DAMAGES TO BRIDGE FOUNDATIONS DURING THE HANSHIN EARTHQUAKE

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by

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ABSTRACT

A bore hole television system was used to survey damage to the foundations of road bridges caused by the Hyogo-ken Nanbu Earthquake. The foundation bodies of some bridges were cracked, but no foundation subsidence, steel reinforcement rupture, nor cover concrete separation damage occurred. But residual displacement was found in some pile foundations near the shoreline where liquefaction caused ground flow. Loading tests were performed on piles which cracked, the results were analyzed, and the analytical results confirmed that the damage to the pile bodies had only a slight effect on the horizontal strength of the foundations.

KEYWORDS : Earthquake damage, Hyogo-ken Nanbu Earthquake, Highway bridges, Foundations, Horizontal strength

1. INTRODUCTION

The Hyogo-ken Nanbu Earthquake of January 17, 1995 caused extensive damage to road bridges: collapsed bridge piers, fallen bridges, etc.[1)]. It was impossible to survey bridge foundation damage immediately after the earthquake because the foundations are underground, but the state of damage to the foundations was surveyed in conjunction with restoration work. At the result, it was confirmed that a number of foundations were cracked or suffered horizontal residual displacement.

This paper presents an outline of the state of damage to foundations of road bridges based on the results of the foundation survey and describes characteristics of the damage. It also reports on vertical loading testing, horizontal loading testing, and pile bending testing performed using damaged pile foundation to clarify the effect of the pile body damage on the horizontal strength of the foundations.

2. STATE OF THE DAMAGE TO BRIDGE PIER FOUNDATIONS

2.1 Survey of the Damage to Bridge Pier Foundations

A survey of the damage to bridge pier foundations was conducted on the No.3 Kobe Line and No.5 Wangan Line of the Hanshin Expressway, at the Hamate Bypass of National Highway No.2, and on the Meishin and Chugoku Expressways. But the survey of the Meishin and Chugoku Expressways was limited to seven viaducts where the damage to the bridge piers was relatively severe (Onishi, Mizudo, Moribe, Tsuto, and Kawaraginishi Viaducts on the Meishin Expressway and the Takarazuka and Kouda Viaducts on the Chugoku Expressway). Figure 1 shows location of the surveyed bridges.

During the planning of the survey on the Hamate Bypass on National Highway No.2, the No.3 Kobe Line of the Hanshin Expressway, the Meishin Expressway, and the Chugoku Expressway, the bridge piers actually surveyed were selected considering the structure of the piers, the degree of damage to each one, local factors, and so on, so that the survey would not be concentrated on a narrow range of pier categories or degrees of damage. On the other hand, on the No.5 Wangan Line of the Hanshin Expressway on the other hand, the bridge piers selected for the survey were mostly at locations where liquefaction caused substantial ground flow.

Table 1 shows the number of bridge piers in the survey area and the number that were actually surveyed. Most of the bridge pier foundations surveyed were pile foundations (cast-in-place pile foundations). It was assumed that spread foundations

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would suffer little damage because they are constructed on good quality ground and evidence was not found in the surrounding ground that these foundations had undergone large deformation, but as a precaution, 17 spread foundations were included in the survey. Most of the caisson foundations surveyed were subjected to the effects of ground flow caused by liquefaction and those supporting bridge piers with large residual horizontal displacement. Five diaphragm wall foundations were selected for inclusion in the survey, because there are few foundations of this kind in the survey area and even where ground flow occurred in the ground surrounding them, almost no residual horizontal displacement appeared in the bridge piers.

The survey of the spread foundations was performed by excavating the ground to the top surface of the footing to visually check for cracking of the footing. Because it would have been difficult to visually survey the pile foundations (cast-in-pile foundations), caisson foundations, and diaphragm wall foundations for cracking by digging down to each foundation, the survey was done with a bore hole television system. To do this, core boring was performed from the top of the footing into the pile or body of the foundation, and a borehole camera was lowered into this hole to inspect the interior of the foundation for cracking. The width of cracks observed by a bore hole television system have been assessed as more than three times the width of the cracks found when the foundation was actually excavated and inspected visually, because during the boring of the concrete, concrete around the cracks is removed, and the illumination used during camera observations produces shadows around the cracking. For the final damage assessments, the actual crack width was considered to be about 1/3 the width found using the bore hole television system (see Photograph 1).

Some of the bridge piers on the No.5 Wangan Line of the Hanshin Expressway were found to have residual horizontal displacement caused by ground flow around the bridge pier under the effects of liquefaction. For this reason, after the earthquake, a survey of bridge pier positions was carried out using the artificial satellite system called the Global Positioning System (GPS) and the findings were compared with management documents to assess the residual horizontal displacement of the bridge piers. The method used to assess the residual horizontal displacement of the bridge piers is discussed in detail as part of 3.

2.2 Damage to Bridge Pier Foundations

1) Damage to Pile Foundations

The degree of damage to pile foundations is categorizes in four ranks from rank a to rank d, as shown in Table 2. The pile foundations did not suffer severe settlement, pile body failure, or failure of their reinforcement for which would effect their overall stability, some of them suffered residual horizontal displacement caused by ground flow under the effects of liquefaction and bending cracking of pile bodies.

Table 3 presents the damage to pile foundations on each road surveyed. It reveals that pile foundations suffered the most serious damage on No.5 Wangan Line of the Hanshin Expressway, with about 11% of those surveyed on this road suffering damage assessed as rank b. This damage is assumed to have been caused by liquefaction or by the ground flow generated by liquefaction. On roads other than the No.5 Wangan Line of the Hanshin Expressway, only minor damage in rank c and d was discovered.

2) Damage to Spread Foundations

No cracking or other damage was found on the 17 spread foundations surveyed on the No.3 Kobe Line of the Hanshin Expressway and the Chugoku Expressway.

3) Damage to Caisson Foundations

Eight caisson foundations were surveyed on the No.5 Wangan Line of the Hanshin Expressway, two on the No.3 Kobe Line of the same expressway, and five on the Hamate Bypass of the National Highway No.2. On the No.5 Wangan Line of the Hanshin Expressway, one caisson foundation located near a canal was damaged; it suffered bending cracking equivalent to rank c damage to a pile foundation. This damage is assumed to have been caused by the relatively large residual horizontal displacement of the foundation and ground deformation caused by ground flow in the surrounding ground. But aside from this one case, the caisson foundations were undamaged, or if they were damaged, it was extremely minor.

4) Damage to Diaphragm Wall Foundations

The results of a survey of five diaphragm wall foundations on the No.5 Wangan Line of the

Hanshin Expressway revealed that the foundation bodies suffered bending cracking equivalent to rank d damage to a pile foundation, but this damage was very slight.

3. CHARACTERISTICS OF THE DAMAGE TO BRIDGE PIER FOUNDATIONS

3.1 State of Crack of Pile Bodies

The No.5 Wangan Line is constructed on reclaimed land with a reclaimed stratum thickness ranging from 9 m to 22 m. The Hyogo-Ken Nanbu Earthquake caused liquefaction in the ground surrounding many foundations and shifted the ground near canals towards the canals. These events resulted in large residual horizontal displacement of bridge piers and bending cracking of pile bodies of pile foundations.

Figure 2 shows examples of cracking of pile bodies. Sample (a) shows the widest crack discovered during the survey. This pile body crack was 4mm wide at its widest point, and many of them were found within the reclamation soil stratum, particularly in the top of the pile. Some cracks also occurred in the alluvial clay stratum. A study within a range of 5 m from the bottom surface of the footing reveals that the sub-total of the crack width equals 8.6 mm(4+1.3+1.3+1.0+1.0), and when calculated in terms of the unit length of the pile, it is 1.7 mm/m. Considering the fact that the diameter of the piles is 1.5 m, this can be considered as small damage. Figure 2 (b) shows the pile foundation for the bridge pier with the largest residual horizontal displacement. Within a range of about 6 m from the bottom surface of the footing, there are 12 cracks with a width of 0.5 mm or greater, but the widest of these cracks is rather small, at only 2 mm.

Table 4 shows the results of the mode of cracks in 17 pile foundations with the rank b degree of damage, the severest rank observed in all the pile foundations surveyed on the No.5 Wangan Line. In the reclaimed stratum, all 17 foundations were cracked. The average values for the 17 foundations are 10 cracks, crack width of 1.5mm, and a reclaimed stratum thickness of 14 m. The damage to these foundation piles can be defined as extremely slight. Cracks also appeared in the alluvial clay stratum, but far fewer than in the reclaimed stratum.

3.2 Residual Horizontal Displacement of the Piers

Along the No.5 Wangan Line, liquefaction accompanied by ground flow occurred in the ground around bridge piers near the shoreline, causing considerable residual horizontal displacement to the bridge piers. For this reason, the analysis included a study and clarification of the relationship of the horizontal displacement of the ground around the bridge piers with the residual horizontal displacement of the bridge piers.

The horizontal displacement of the ground was found using the results of an aerial photography survey carried out by Hamada et al. [2] They used three survey stations established on Rokko Island as control points for the aerial photography survey, but for this study, six survey stations established for the survey of the bridge pier locations for the No.5 Wangan Line of the Hanshin Expressway were used as the control points. As examples, Figure 3 and Figure 4 present results showing the horizontal displacement of the ground and the residual horizontal displacement of the bridge piers of the Rokko Island Bridge and its approach that connect with Rokko Island and Uozaki Hama. While the aerial photography survey of Hamada et al. found the displacement vectors of manhole covers and other fixed objects on the ground surface, in addition to that, this survey found the displacement vectors at intersection points of a grid crossed at intervals of 20 m. The residual horizontal displacement of bridge piers, found from another survey performed after the earthquake, represents the displacement of bridge pier body at approximately 1 m height above the ground.

When the horizontal displacement vectors of the ground and bridge piers are found in this way, almost along No.5 Wangan Line they include about 20 cm displacement evenly in the south-west direction. And triangulation point near the No.5 Wangan Line also shifted the same distance to the south-west. This displacement can be interpreted in various ways: as ground displacement caused by fault movement or as a wide-area ground movement, but because uniform displacement occurred over a certain range, the horizontal displacement of the ground and the residual horizontal displacement of the bridge piers were modified after deducting this value. The horizontal displacement vectors found in the way include a certain degree of error because of differences in the precision of the photographic surveys performed before and after the earthquake, and of variations in the way the aerial photographs. For this analysis, the precision of the measurement of the horizontal displacement of the ground is estimated to be ± 30cm, and the bridge pier residual horizontal displacement measurement precision is estimated to be ± 10cm.

Figure 5 shows the relationship of the residual horizontal displacement of the bridge piers with the horizontal displacement of the ground around the bridge piers in Rokko Island, Uozaki Hama, and Fukae Hama. The results are considerably scattered, but overall, the residual horizontal displacement of the bridge piers tends to increase as the horizontal displacement of the surrounding ground rises. But the extent of the displacement of bridge piers which occurs when certain ground displacement occurs varies according to the rigidity of the foundation, and the residual horizontal displacement is smaller in the case of caisson foundations or diaphragm wall foundations: types with greater stiffness than pile foundations.

4. HORIZONTAL STRENGTH OF DAMAGED PILE FOUNDATIONS

4.1 Pile Loading Tests

To confirm the effect of pile damage on overall pile foundations, loading testings were performed on piles of the No.3 Kobe Line of the Hanshin Expressway. The degree of damage to the pile foundation was assessed as rank c damage:a crack with a width of about 2 mm was found near the top of the pile as shown in Photograph 2 but its concrete was not crushed and its reinforcement bars did not swell out.

The loading testing included three tests : pile body bending,vertical loading,and horizontal loading tests. Three of the 19 piles were cut for use as test piles. Specimens were taken from these cut test piles for use in compressive strength testing of the concrete cores and for tensile strength testing of the reinforcement bar. Table 5 shows the results of the compressive strength testing of the concrete cores. The average value of the strength of the concrete of the pile bodies was about 1.8 times the design strength of 240kgf/cm ^{2} and represents considerable strength. Table 6 presents the results of the tensile testing of the reinforcement bar. The results, that the yield points of three of the five reinforcement bar are not clear, shows that these reinforcement bars received a stress history that exceeds the yield point. An examination of arrangement of the reinforcement at the cut section of the piles bodies showed they were as shown as designed.

Pile body bending testing was performed on the pile tops where cracking appeared as shown in Figure 6. Test piles were obtained by cutting the pile bodies at a depth of 2.8 m below the bottom surface of the footing, then horizontal loading was done at a depth of 2.5 m below the footing using adjacent piles as the reaction piles. The loading, which was one-direction multi-stage loading, was performed up to 25 tf, equivalent to about 60% of the calculated yield bending moment of the tops of the piles. Figure 7 shows the relationship of the horizontal load with the horizontal displacement at the loading point. In order to grasp the effects of the decline in stiffness of the top of the piles,the relationship of the horizontal loading with the horizontal displacement of the piles when the pile tops are assumed to be sound was found through analysis, and this was compared with the results of the loading testing. The analysis of a sound pile referred to here was performed using the stress-strain relationship of concrete indicated in the "Guide Specifications for Reconstruction and Repair of Highway Bridges Which Suffered Damage due to the Hyogo-ken Nanbu Earthquake" (Ministry of Construction, Feb.24, 1995), and in this analysis the horizontal displacement by pulling the main reinforcement bars out of the footing is included. According to the material testing described above, the yield strength of the reinforcement bar and the compressive strength of the concrete in the pile body were assessed as 3,750kgf/cm ^{2} and 425kgf/cm ^{2} respectively. The horizontal displacement of the loading testing is greater than the analytical value for the same horizontal load when the pile tops are considered to be sound, and the stiffness of the pile tops declines.

To perform the vertical loading testing and the horizontal loading testing, two piles were cut at a depth of 1.2 m from the bottom surface of the footing, and the piles below this level used as the specimens for the two tests. Vertical loading was applied to the top of one pile and horizontal loading to the top of the other. Figure 8 shows the amount of loading - amount of settlement relationship for the vertical loading testing. It confirmed a bearing capacity as high as 450 tf : a value exceeding the design ultimate bearing capacity of 436 tf calculated by the present Specifications for Highway Bridges. The pile top settled 1.3cm, much less than 10cm, which is 10% of the pile diameter, and the amount of settlement usually forecast when calculating the ultimate bearing capacity of piles, which confirms that the ultimate bearing capacity of the pile exceeds the design ultimate bearing capacity. Figure 9 presents the amount of loading - horizontal displacement curve obtained from the horizontal loading testing. This figure shows that the value of the coefficient of ground reaction in the horizontal direction found assuming that the horizontal displacement is 1% of the pile diameters is 1.9 kgf/cm^3, which coincides closely with 2.3kgf/cm^3, the coefficient of ground reaction in the horizontal direction estimated from the N value obtained from a standard penetration test according to Specifications for Highway Bridges.

4.2 Evaluation of the Strength of the Pile Foundations

In order to evaluate the effect of the earthquake damage to piles on the behavior of overall foundations, the foundations which underwent the loading testing were used as the object of an analysis performed to find the resistance properties of pile foundations employing a method which accounts for the non-linear behavior of foundations. The analytical model is shown in Figure 10.

The resistance properties in the axial direction of a pile are modelled as a bi-linear model with the ultimate bearing capacity and the ultimate pull-out force as the upper limit values by treating the axial direction spring constant Kv of the pile found from the vertical loading testing as the initial gradient. The ground resistance in the direction perpendicular to the axial direction of the pile is modelled as a bi-linear model with the upper limit p_{HU} and the initial gradient k_{Hd} calculated from the following formulae.

$$k_{Hd} = \eta_k \cdot \alpha_k \cdot k_H \quad (1)$$

$$p_{HU} = \eta_p \cdot \alpha_p \cdot p_u \quad (2)$$

Where:

k_{Hd} : Design horizontal subgrade reaction coefficient (kgf/cm^3)

p_{HU} : Upper limit value of the horizontal subgrade reaction (kgf/cm^2)

k_H : The horizontal subgrade reaction coefficient (kgf/cm^3) during the earthquake, it is found from the Specifications for Highway Bridges. Here it is set based on the horizontal loading testing of the pile.

p_u : The passive earth pressure strength (kgf/cm^2) during the earthquake, it is found using Coulomb's passive earth pressure coefficient based on the ground constant obtained from the soil testing. Here it considers the weight of the soil up to the ground surface to be the overburden load.

α_k : Corrective coefficient of the horizontal subgrade reaction coefficient of a single pile

α_p : Corrective coefficient of the upper limit value of the horizontal subgrade reaction of a single pile

η_k : Corrective coefficient of the horizontal subgrade reaction coefficient accounting for the pile group effect

η_p : Corrective coefficient of the upper limit value of the horizontal subgrade reaction accounting for the pile group effect

The values used for α_k and α_p are shown in Table 7. These were found from an analysis of the results of horizontal loading testing of existing single piles.

The corrective coefficient of the horizontal subgrade reaction coefficient accounting for the pile group effect η_k used was the following value.

$$\eta_k = 2/3 \quad (3)$$

The corrective coefficient of the upper limit value of the horizontal subgrade reaction accounting for the pile group effect η_p used was the following value.

Cohesive Soil : $\eta_p = 1.0$ (4)

Sandy Soil :

$\eta_p \cdot \alpha_p$ = Center interval between the piles in the direction perpendicular to the loading / pile diameter ($\leqq \alpha_p$) (5)

In the case of piles other than the front row of piles in sandy ground, it is 1/2 of the value shown in formula (5). The value of η_k and η_p for these piles was found based on the results of the analysis of loading testing of pile groups.

The ground resistance and bending stiffness of the piles were estimated based on data obtained from the loading testing and material testing described above. Because the bending test of the pile indicates that as shown in Figure 9, earthquake reduces the bending stiffness of the pile top, the bending stiffness of the pile top is reduced as shown in Figure 11 to a value about 2/3 of that when the pile top is assumed to be sound, so that analytical result of the horizontal load - horizontal displacement relationship of a pile will be equivalent to the bending testing results.

Figure 12 shows the results of the above described analysis of the horizontal load - horizontal displacement relationship of the overall pile foundation. A comparison of this relationship when the pile has not been damaged with the relationship in a case where the pile top is assumed to have been damaged reveals that in the damaged case, the horizontal displacement under the same horizontal loading is slightly larger, but that the maximum horizontal bearing strength of the pile foundation hardly declines at all, demonstrating that damage to the pile body has only a slight effect on the overall pile foundation.

5. CONCLUSIONS

The results of survey of the damage to bridge pier foundations by the Hyogo-ken Nanbu Earthquake have been studied and organized and an outline of the damage and its characteristics prepared. Loading testing was performed on cracked piles to clarify the effects of the damage to the pile bodies on the horizontal strength of the foundations. The main results obtained from these survey are summarized as follows:

(1) The foundations did not suffer severe settlement, pile body failure, or failure of their reinforcement for which would effect their overall stability.

(2) Near the channels where liquefaction caused ground flow, some foundations suffered horizontal residual displacement. There was little residual displacement in the case of caisson foundations, diaphragm wall foundations, with a high degree of stiffness, even those at locations where equally severe ground flow occurred.

(3) Vertical loading testing, horizontal loading testing, and pile bending testing were performed on damaged pile foundation. The results revealed that despite a decline in stiffness at the tops of the cracked piles, the earthquake did not effect the vertical bearing strength or horizontal resistance of the piles.

(4) In order to evaluate the effect of the damage to pile bodies on the behavior of overall foundations, the foundation which underwent the loading testing were used as the object of an analysis performed to find the resistance properties of the pile foundations. When the damage to the pile bodies was accounted for, the horizontal displacement produced by the same horizontal load increased slightly, but there was almost no decline in the maximum horizontal strength of the pile foundation.

In order to perform structural design accounting for an earthquake as severe as the Hyogo-ken Nanbu Earthquake, it is essential to study the displacement properties and dynamic strength of foundations during earthquakes. A method of evaluating displacement properties and dynamic strength during earthquakes that accounts for the non-linear properties of ground resistance must be developed.

This paper is quote from the Report on the Damage of Highway Bridges by the Hyogo-ken Nanbu Earthquake, Committee for Investigation on the Damage of Highway Bridges by the Hyogo-ken Nanbu Earthquake [5].

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4) Japan Road Association : Specifications for Highway Bridges, 1994.

5)Ministry of Construction : Report on the Damage of Highway Bridges by the Hyogo-ken Nanbu Earthquake, Committee for Investigation on the Damage of Highway Bridges by the Hyogo-ken Nanbu Earthquake, 1995.

Table 1 Number of Bridge Piers in the Survey Area and Number of Bridge Piers Surveyed
(Number of Bridge Piers)

Road	Category	Type of Foundation				Totals
		Spread Foundation	Caisson Foundation	Pile Foundation	Diaphragm Wall Foundation	
No.3 Kobe Line Hanshin Expressway	All Bridge Piers in the Area Surveyed	133(12%)	44(4%)	929(84%)	0(0%)	1106 (100%)
	Bridge Piers Surveyed	12	2	109	0	123
No.5 Wangan Line, Hanshin Expressway	All Bridge Piers in the Area Surveyed	0(0%)	52(15%)	280(81%)	13(4%)	345 (100%)
	Bridge Piers Surveyed	0	8	153	5	166
National Highway No.2, Hamate Bypass	All Bridge Piers in the Area Surveyed	0(0%)	15(21%)	57(79%)	0(0%)	72 (100%)
	Bridge Piers Surveyed	0	5	20	0	25
Meishin Expressway and Chugoku Expressway	All Bridge Piers in the Area Surveyed	152(22%)	0(0%)	532(78%)	0(0%)	684 (100%)
	Bridge Piers Surveyed	5	0	21	0	26

Table 2 Categorization of Damage to Pile Foundation

Degree of Damage	Definition
a	Settlement of the foundation accompanied by considerable residual horizontal displacement.
b	Considerable residual horizontal displacement of the foundation. Bending cracking of the pile body.
c	Minor bending cracking of the pile body.
d	No damage to the pile or slight bending cracking.

Table 3 Degree of Damage to Pile Foundations (Number of Bridge Piers)

Road	Degree of Damage				
	a	b	c	d	計
No3.Kobe Line, Hanshin Expressway	0 (0%)	0 (0%)	17 (16%)	92 (84%)	109 (100%)
No.5 wangan Line, Hanshin Expressway	0 (0%)	17 (11%)	57 (37%)	79 (52%)	153 (100%)
National Highway No.2, Hamate Bypass	0 (0%)	0 (0%)	10 (50%)	10 (50%)	20 (100%)
Meishin Expressway and Chugoku Expressway	0 (0%)	0 (0%)	0 (0%)	21 (100%)	21 (100%)

Table 4 Occurrence of Cracking in Pile Bodies at 17 Pile Foundations With Damage in Rank b (No.5 Wangan Line of the Hanshin Expressway)

Stratum	Number of Bridge Piers with Cracking	Average Stratum Thickness (m)	Average Number of Cracks in the Stratum	Average Crack Width (mm)
Reclamation Stratum	17	14	10	1.5
Alluvial Clay Stratum	3	6	3	1.2

Table 5 Results of the Compressive Strength Test of the Concrete Core of the Pile Tops (No.126 Pier)

Core No.	Compressive Strength (kgf/cm^2)
1	396
2	429
3	450
Average Value	425

Table 6 Result of the Tensile Test of the Reinforcement Bars (D29) of the Pile Tops (No.126 Pier)

Number of Reinforcement Bar	Yield Strength (kgf/cm^2)	Tensile Strength (kgf/cm^2)
1	3,860	5,790
2	3,640	5,390
3	No yield point	5,540
4	〃	5,350
5	〃	5,350
Average	3,750	5,480
Standard Values	>3,000	4,900 ~ 6,300 *

*) Predicted value in current JIS standard is 4,500 to 6,100 kgf/cm^2

Table 7 Corrective Coefficient

Type of soil Layers	α_K	α_P
Sandy Soil	1.5	3.0
Cohesive Soil	1.5	1.5

Note: α_P =1.0 in Soft Layers with $N \leqq 2$

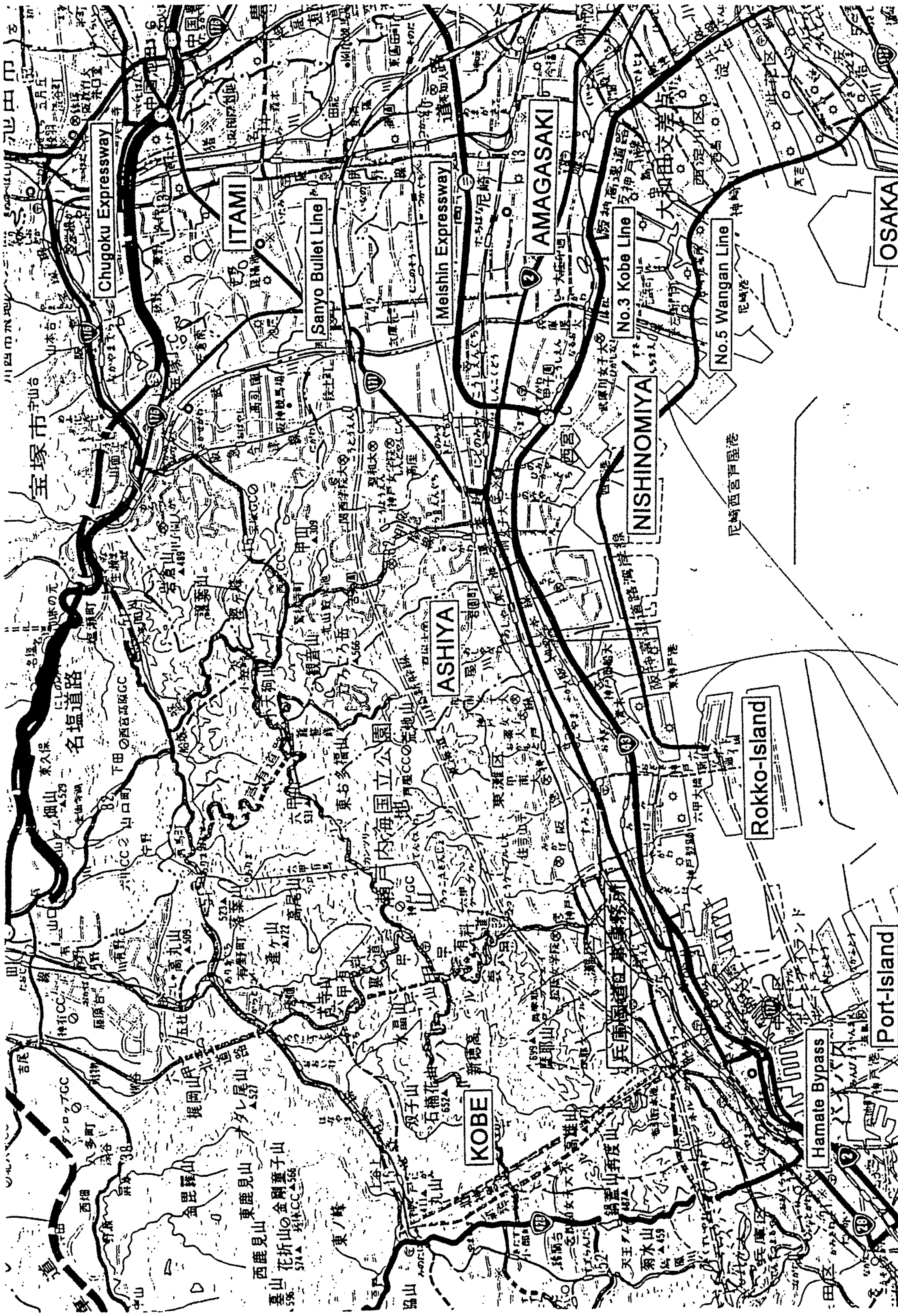
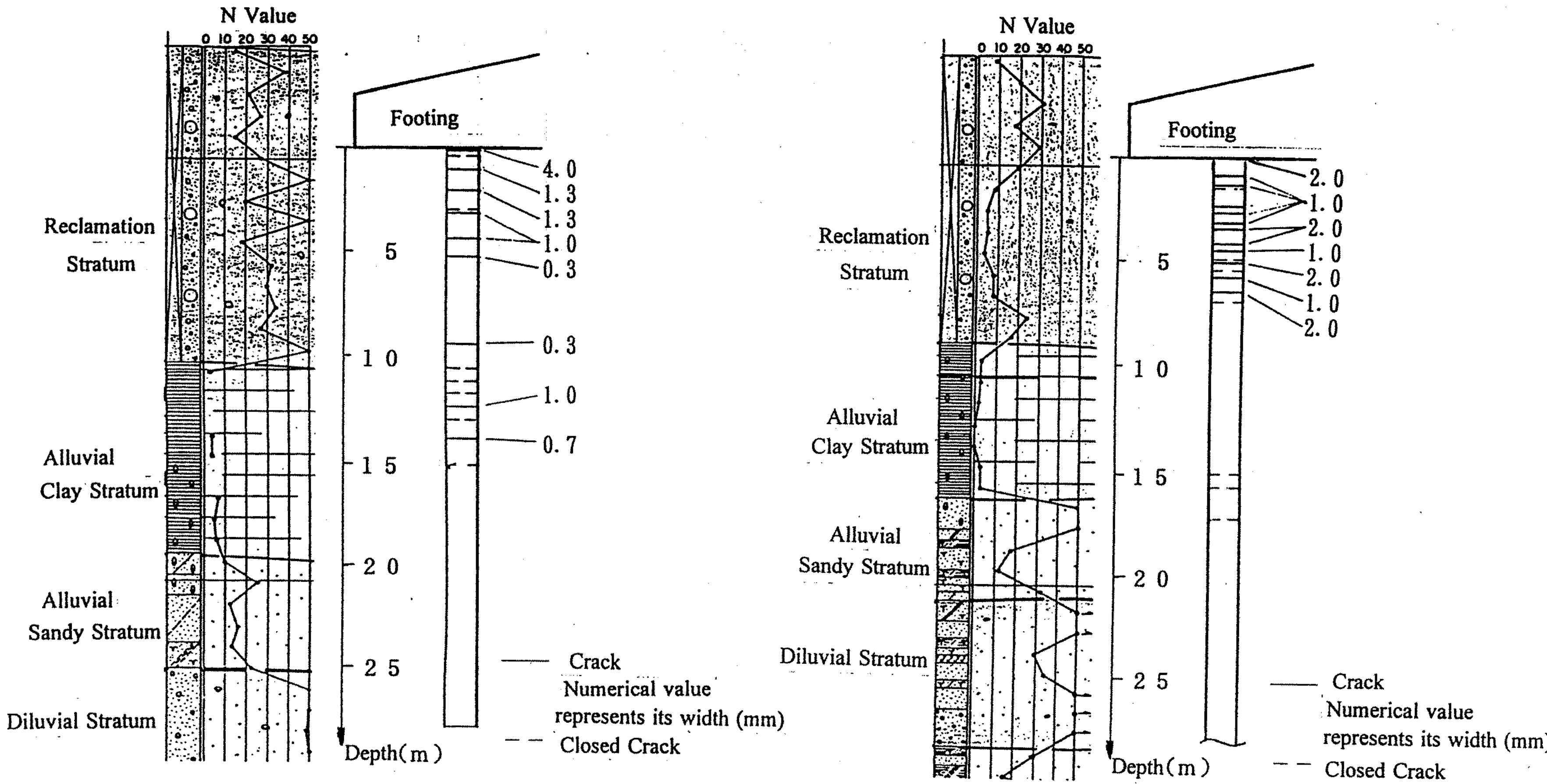


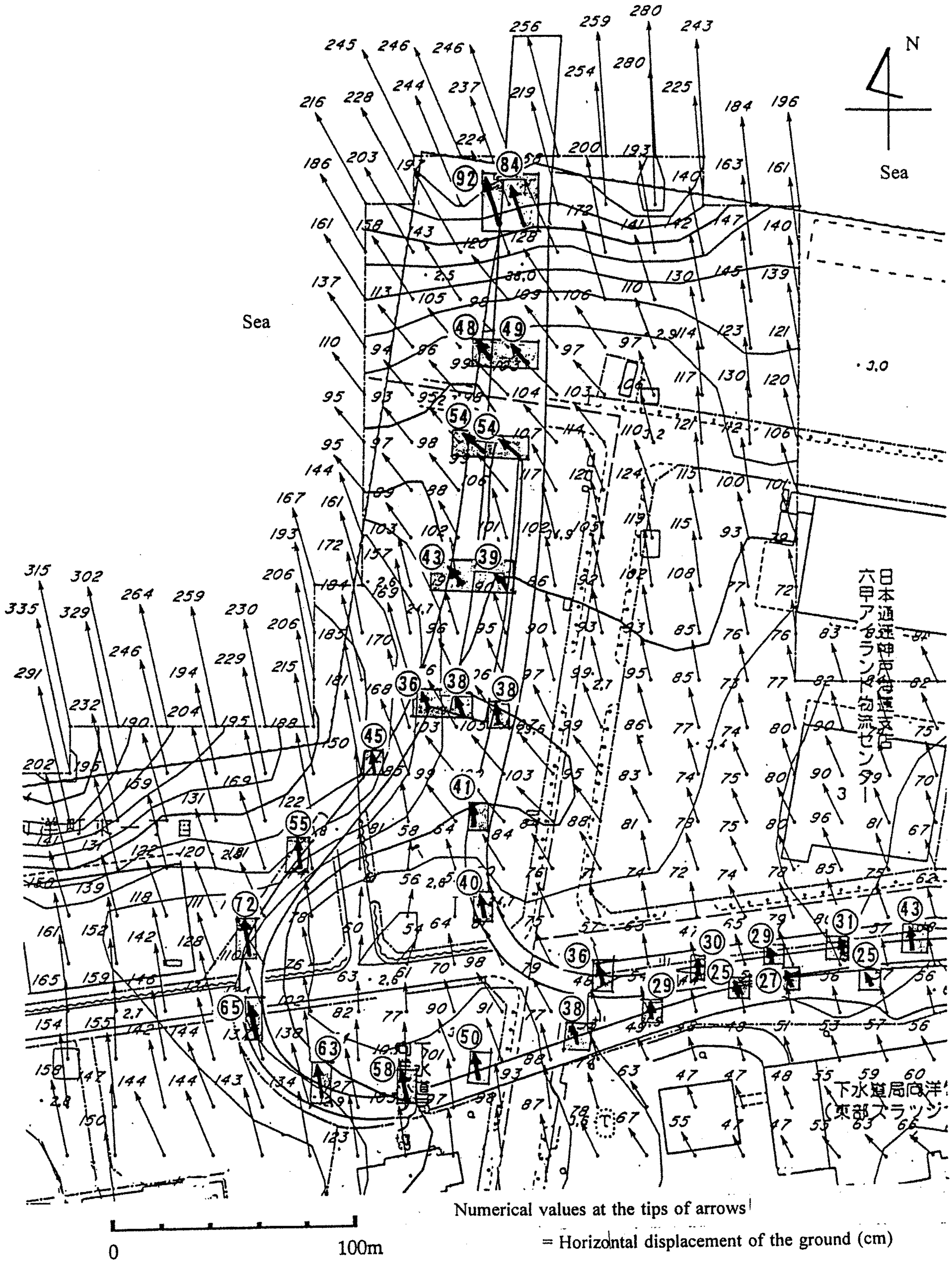
Figure 1 Map of Surveyed Bridges



(a) Example of Pile with Wide Cracks

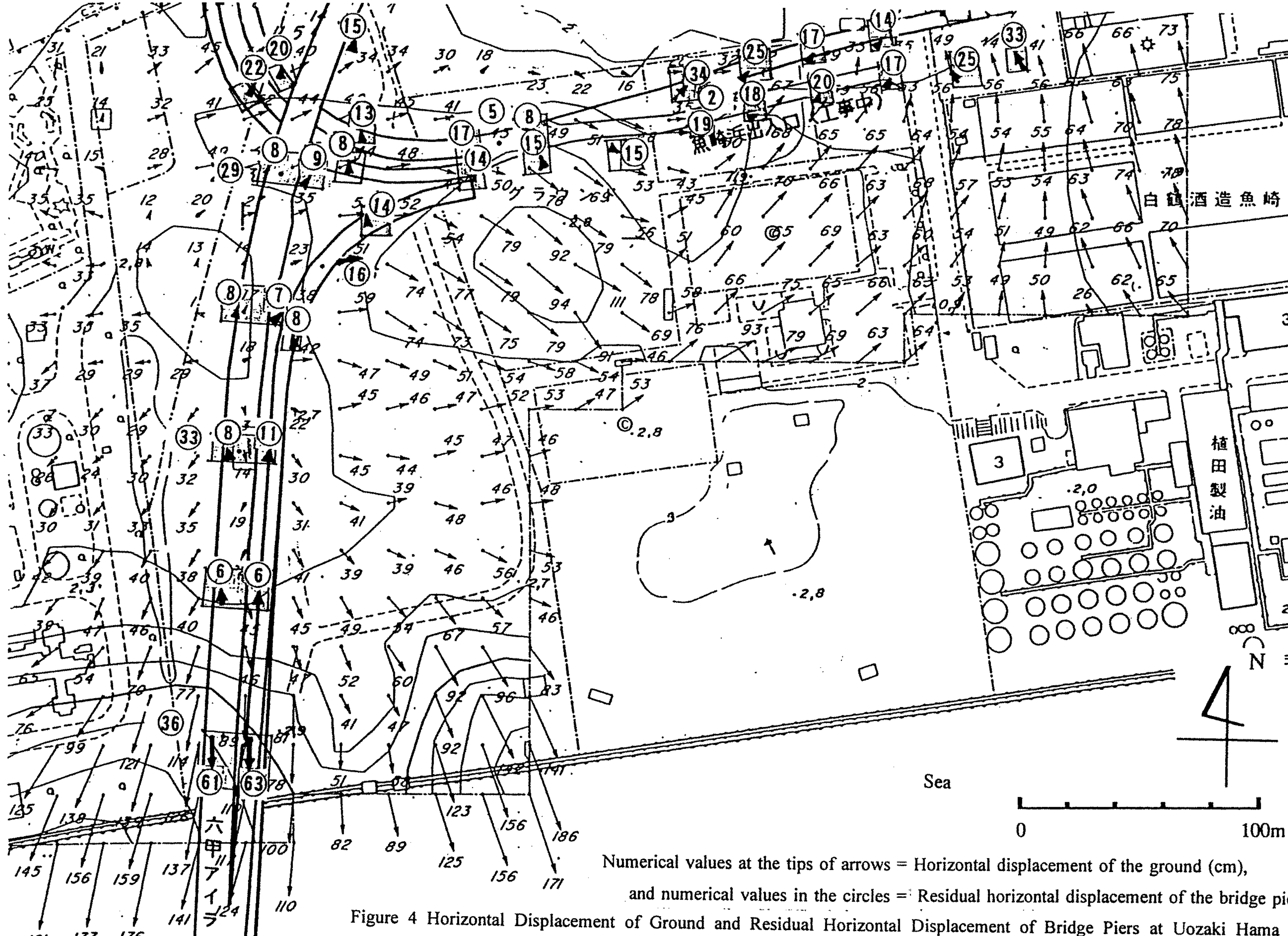
(b) Example of Pile with Large Residual Horizontal Displacement of a Bridge Pier

Figure 2 Examples of Cracking of Pile Bodies



Numerical values at the tips of arrows
= Horizontal displacement of the ground (cm)
Numerical values in the circles
= Residual horizontal displacement of the bridge piers (cm)

Figure 3 Horizontal Displacement of Ground and Residual Horizontal Displacement of Bridge Piers at Rokko Island
(Horizontal Displacement of the Ground Obtained by Modifying the Results of a Survey by Hamada et al. [2])



Numerical values at the tips of arrows = Horizontal displacement of the ground (cm),

and numerical values in the circles = Residual horizontal displacement of the bridge piers (cm)

Figure 4 Horizontal Displacement of Ground and Residual Horizontal Displacement of Bridge Piers at Uozaki Hama (Displacement of the Ground Obtained by Modifying the Results of a Survey by Hamada et al. [2])

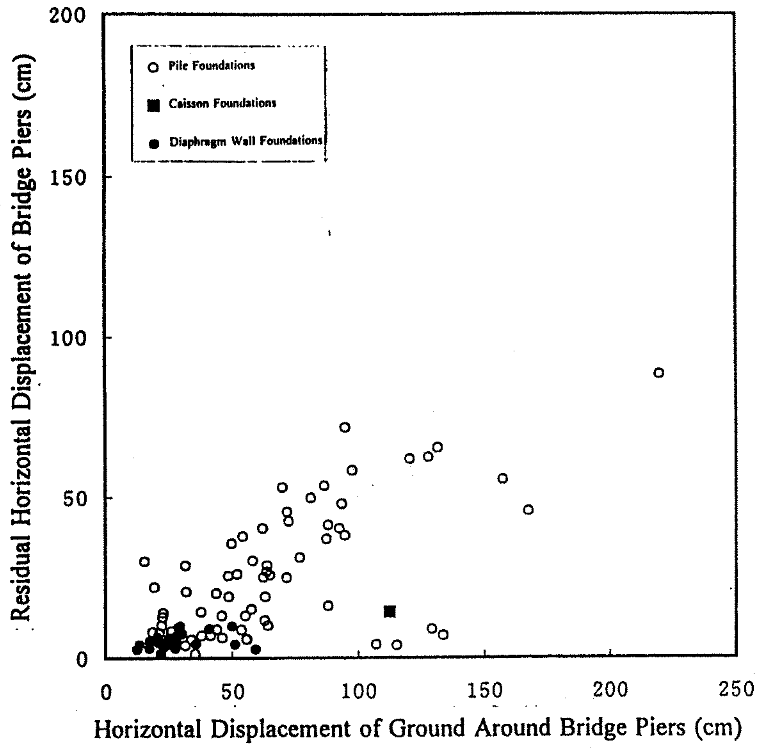


Figure 5 Ground Horizontal Displacement - Bridge Pier Residual Horizontal Displacement Relationship (For Bridge Piers on the No.5 Wangan Line of the Hanshin Expressway at Rokko Island, Uozaki Hama, and Fukae Hama)

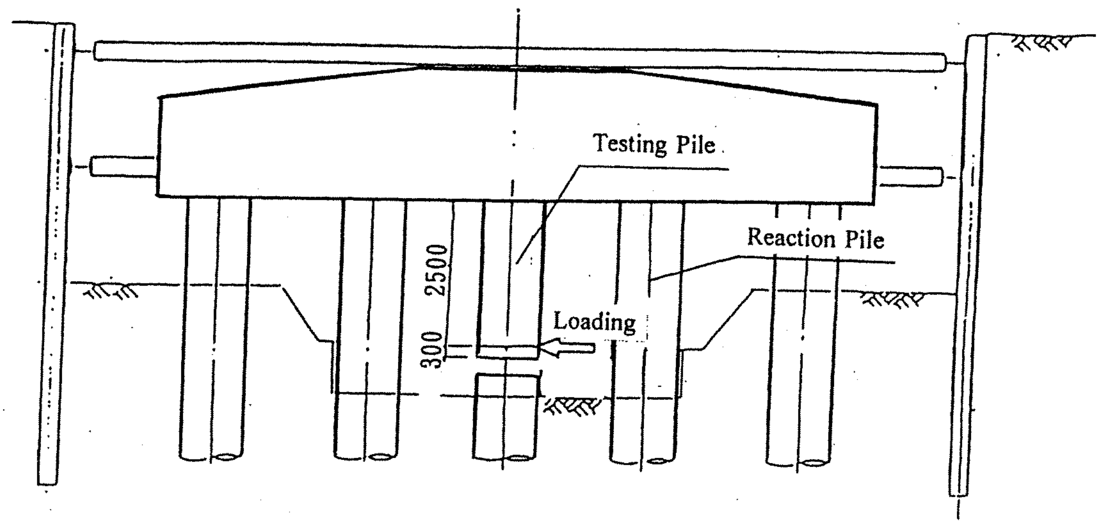


Figure 6 Pile Bending Test (No.126 Pier)

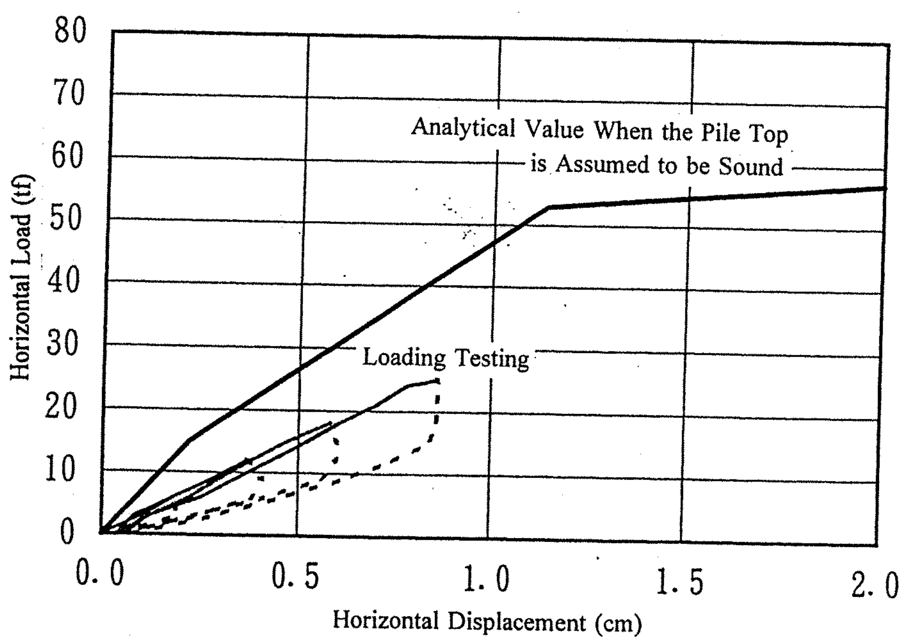


Figure 7 Horizontal Load - Horizontal Displacement at the Loading Point During Pile Bending Testing (No.126 Pier)

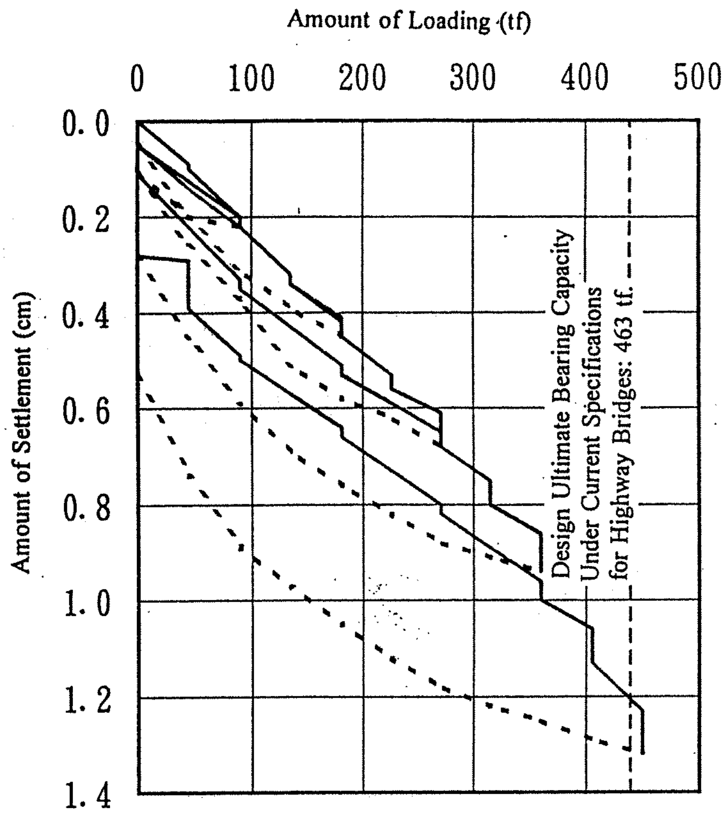


Figure 8 Amount of Loading - Amount of Settlement Curve During the Vertical Loading Test of the Piles (No.126 Pier)

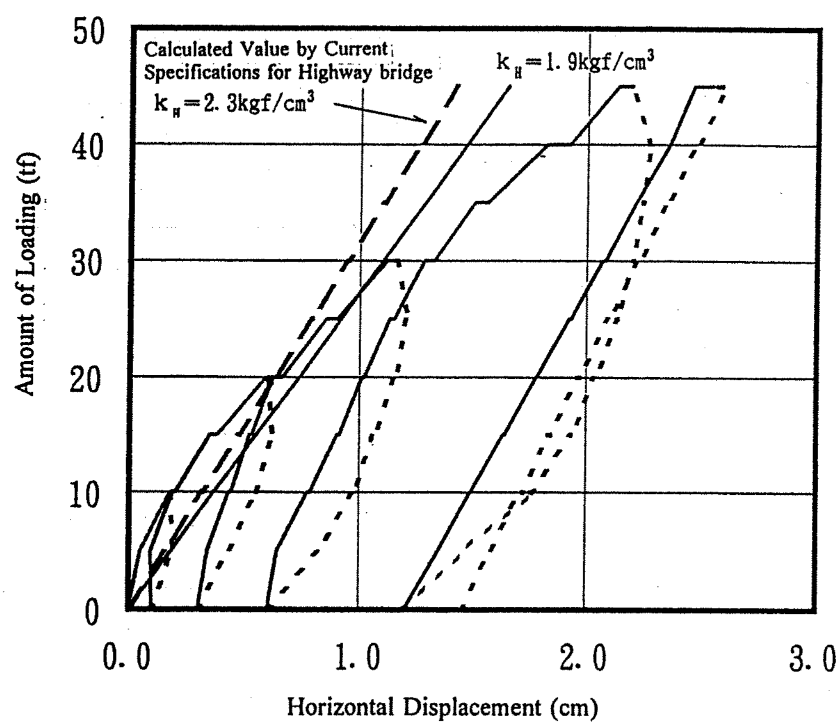
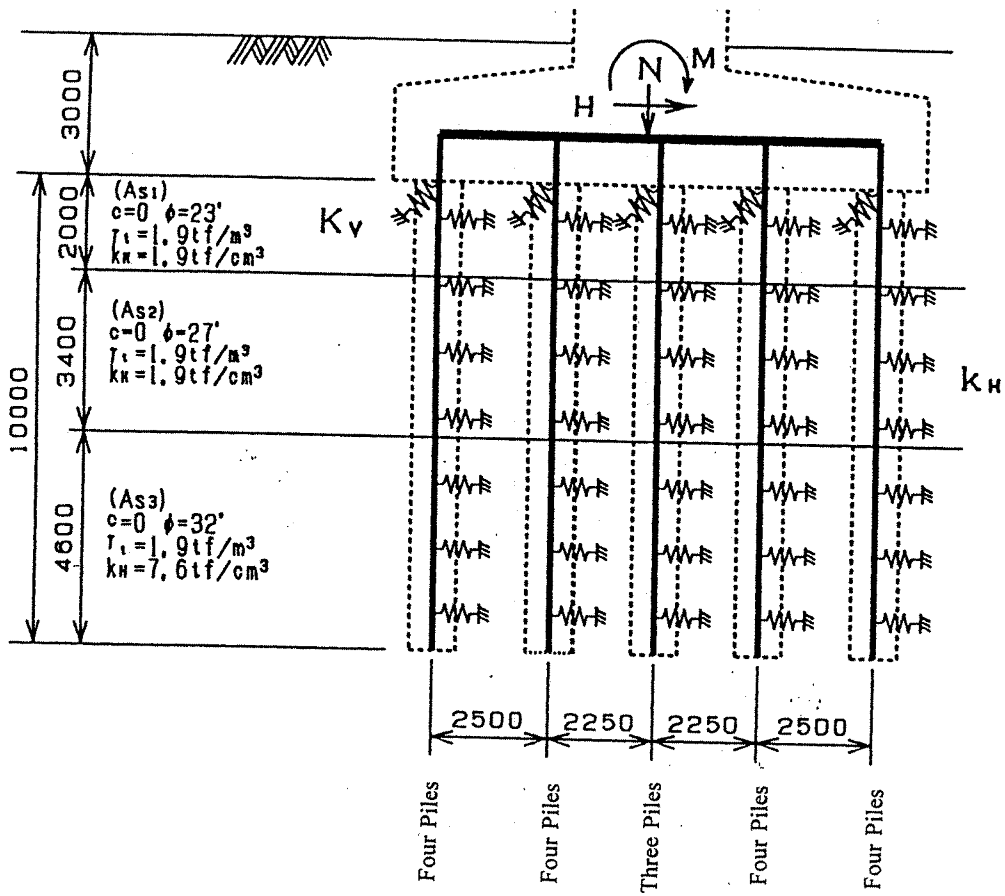
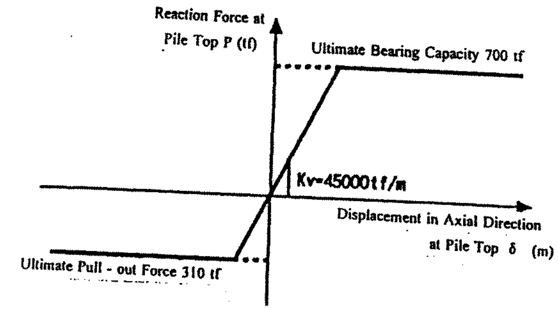
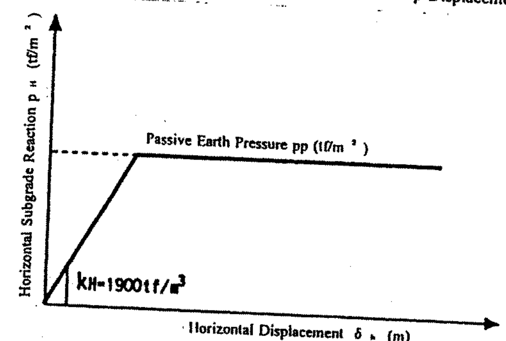


Figure 9 Amount of Loading - Horizontal Displacement Curve for the Horizontal Loading test of the Piles (No.126 Pier)

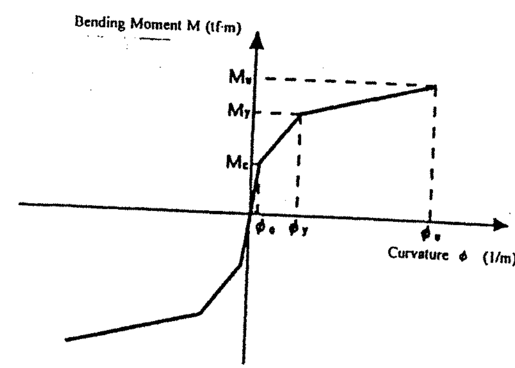




Reaction Force at Pile Top in Axial Direction at Pile Top Displacement



Horizontal Subgrade Reaction - Horizontal Displacement



Bending Moment - Curvature of pile Body

Figure 10 Analytical Model Using a Method Accounting For Non - linear Behavior of Pile Foundations (No.126 Pier)

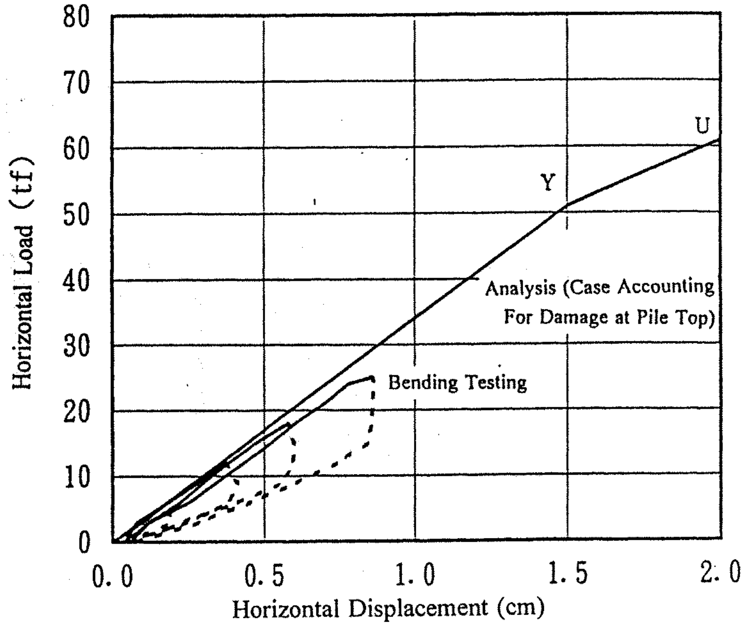


Figure 11 **Horizontal Load** - Horizontal Displacement Curve at the Loading Point During the Pile Bending Test (No.126 Pier)

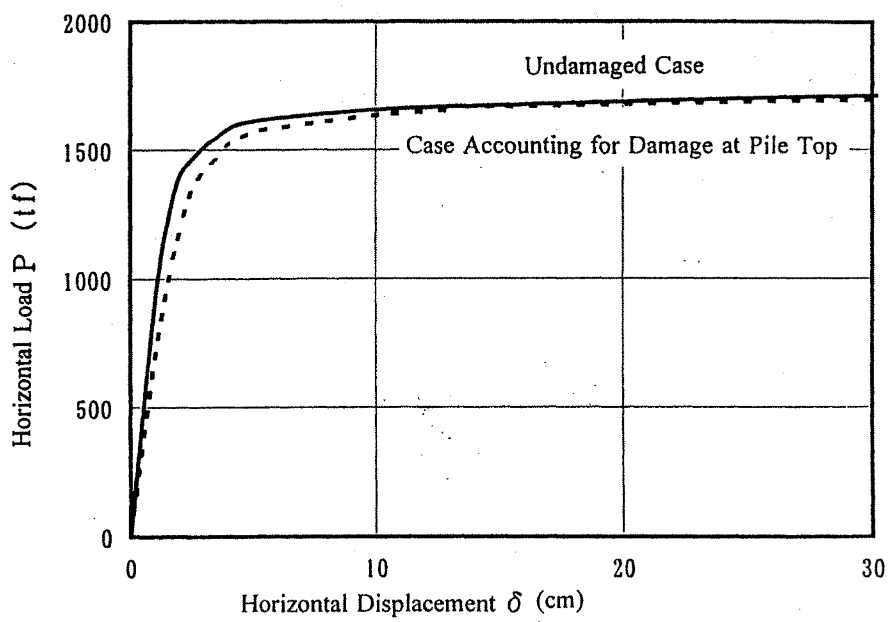
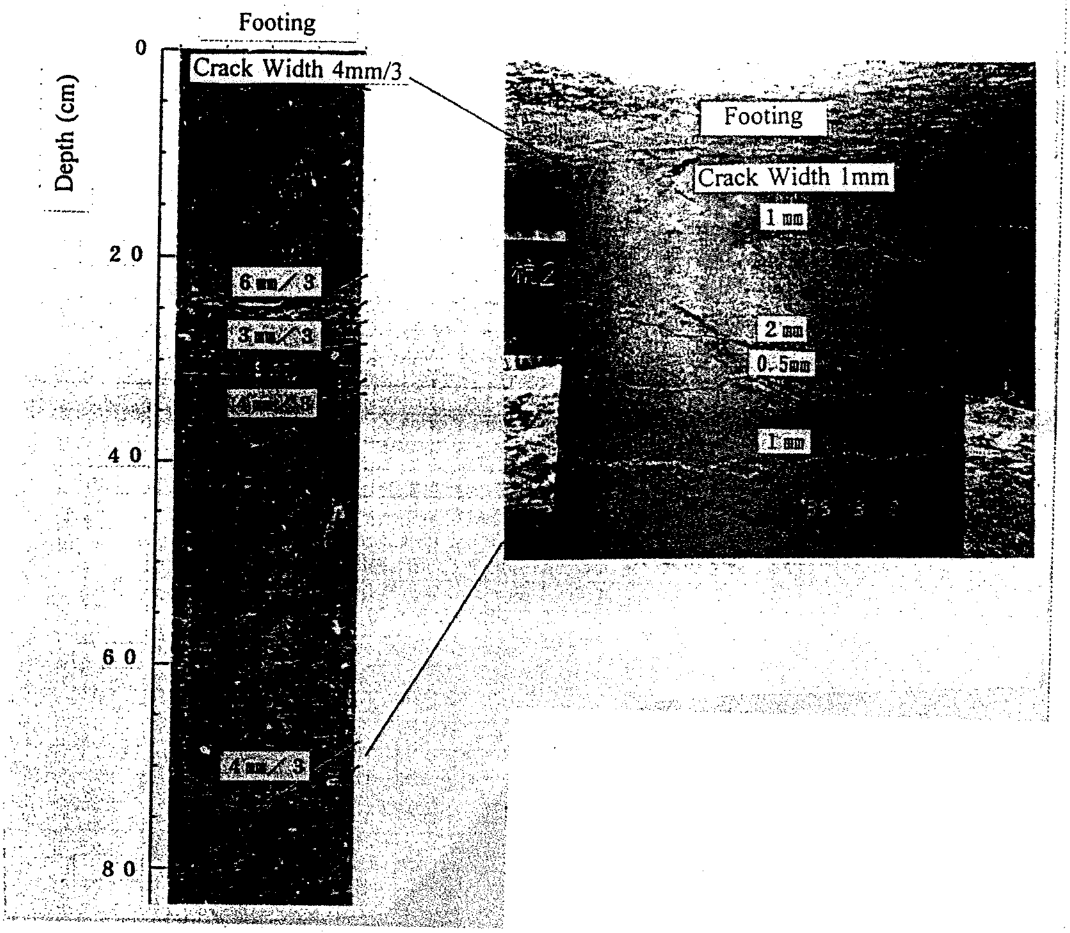
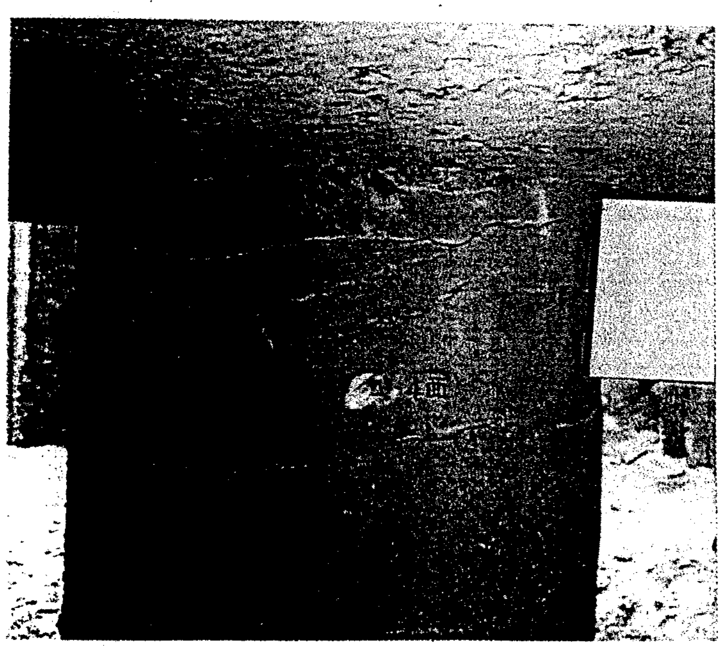


Figure 12 **Effect of Pile Body Damage on the Horizontal Load Horizontal Displacement Curve of the Foundation** (No.126 Pier)



(a) Bore Hole Television System (b) Excavating

Photograph 1 Survey the Damage to Foundations



Photograph 2 Damage to Pile Body (No.126 Pier)