Cement and Concrete Composites 19 (1997) 259–279

0958-9465/97/$17.00

PII: S0958-9465(97)00019-X

Damage to Concrete Piles in Buildings

Koushiro Nagai

Setsunan University, 17-8 Ikeda Nakamachi, Neyagawa-shi Osaka-hu, 572, Japan

Abstract

In the first place, a comparison is made with the distribution on the geomorphological maps of the damage to superstructures and foundations in the quake, then four cases of damage to concrete piles are presented with an outline of the buildings and damage photos with the emphasis placed on the damage to high quality concrete piles due to low ductility. © 1997 Elsevier Science Ltd. All rights reserved.

INTRODUCTION

The Kinki branch of the Architectural Institute of Japan (A.I.J.), which is composed of the members who live in the region hit by the earthquake, collected 180 cases which contain information on the condition of the foundations in the engineered buildings with their superstructures severely damaged or tilted. Their locations were dotted on geomorphological maps and there were about 80 cases among them which detailed what the buildings were and their damage (e.g. the plan, the facade, the details of the foundations and the damage photos), were arranged for the case-sheets. Most of them were cases concerning pile foundations. The working group of the branch also examined pile heads which had been dug out. Of the 12 cases examined, four we have discussed below. Before that, however, a brief overview of the use of pile in Japan is given and also their performance in the 1995 earthquake.

In the foundations of buildings in Japan, H-piles are rarely used and steel pipe piles are also restricted to the particular sites, where

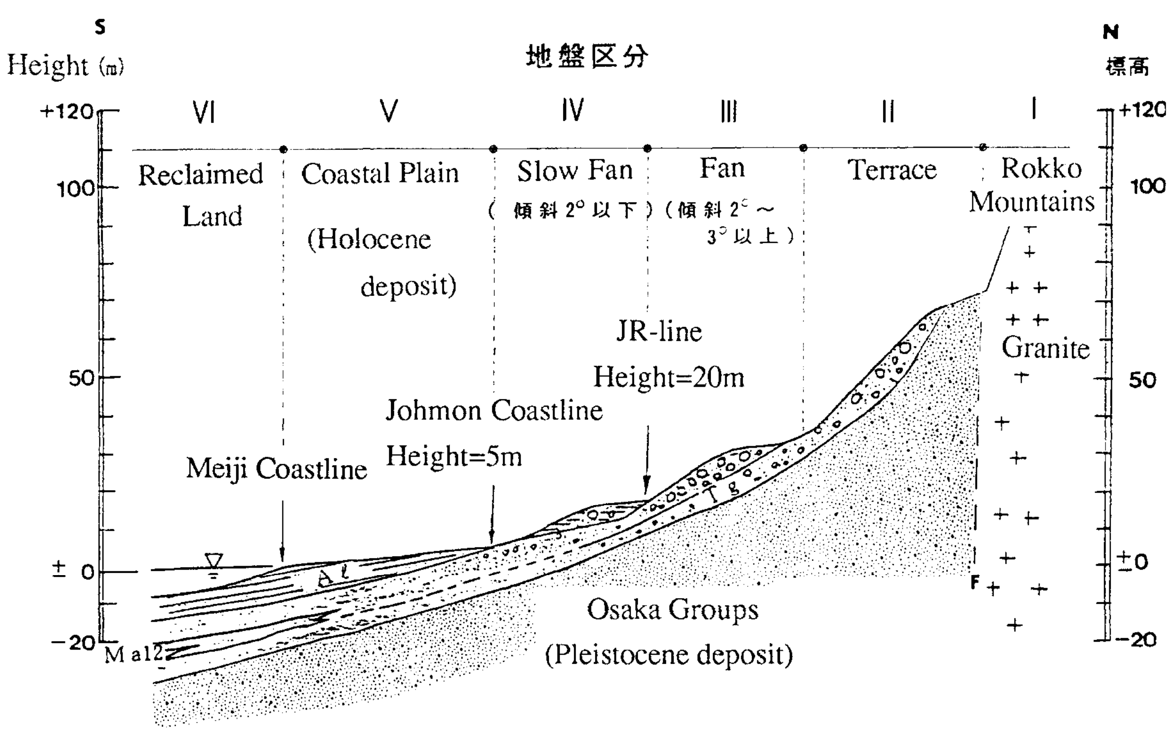

Fig. 1. Geologic cross-section of Kobe.

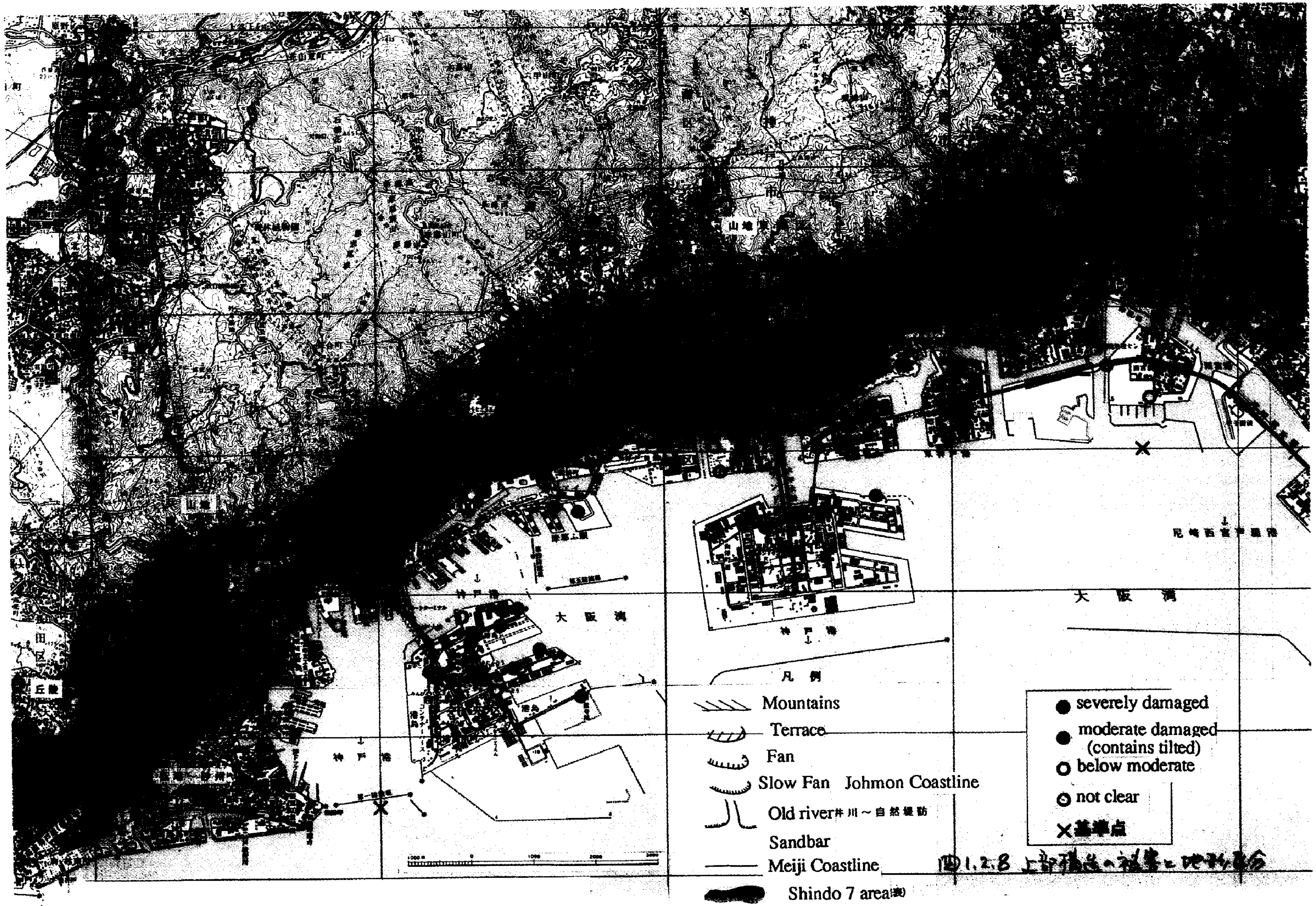

Fig. 2. (a) Distribution of the superstructures severely damaged or tilted.

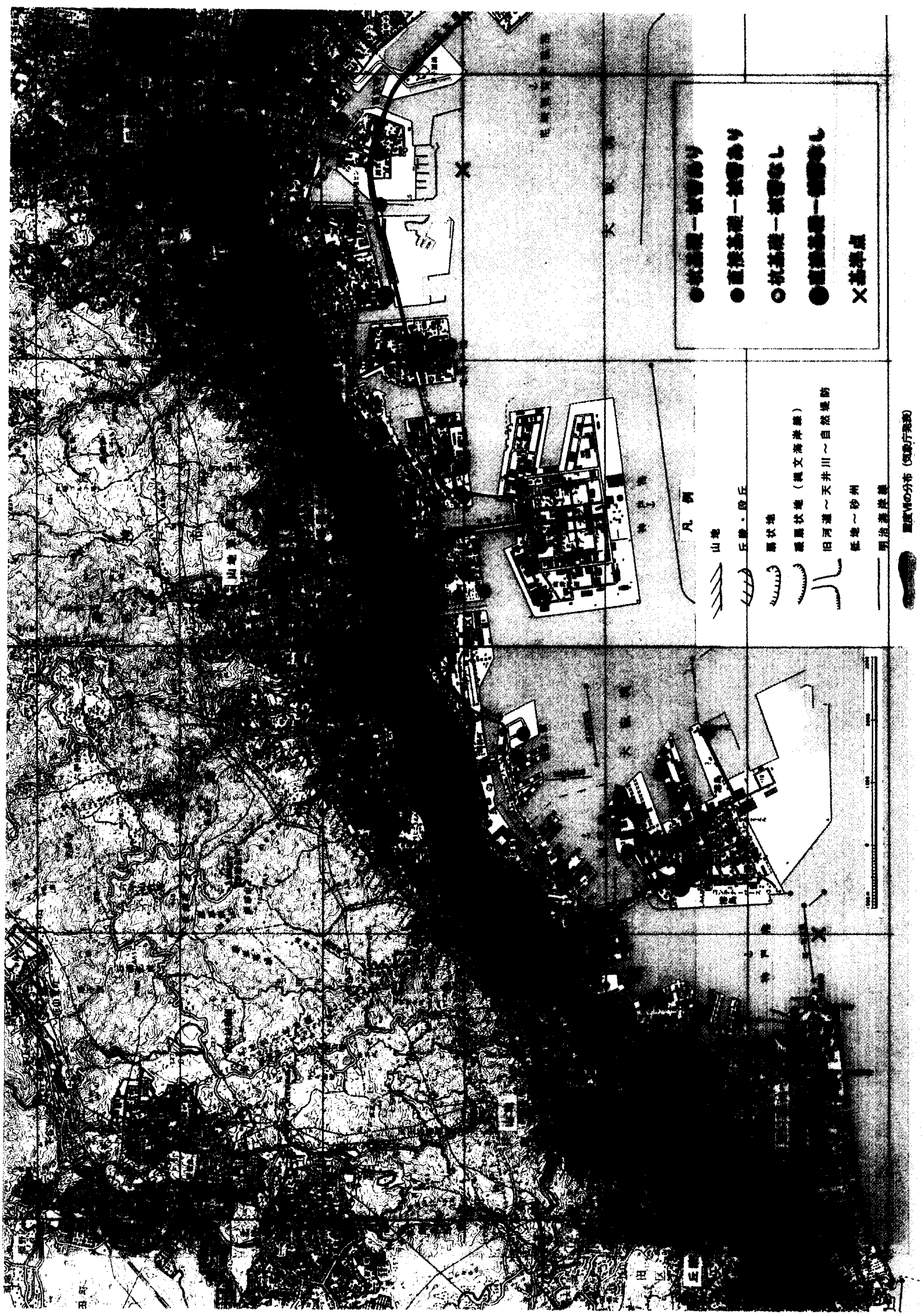

Fig. 2. (b)

Fig. 3. (a) Distribution of damaged or non-damaged pile or spread foundations.

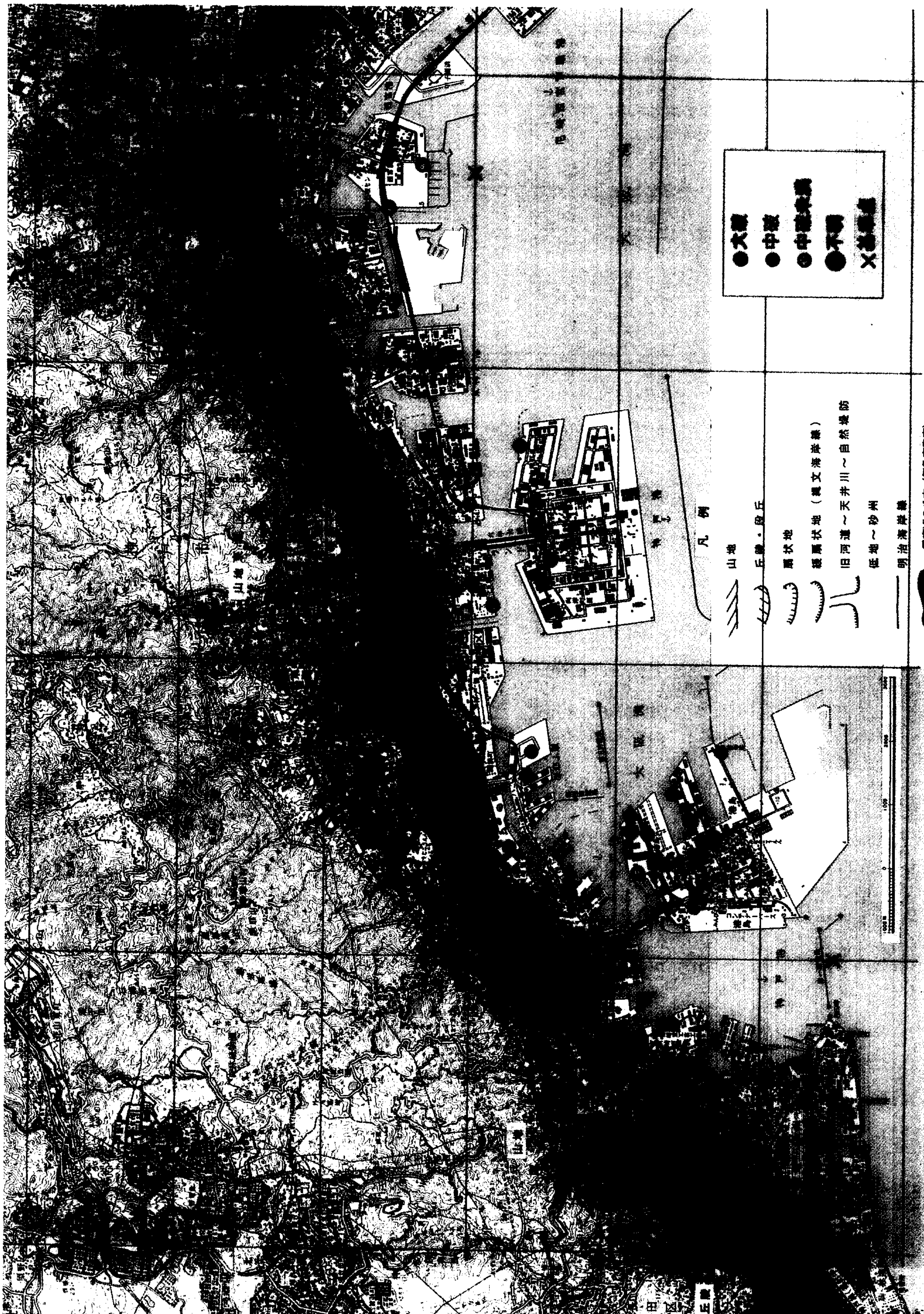

Fig. 3. (b)

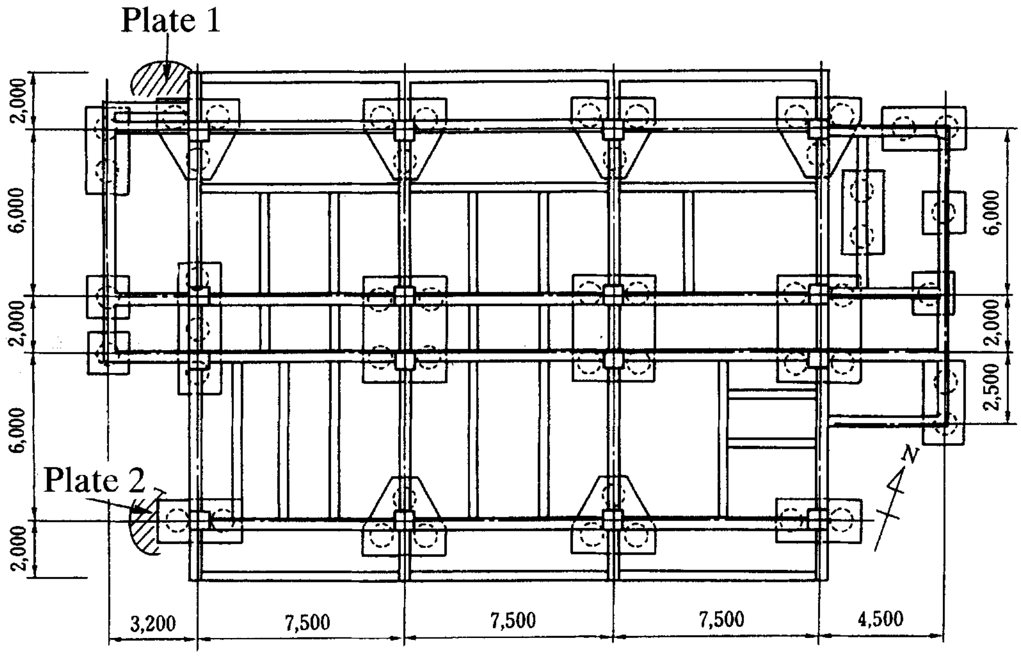

Fig. 4. Foundation plan.

their ductility is available at great expense, such as piers or silos in the seashore and public facilities on reclaimed land where, the liquefaction-induced lateral spreading was noticed in this quake. In a school building on reclaimed land, the steel pipe Piles, $D = 0.5$ m in diameter, $t = 9.5$ mm thick and $L = 30$ m long, were inclined slightly, their bodies appeared sound and cracks were obseved in the pile caps made of reinforced concrete.

A 12-story residential building with cast-in-place concrete piles collapsed as a result of column failures at the fourth story, columns of which consisted of steel-encased reinforced concrete with open web members. The reason for the collapse was assumed to be that the open web' buckled after the concrete was crushed. In the pile heads, which were dug out, no damage

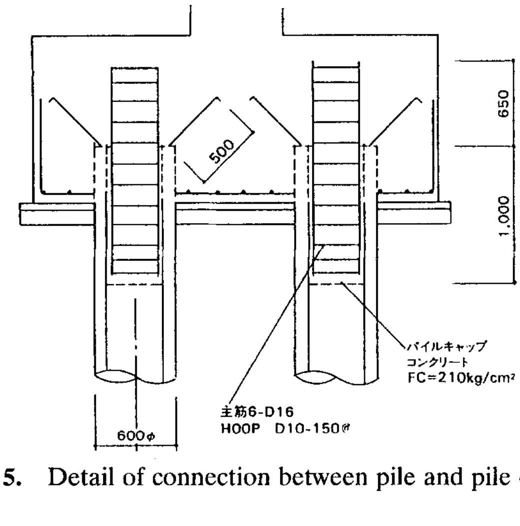

Fig. 5. Detail of connection between pile and pile cap.

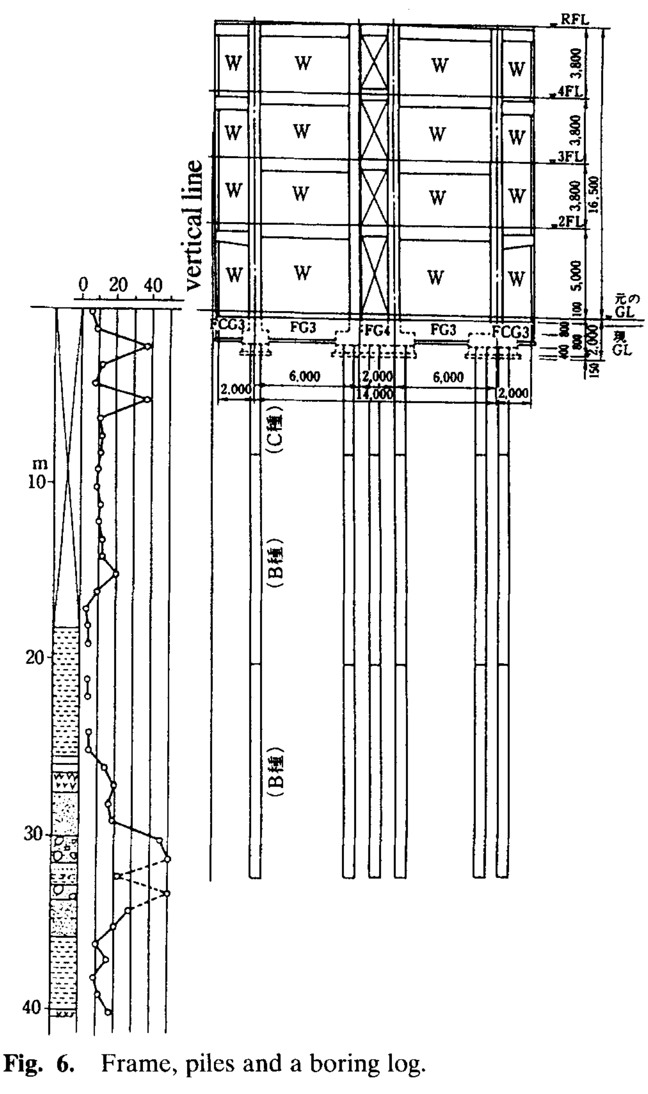

Fig. 6. Frame, piles and a boring log.

Plate. 1. Damage to a pile head in the north.

Plate. 2. Damage to a pile head in the south.

was found. In this case, the columns appeared to be the most brittle among the structure including piles with a 28-day strength of $Fc = 18$ MPa, $D = 1.1$ m and $L = 14$ m.

Fig. 7. Detail of Plate 1.

Fig. 8. Detail of Plate 2.

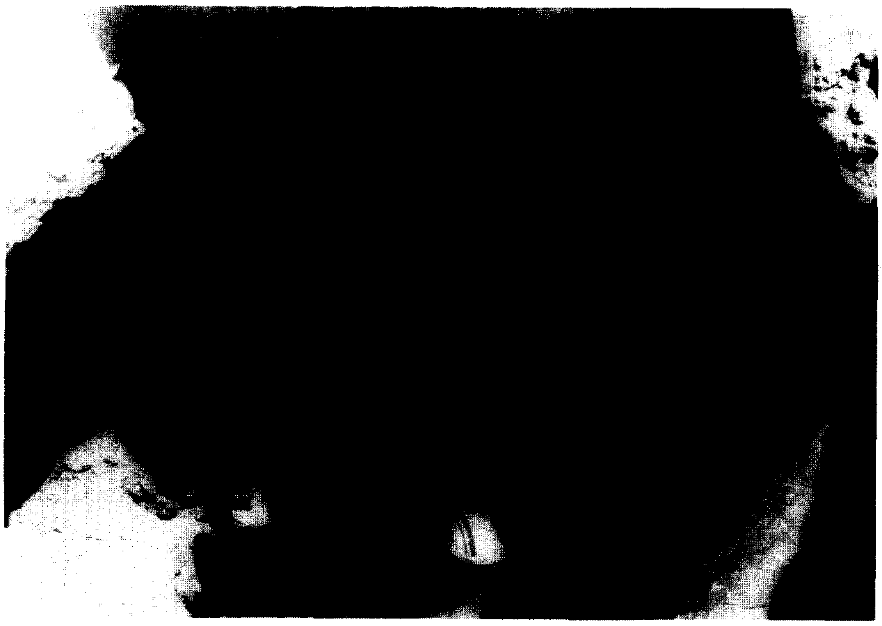

Plate. 3. Cracks in a pile cap in the north side.

Of course, these examples do not mean that piles of these types did not suffer damage. There are cases of local buckling, in the heads of pipe piles and cast-in-place piles whose concrete were cracked and then dropped in the heads. Some of other cast-in-place piles without carrying loads, such as those of the buildings under construction, were fissured horizontaly in the fill. Despite the fact that these are important problems, the striking features of the damage in this quake is that ready-made high-quality concrete (thick-walled cylinder) piles with $Fc = 50 \sim 85$ MPa, prestressed by $4 \sim 1.0$ MPa, usually $D = 0.35 \sim 0.6$ m, which are most utilized among the piles in Japan, were extensively damaged. This suggests that prestressed ready-made concrete piles are less ductile than cast-in-site piles or steel pipe piles.

Four cases that are concerned with the problems of reinforced concrete, which are contained in the report published by the Kinki branch of A.I.J.,[1] are presented in this paper, with emphasis placed on the damage to high quality concrete piles. The overview of the extensive damage to the foundations and piles are found in Tokimatsu *et al.*[2]

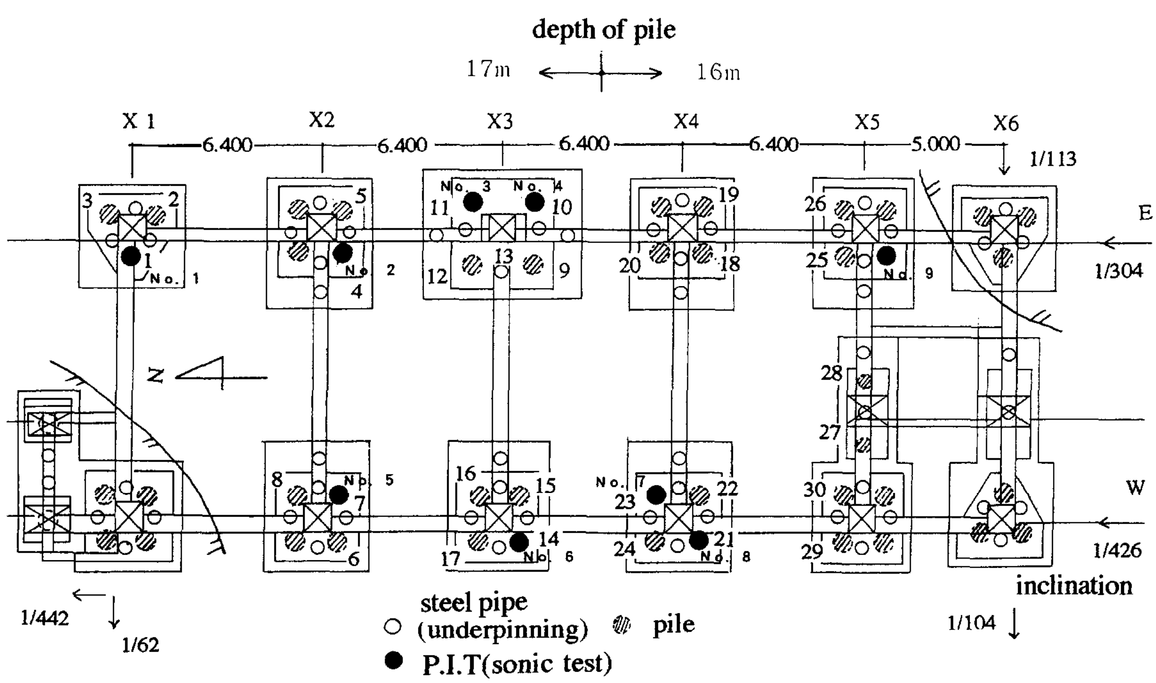

Fig. 9. Plan of pile foundations and values of building inclination.

DISTRIBUTION MAP OF THE DAMAGE TO FOUNDATIONS

A typical geologic cross-section of Kobe is shown in Fig. 1. In the above report, each of the numbers I ~ VI in the figure indicate the zoning of ground conditions of the building site. Figure 2, shown in the same report, shows the distribution of the engineered buildings whose superstructures are severely damaged or tilted in the main. It should be noted that the data in this figure are only a fraction of the entire number of cases, such as the above intensities of damage. The severely damaged buildings (marked red on the map) are concentrated in the Shindo 7 area, the severest intensity area of the damage to the wooden houses recorded by the Japanese Meteorogical Agency, which are ranged extensively in/along the zone IV of slow or alluvial fan.

Figure 3 shows the distribution of the damage or non-damage to each foundation type, i.e. spread foundation or pile foundation. Pile foundations are concentrated in the coastal plain and on the reclaimed land (zone V and VI), whereas the spread foundations, which are fewer, are scattered over the entire region. In comparison with the distribution of the damage to buildings in Fig. 2, the cases of damage to foundations, which are mainly damage to pile foundations, range in the zones V and VI out of Shindo 7 area. When we compare Figs 3 and 2 we observe less data in the Shindo 7 area in the former: the main reason being that the heavily damaged buildings, such as collapsed ones, have been demolished without surveying the damage to the foundations. We can only say that many pile foundations, which suffered from liquefaction-induced lateral spreading, were surveyed in order to restore on reclaimed land and a lot of damage including slight damage of pile heads was observed. There are also cases of heavy

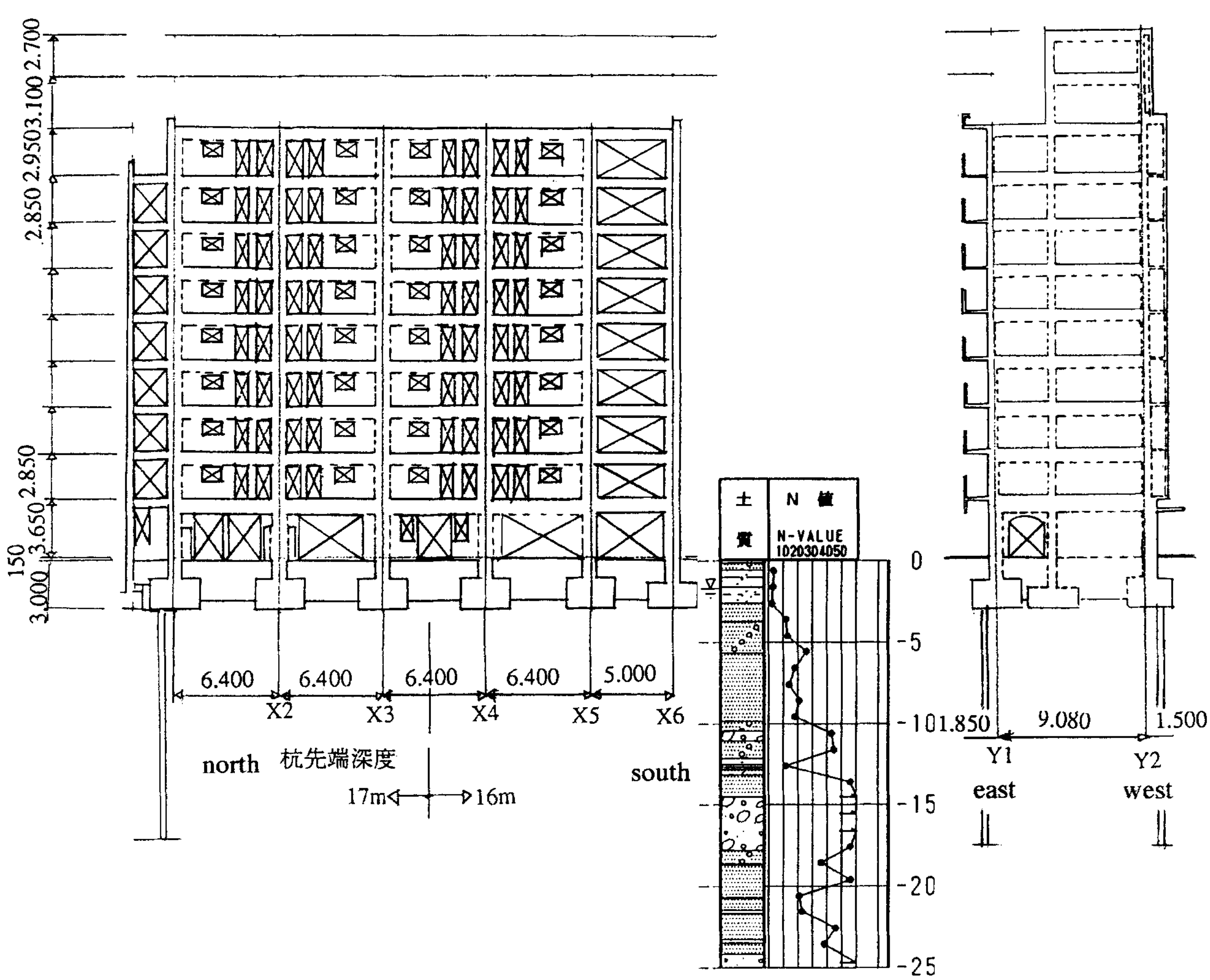

Fig. 10. Frame, pile and a boring log.

damage that involve important problems of reinforced concrete in zone IV, one of which is presented later in this paper.

HIGH QUALITY CONCRETE PILES IN THE RECLAIMED ISLAND (COMPLETED IN 1979)

Let us now examine the first of the detailed case studies. The high quality concrete piles with $Fc = 80 \sim 85$ MPa, $D = 0.6$ m and $L = 33$ m, supported the four-story reinforced concrete office building, the superstructure of which, remaining intact, tilted towards the sea (the north) by $1/70 \sim 1/75$. The site is located in the geological zone VI in Fig. 1. The foundation plan of the building is shown in Figs 4 and 5 shows the detail of connection between the pile head and pile cap.

In Fig. 6, the frame which is tilted by 1/70, piles which have inclination of 1/24 (observed) and a boring log are shown. The pile has three segments. The upper segment is a 'Type C'

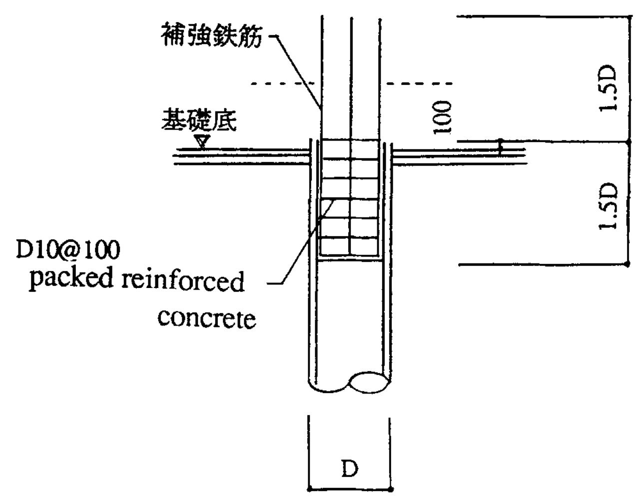

Fig. 11. Detail of connection between pile and pile cap.

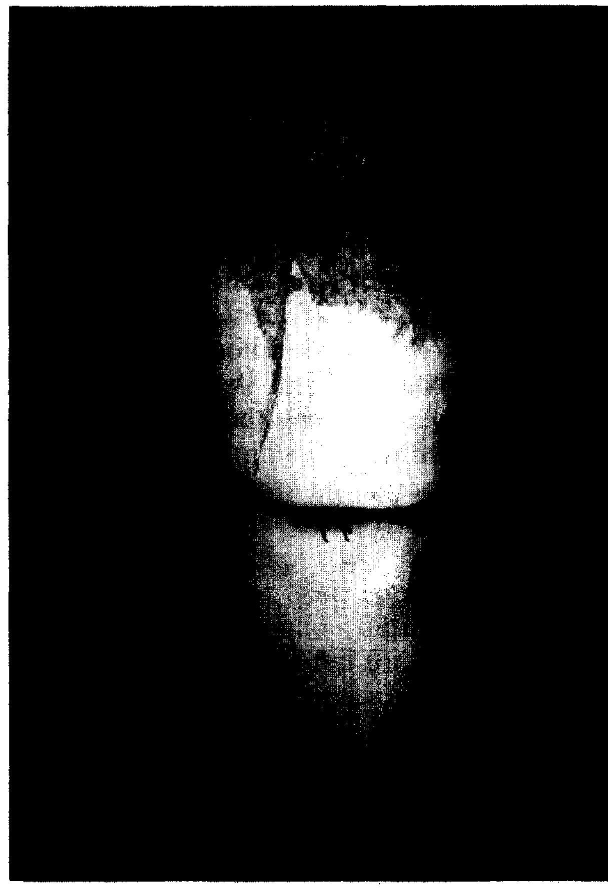

Plate. 4. Cap W-X2 (pile no. 7).

Plate. 5. Cap E-X2 (left: pile no. 4. right: pile no. 5).

Plate. 6. Cap E-X3 (from left: pile no. 11, 13, 12).

which is prestressed by 10 MPa, the middle and the lower are a 'Type B' prestressed by 8 MPa.

The pile head dug out in the north side of the building had been compressed to failure and packed reinforced concrete (see Fig. 5) in the head appeared as shown in Plate 1. In the pile head in the south side, tension cracks were noticed as shown in Plate 2. In Figs 7 and 8 which show fissures or wrinkles, invisible in the above photos, we can see the longitudinal fissures along the tension bars (in Fig. 7) and ones caused by the packed concrete (in Fig. 8), Plate 3 shows cracks in the pile cap in the north side.

Although ground failure was not found in this site, this region was liquefied and the nearby quay wall failed because of lateral spreading. We should assume that the pile heads moved north towards the sea. In addition,

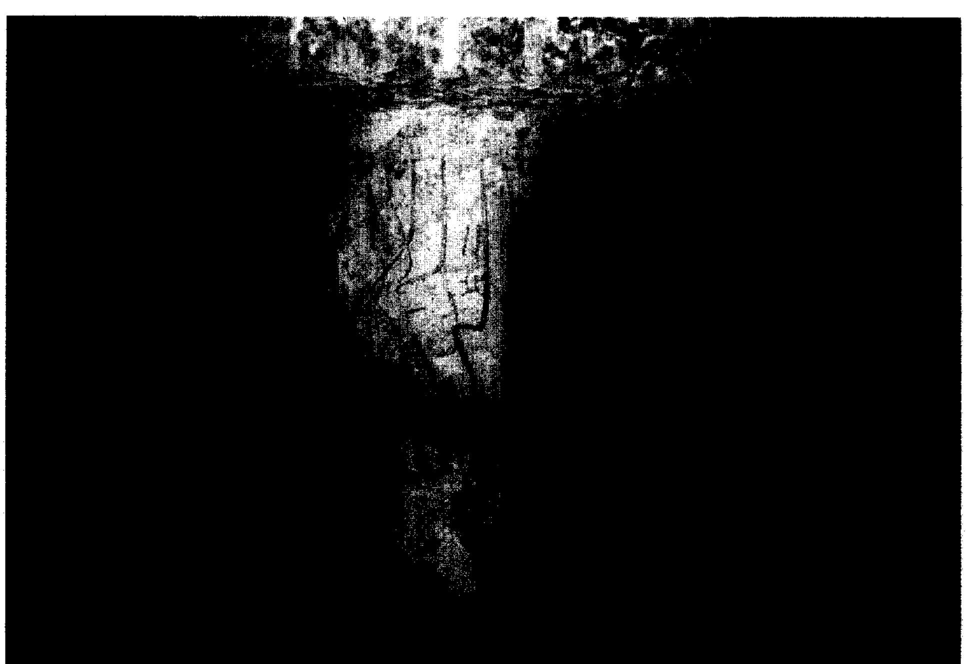

Plate. 7. Cap W-X3 (pile no. 16).

the inertia force acting on the shear wall caused a large shear force and large axial force on the pile heads under the conditions of soil liquefaction of their foundation soils.

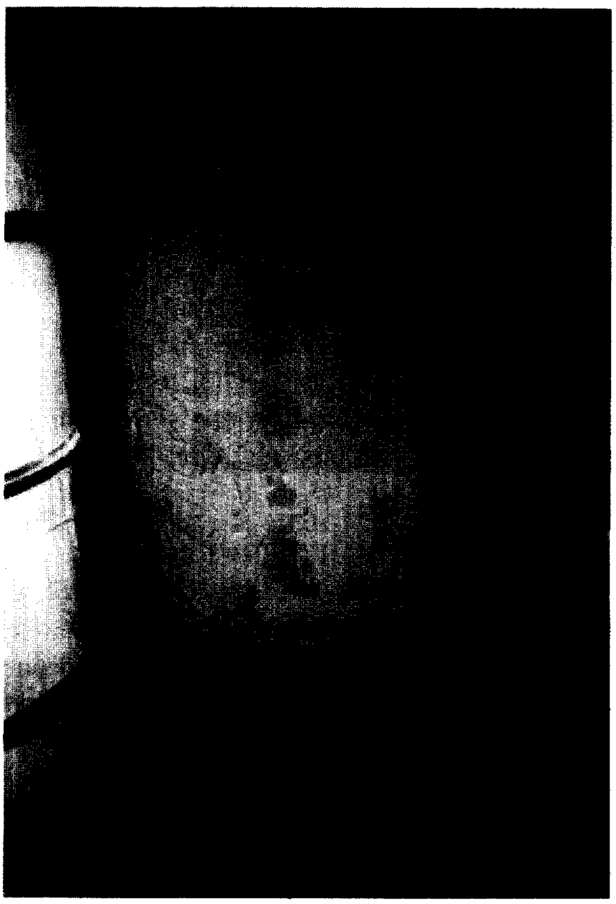

Plate. 8. Cap E-X3 (pile no. 9).

HIGH QUALITY CONCRETE PILES SUPPORTING A HIGH ASPECT RATIO BUILDING (COMPLETED IN 1987 ~ 1989)

The second detailed case study is given. The high quality concrete piles, $D = 0.6$ m, $L = 16 \sim 17$ m supported the nine-story steel encased reinforced concrete residential building. The site is located in the geological zone V-alluvial fan in Fig. 1. In this site, soil liquefaction was not observed. In Fig. 9, the plan of pile foundations and also the values of inclination of the building are shown. The building was inclined towards the west, remaining intact except that non-structural partitions were fissured.

The sections of the building are shown in Fig. 10 with piles and a boring log. The aspect ratio in the east–west section is about three excluding penthouse height. The detail of the connection between pile head and pile cap is shown in Fig. 11. The pile has two segments. The upper, 9 m long, was a 'Type B' and the lower was a 'Type A', which was prestressed by 4 MPa. As the pile head had been cut off by $1.5 \sim 2$ m, pressure did not exist corresponding to that of a 'Type B', 8 MPa.

The damage to the piles is shown in Plates 4–10. Plates 4, 7 and 9 show the damage under the west side pile caps and the Plates 5, 6, 8 and 10 show the east side damage. From these photos, we can see that the damage to the piles in

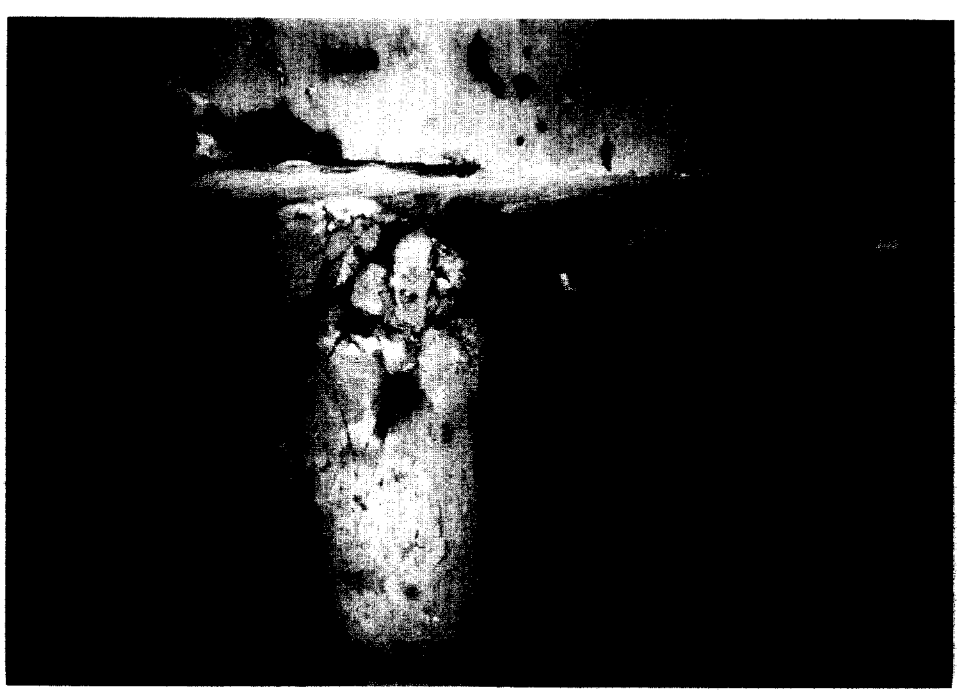

Plate. 9. Cap W-X4 (pile no. 21).

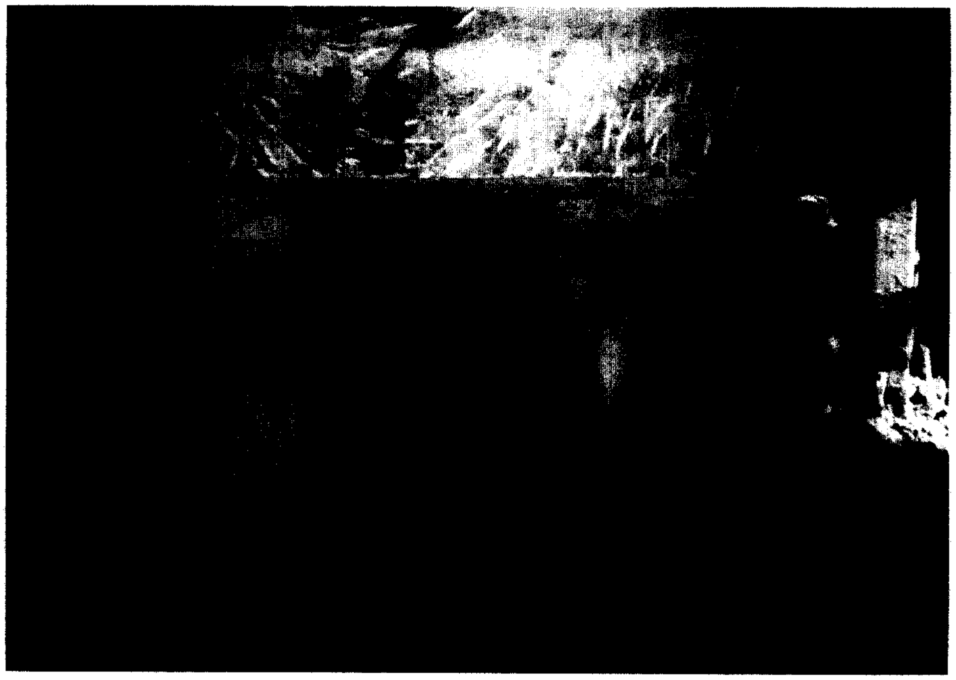

Plate. 10. Cap E-X4 (left: pile no. 20, right: pile no. 18).

the west side is heavier than in the east side, in which sound piles also exist.

One possible cause of the heavy damage to the piles is that pile heads, which were released from stress state, were easily torn and sheared by the packed reinforced concrete (see Fig. 11), but there is another, more important cause as follows.

PROBLEMS OF THE HIGH QUALITY CONCRETE PILES

Typical transverse and longitudinal sections of high quality concrete pile are shown in Fig. 12. There are three kinds of piles which have the different number of deformed steel bars/wires to introduce different values of prestress. The thin spiral wire, about $3 \sim 5$ mm in diameter, which in the figure, fixes the position of the steel bars, is not expected to confine the concrete. As a result, the pile suffer partial disintegration (see Plate 1).

Theoretical relation between the bending moment M and curvature ϕ imposed on the pile carrying various axial forces are shown in Fig. 13. The figure indicates that the concrete and the steel bars tend to yield at the same time, with decreasing curvature as axial force increases. This means that the more the pile head is compressed, the less ductile it becomes. Though this fact is verified with loading test of columns in superstructures, it is not familiar to the pile foundations in soils.

Usually, these facts combine with the following conditions. The pile head and pile cap are connected loosely to each other as shown in the Fig. 11, because it is difficult that a pile head is well enbedded in the pile cap owing to the existence of steel bars of the pile cap. If such a loose connection is compressed with great axial force, it will be fixed tightly. Therefore, in the

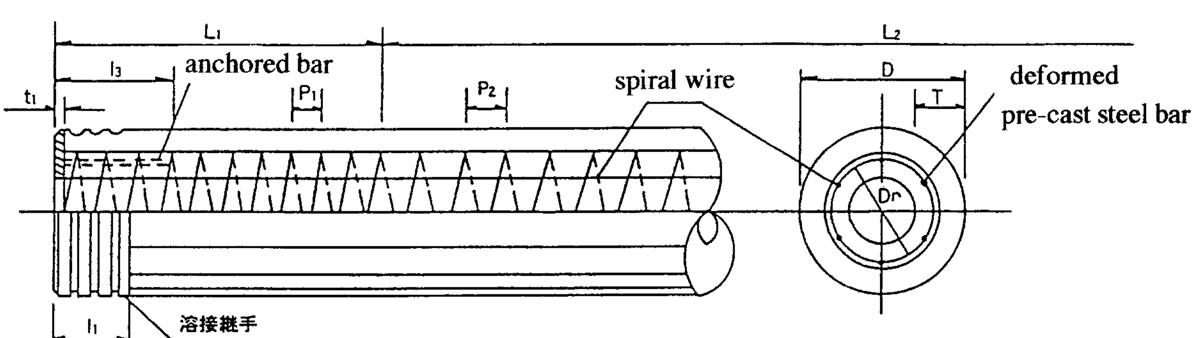

Fig. 12. Sections of high quality concrete pile.

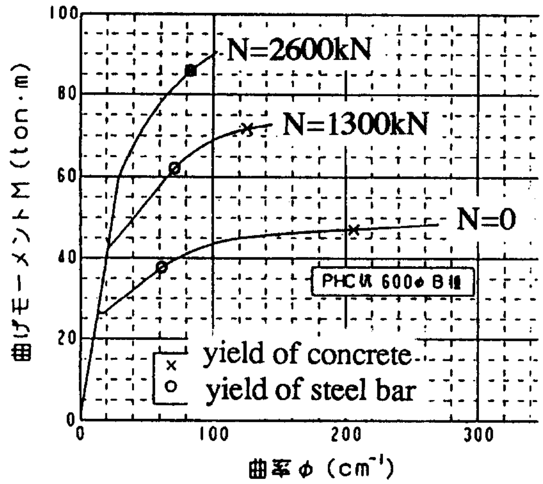

Fig. 13. $M \sim \phi$ relations under the various axial forces.

above case we should assume that the concentration of inertia force in the west side pile caps resulted from the large axial force with subsidence caused by large overturning moment due to a high aspect ratio.

BREAKAGE AT THE LOWER END OF STEEL PIPE ENVELOPING CONCRETE PILE (COMPLETED IN 1989)

The third case follows. The high quality concrete piles, $D = 0.5$ or 0.6 m, $L = 31$ m, has three segments, the upper concrete segment of which was enveloped by steel pipe, 6 m long, considering the aseismatic design and the lowest

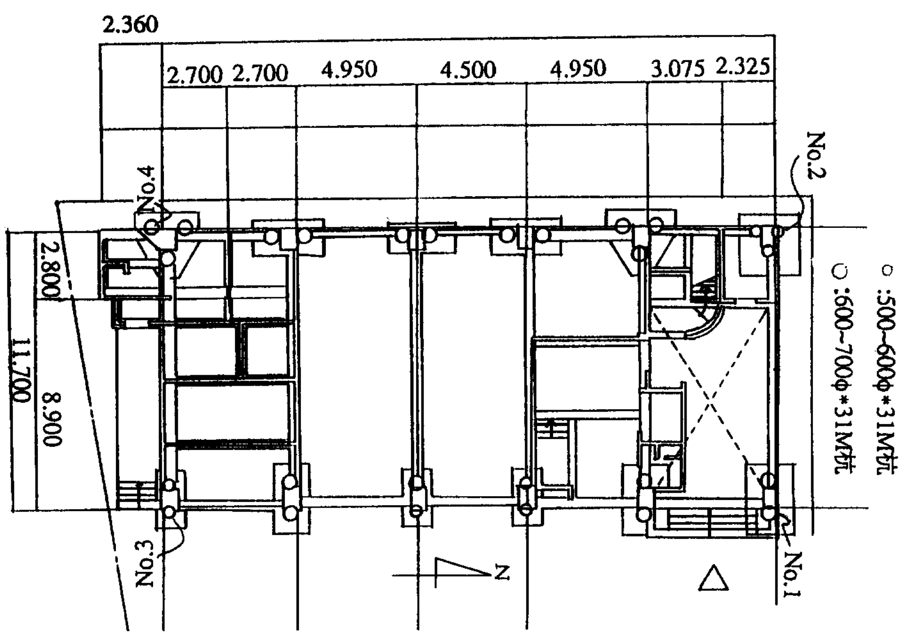

Fig. 14. Plan of pile foundation.

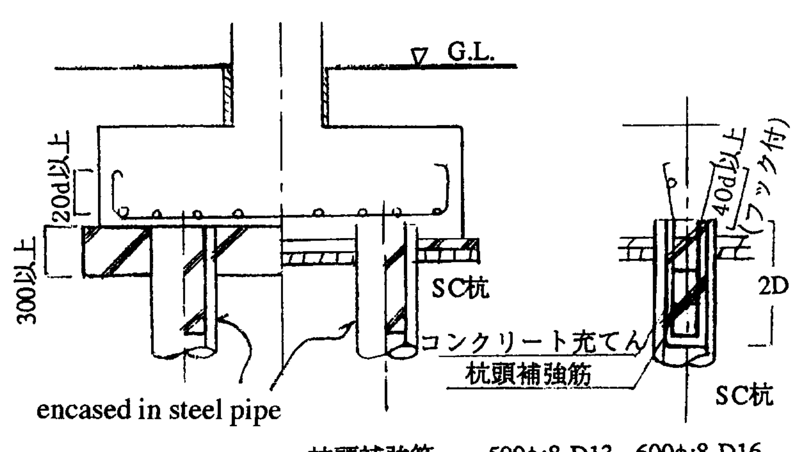

Fig. 15. Detail of connection between pile and pile cap encased in steel pipe.

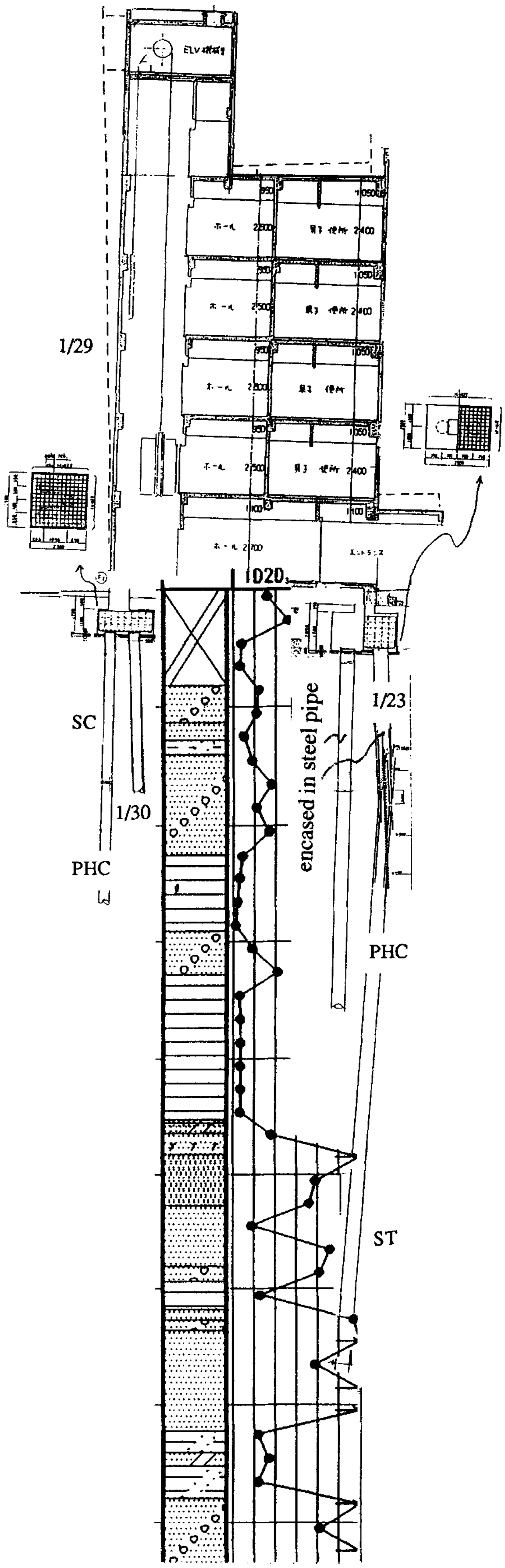

Fig. 16. Frame, piles and a boring log.

segment of which is spreading at the toe, $D = 0.6$ or 0.7 m, for increasing the bearing capacity. The site located in the geological zone VI in Fig. 1.

The plan of the pile foundation is shown in Fig. 14, piles of which are laid out according to the load carried from the column. The detail of connection between pile head and pile cap is shown in Fig. 15. The superstructure with prestressed precast concrete beams, remaining intact, tilted towards the north–east as shown in Fig. 16. The breakage in the figure at the lower end of steel pipe was surveyed by boring through the pile cap. Every pile that was dug out at the No. $1 \sim 4$ of pile cap has an inclination of $1/23 \sim 1/30$ towards the west and of 1/60 north. These directions correspond to the movement of the ground surface. A pile head is shown in Plate 11 in which the concrete of a pile cap was torn and then dropped, leaving steel bar for installation exposed. It is assumed that the breakage resulted from the movement of soil surface due to soil liquefaction.

CRACKS IN CAST-IN-PLACE CONCRETE PILES UNDER THE BASEMENT (COMPLETED IN 1973)

The last case is not the ready-made concrete pile. The cast-in-place concrete piles, $D = 1.1 \sim 1.2$ m and $15 \sim 16.6$ m supports the steel-encased reinforced concrete office building with eight stories above ground and one below. The site located in the geological zone V–coastal plain in Fig. 1 and in this site soil liquefaction was observed.

Figures 17 and 18 show, respectively, the section and plan of the building. In Fig. 19, the elevation and a section of the steel bar arrangement in the pile are shown. A pile was cored down to a depth of 12.4 m from the first basement floor and a television observation was made. Plates 12 and 13 show that several horizontal cracks appeared at a depth of about 10 m as well as near the pile heads. This suggests that the alluvial deposit down to a depth of about 10 m might have liquefied and slid leading to the failure of piles. It was noticed that the ground water flowed into the bored hole through the fissures.

Figure 20 shows, with a boring log, lateral maximum displacement of soils obtained from

Plate. 11. Concrete of pile cap was torn and dropped.

nonlinear effective stress analysis. Large relative displacement between the head and middle height is 1/50 and the portion of the middle height of the pile, in which fissures of no. 4$\sim$9 were found, is not displaced relatively. According to the result, the maximum bending moment appeared at the middle height; it is unclear whether only the repeated bending moment caused the fissures which reach to the center of the pile without force being sufficient

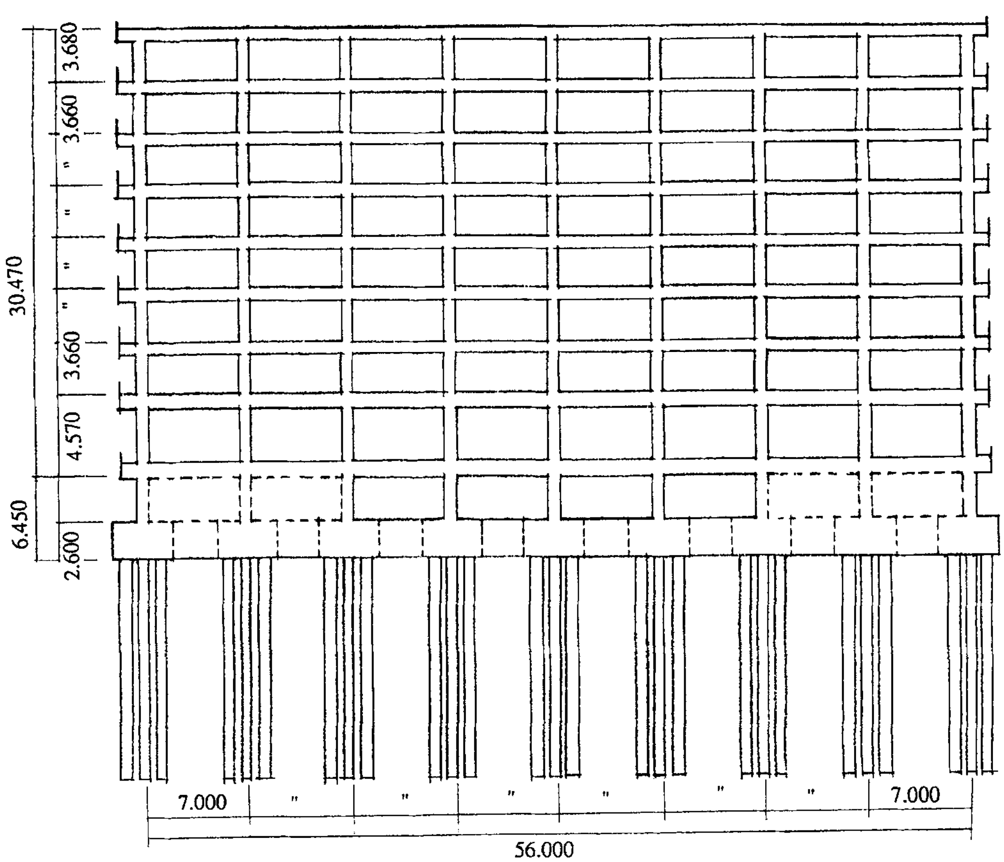

Fig. 17. Section of the building.

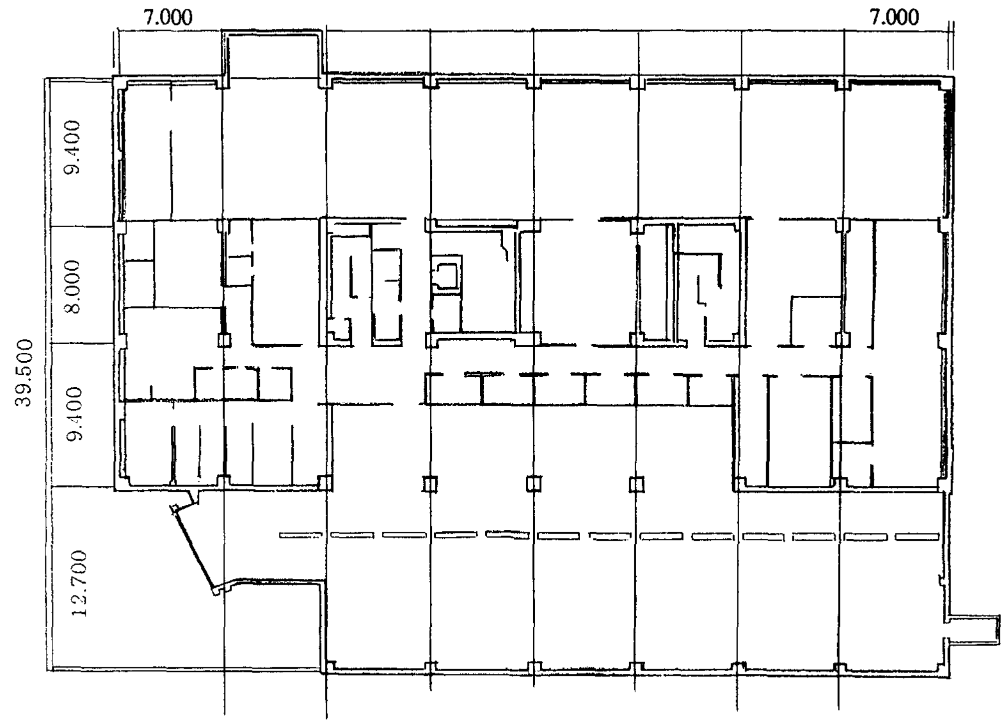

Fig. 18. Plan of the building.

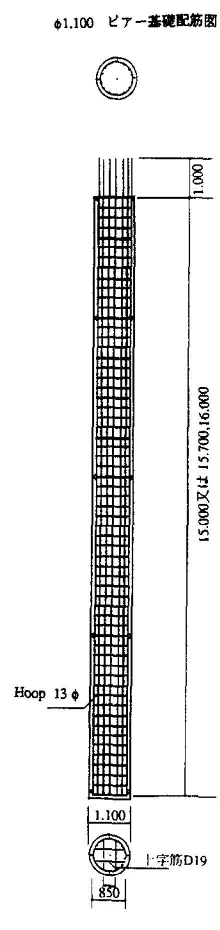

Fig. 19. Steel bar arrangement in the pile.

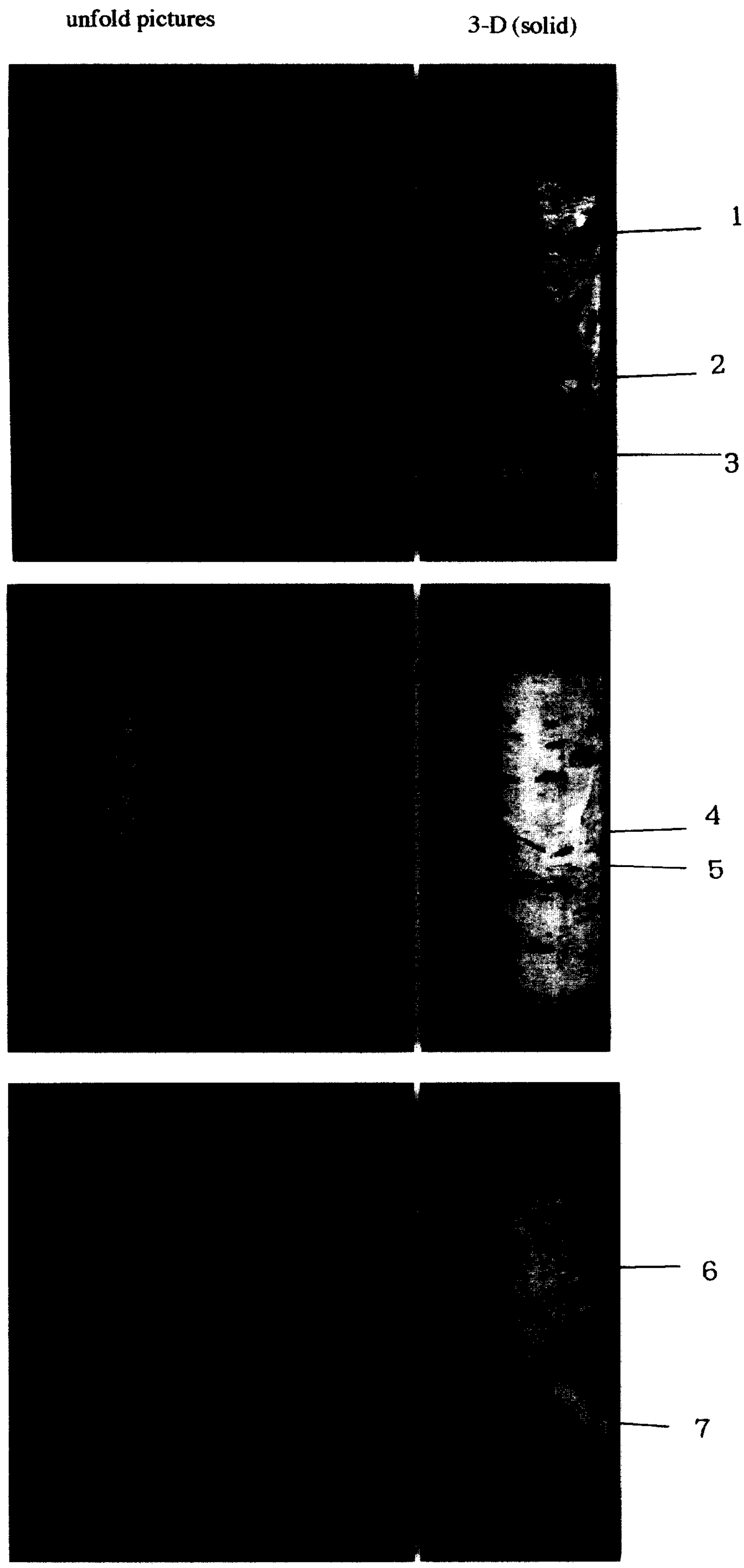

Plate. 12. Cracks detected by television observation (1).

to be sheared or stretched. It would become clear if the fissured portion could be dug out.

CONCLUSION

In comparison with the distribution of damage to superstructures, which are severely damaged in the slow fan, the damage to foundations, which mostly means the damage to piles, appears to be concentrated in the coastal plain or reclaimed land, because the severely damaged buildings have been demolished without surveying the damage to the foundations. Three cases of the damage to high quality concrete piles were presented in this paper. The first of them in the reclaimed land is a case of large axial force being applied on the pile head under a structural wall. The second of them in the slow fan suggests that high quality concrete piles in the buildings with high aspect ratio, such as residential buildings, might also suffer damage under the large axial force. This involves the problem of the connection between

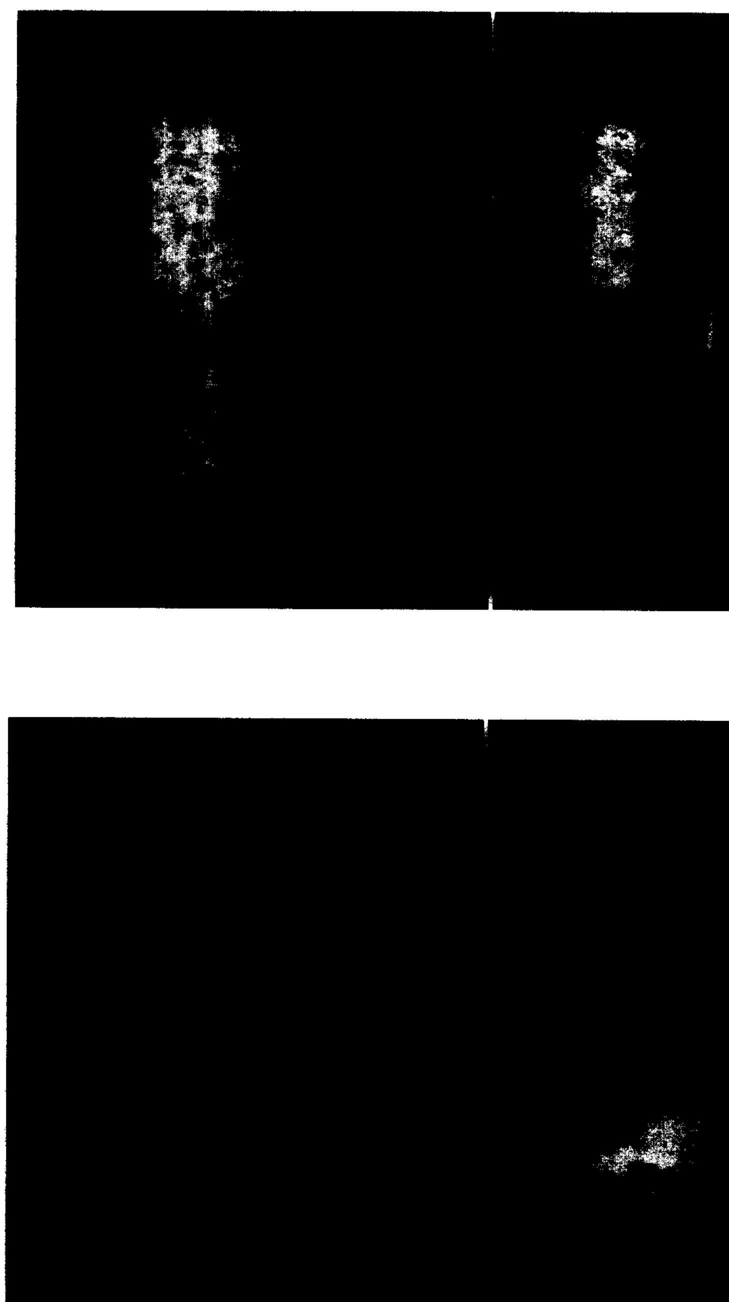

Plate. 13. Cracks detected by television observation (2).

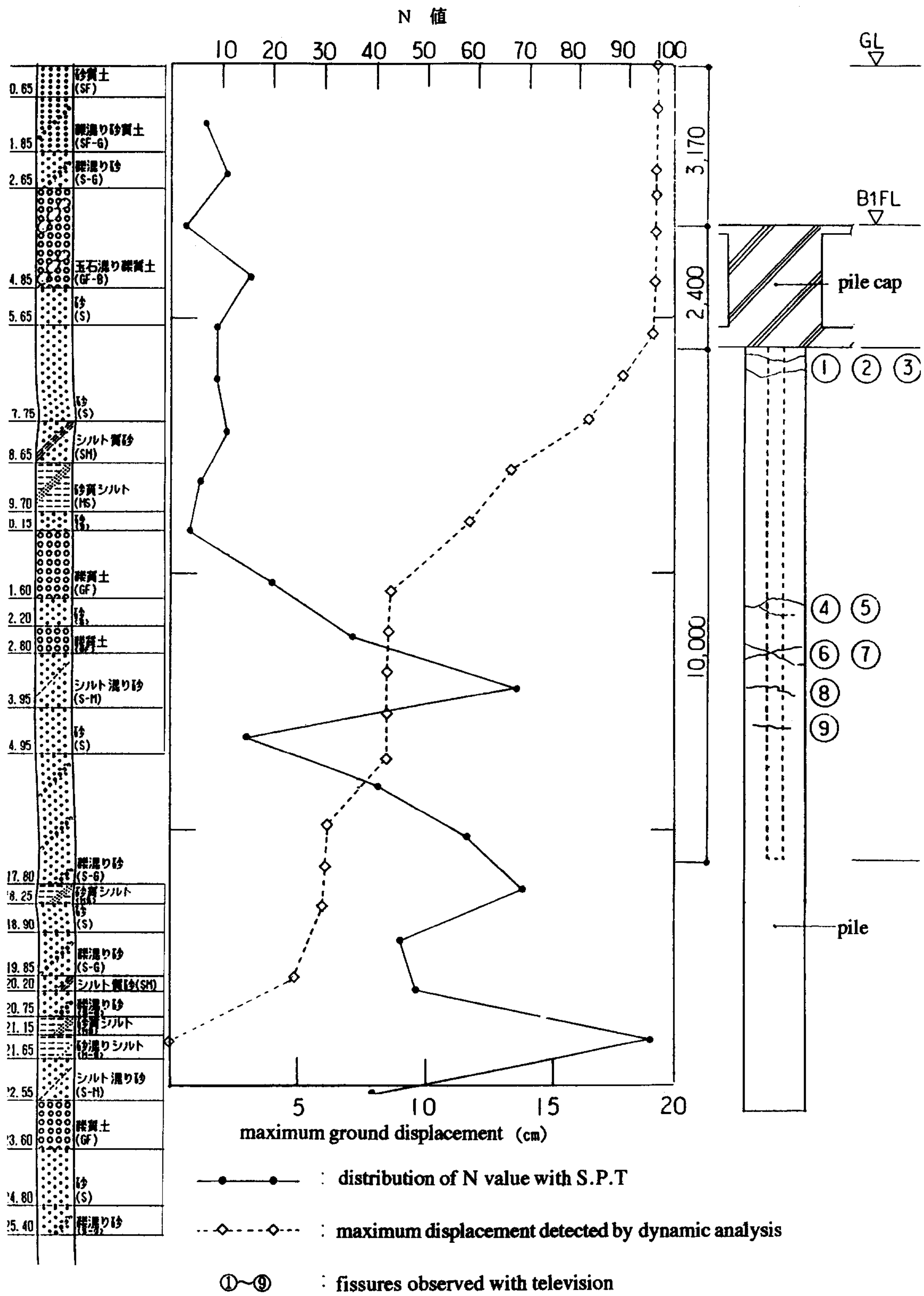

Fig. 20. Analyzed lateral maximum displacement and a boring log.

the pile and the pile cap and low ductility of high quality concrete pile. On the other hand, the pile encased in steel pipe, which is ductile enough in the head, was broken at the low end of the pipe as shown in the third example. In the fourth case, it is difficult to show clearly what caused fissures reaching to the center of the cast-in-place pile, a pile type which otherwise appeared to perform well in this quake.

REFERENCES

1. The Kinki branch of A.I.J., *The report of the cases searching the damage to foundations in buildings due to Hyougoken Nambu Earthquake.* The Kinki branch of

the Architectural Institute of Japan, July 1996 (in Japanese).
2. Tokimatsu, W., Mizuno, H. and Kakurai, M., *Building damage associated with geotechnical problems*. Special issue of Soils and Foundations on geotechnical aspects of the January 17 1995 Hyougoken-Nambu earthquake, Japanese Geotechnical Society, January 1996, pp. 129–234.