10 gives results at the boundary between upper and lower layers. Table 6 shows yield moments for respective piles. While the bending moment exceeded the yield moment for pre-cast piles and cast-in-situ piles both at the top of the pile and at the boundary between upper and lower layers, high-capacity micropiles remained elastic. Since displacement response of soil had a predominant influence on that of pile foundation, the same displacement occurred at pre-cast piles and cast-in-situ piles as soil displacement. As a result, the bending moment of concrete piles with lower ductility than high-capacity micropiles exceeded the yield moment.



@@@@@ a)case1 b)case2 c)case3 d)case4

Fig. 9 the relationship between bending moment and curvature (top of the pile)



@@@@@ a)case1 b)case2 c)case3 d)case4

Fig. 10 the relationship between bending moment and curvature (the boundary between upper and lower layers)

Table 6 the yield moments for respective piles

	Cracking		Yield	
	Bending Moment (tf·m)	Curvature (1/m)	Bending Moment (tf·m)	Curvature (1/m)
case1	20.90	1.026E-03	41.40	7.100E-03
case2	37.10	1.287E-04	141.00	2.107E-03
case3			23.08	4.364E-02
case4				

CONCLUSIONS

The following knowledge was obtained by dynamic response analysis under varying soil conditions and for different pile types.

(i) Horizontal response of footing was almost the same regardless of the pile type. This is because the horizontal response of footing was influenced by soil response. Nonlinear analysis produced similar results.

(ii) Vertical response of footing and horizontal response of structure varied more substantially for softer soils. Use of high-capacity micropiles as raking piles in particular controlled vertical response. Nonlinear analysis revealed that the use of high-capacity micropiles as raking piles caused horizontal and vertical responses of footing to be out of phase with each other, and controlled the response of a still upper structure above an upper structure. Such an result was produced because the raking piles in the front pushed up the footing and those in the rear pushed it down with the increase of horizontal deformation of the footing. The result was outstanding in the nonlinear analysis where there was large deformation.

(iii) During a great earthquake, high-capacity micropiles maintained linearity while pre-cast piles and cast-in-situ piles yielded. Thus high-capacity micropiles proved to have high ductility and resistance against earthquakes.

Judging from the above, small-diameter piles, though generally considered unfit for supports against earthquakes, have proved to be an effective piles even against earthquakes if they facilitate construction of raking piles and produce high bending strength like high-capacity micropiles.

In the future, the authors plan to carry out vibrating table tests to study dynamic response of structures supported by high-capacity micropiles.