16th World Conference on Earthquake, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 1354 (Abstract ID)
Registration Code: S- P1463134928

Study on damage to cast-in-place reinforced concrete piles during the 1995 Hyogo-ken Nanbu Earthquake in Japan

R. Tanaka(1), M. Iiba(2), K. Kobayashi(3), S. Sasaki(4), T. Hirade(5), H. Kashiwa(6)

(1) *Master of Engineering, Fujita Corporation, ryoichi.tanaka@fujita.co.jp*
(2) *Doctor of Engineering, Professor, Hokkaido University, iiba-m@eng.hokudai.ac.jp*
(3) *Doctor of Engineering, Fujita Corporation, katsumi.kobayashi@fujita.co.jp*
(4) *Doctor of Engineering, Fujita Corporation, ssasaki@fujita.co.jp*
(5) *Doctor of Engineering, Building Research Institute, hirade@kenken.go.jp*
(6) *Doctor of Engineering, National Institute for Land and Infrastructure Management, MLIT, kashiwa@kenken.go.jp*

Abstract

This paper reports the results of investigations into the cast-in-place reinforced concrete piles of an 8-story steel reinforced concrete structure that were damaged by the 1995 Hyogo-ken Nanbu Earthquake in Japan. The damage to the piles could be observed during seismic isolation retrofit work on the building 18 years after the earthquake. Almost all the piles were damaged. Initially, pile damage was classified into four categories based on the degree of cracks in the concrete and damage to the reinforcing bar. Each category of damage was explained in detail. Subsequently, the damage was summarized and the factors behind the damage to the piles were considered.

Keywords: Cast-in-place reinforced concrete pile, Damage of piles during earthquake, Factors of damage to piles

1. Introduction

In 2012, seismic isolation retrofit work was carried out on an 8-story steel reinforced concrete structure building in Kobe. At the time of this construction work, damage to the piles of this building was observed. It is known that the Hyogo-ken Nanbu earthquake (Mw = 6.9) occurred in Kobe, Japan in 1995. This earthquake struck numerous structures in Kobe and neighboring cities.

After the earthquake, an urgent investigation of the damage to this building was carried out in the same year. This investigation reported the following [1]:

- Liquefaction of soil occurred around the site of the building
- Despite ground subsidence around the site, no incline of the building was observed
- Some reparable damages of the building were observed
- In this investigation, only one pile was picked up to inspect damage in detail. Several cracks were observed at the pile head and at deeper parts (deeper than GL-10 m).

It was concluded that damage to the building was not serious. Therefore, after repairs the building continued to be used normally.

18 years after the earthquake, an extensive investigation was carried out during the seismic isolation retrofit work. Although there have been some previous studies into earthquake damage to precast concrete piles, this paper is one of the few that report on damage to cast-in-place reinforced concrete piles by the earthquake.

2. Outline of building and pile foundations

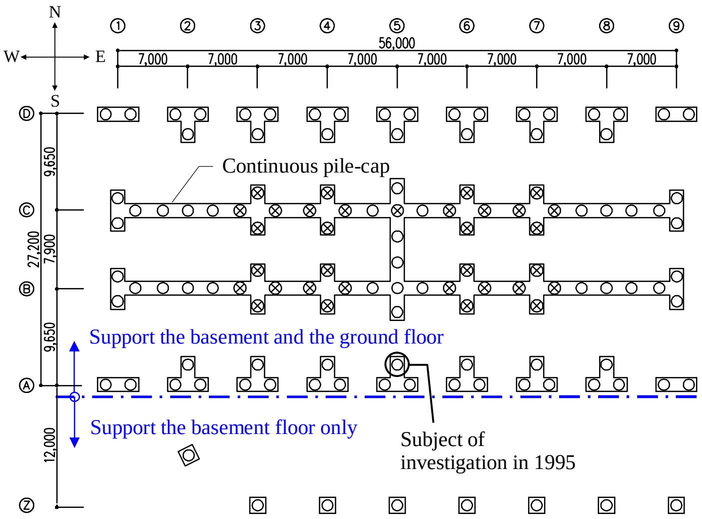
The building was constructed in 1973. The outline of the building and pile foundations are summarized in Table 1 and Table 2 respectively. The superstructure was supported by 124 piles. The plan of the pile foundation and the framing elevation including the scope of investigation are shown in Fig. 1 and Fig. 2, respectively. The length of piles is 15.0-16.6 m. The boring log, the level of the pile foundation and flexural cracks of pile concrete observed during the 1995 investigation are shown in Fig. 3. As mentioned later, it is consistent with the result of investigation in 2012 that the cracks were observed at the pile head. The cross section and the properties of piles are shown in Fig. 4.

Table 1 – Outline of building

Building use	Office
Completed year	1973
Site area	6,756 m^2
Total floor area	15,987 m^2
Building height	42 m
Number of floors	Ground floors: 8 stories Penthouse floor: 1 story Basement floor:1 below
Structural Type	Steel reinforced concrete structure Frame structure with shear wall

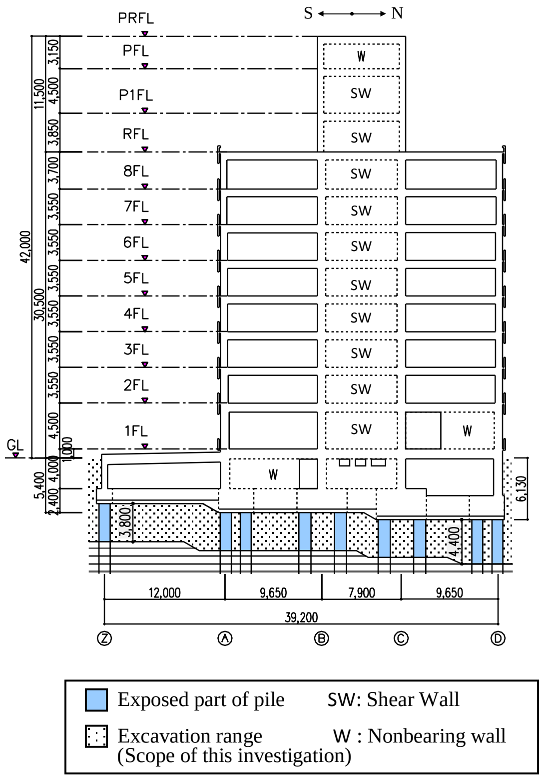
Table 2 – Outline of pile foundations

Foundation Type	Cast-in-place reinforced concrete pile
Number of piles	124
Diameter of piles (ϕ)	ϕ1200 mm (33 piles) ϕ1100 mm (91 piles)
Length of piles (L)	L=15.0-16.6 m



Unit of drawing dimension: mm

Fig. 1 –Plan of pile foundations



Unit of drawing dimension: mm

Fig. 2 – Framing elevation (7th frame)

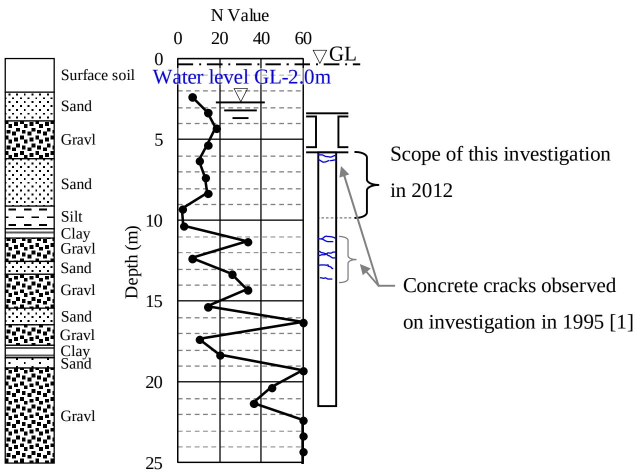
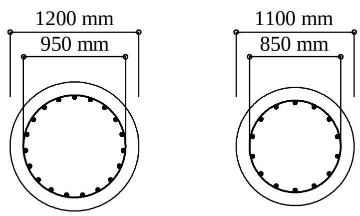


Fig. 3 – Boring log and pile foundation



(a) ϕ1200 mm
Rebar: 16-D19 mm
(SD30)

(b) ϕ1100 mm
Rebar: 14-D19 mm
(SD30)

Common properties
Transverse bar: 13 mm@250 mm (SR24)
Concrete design strength: 210 kgf/cm^2

Fig. 4 – Cross section and properties of piles

3. Failure types of pile foundation

In this investigation in 2012, damage was observed to almost all the piles. The damage was classified into four types based on cracking of concrete and reinforcing bar conditions;

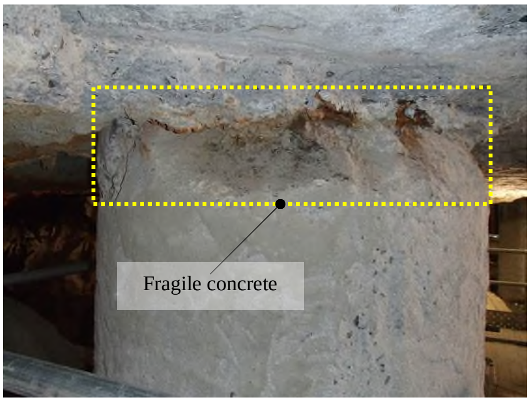
A) Bending failure at pile head joint ("pile head joint" means pile to pile head connection)
B) Bending failure of pile
C) Shear failure
D) Slip failure at the connection.

The characteristics of each type of damage is explained in this section.

Type A) Bending failure at pile head joint

Photo 1 shows the example of bending failure at pile head join. There were fragile parts of concrete at the pile head as shown in Photo 1 (b) to (d). Removing the fragile parts, local buckling of the main rebars at the pile head joint was found. This type of failure is most common type of damage. It was observed in 107 of 124 piles including those with combined failures. About 90 % of all piles had fragile concrete at their pile head joint.

(a) After excavating (Location; B-5)



(b) After removing surface concrete (B-5)

(c) After removing fragile part of concrete (B-5)

(d) After removing cover concrete of pile head (B-5)
Local buckling of main rebar at pilehead joint

Photo 1 – Type A); Bending failure at pile–pile cap connection

Type B) Bending failure of pile

Bending failure was observed in 11 piles. Photo 2 shows an example of this type of damage. Damage was found to the cover concrete at the part of pile head, about 1-meter (almost same as the diameter of the pile). Removing the cover concrete, it was found that local buckling of main rebar was longer than that observed for Type A) as shown in Photo 2 (b) and (d).

(a) Damage of cover concrete at pile head (A-6)

(b) After removing cover concrete of pile head (A-6)

(c) Damage of cover concrete at pile head (D-5)

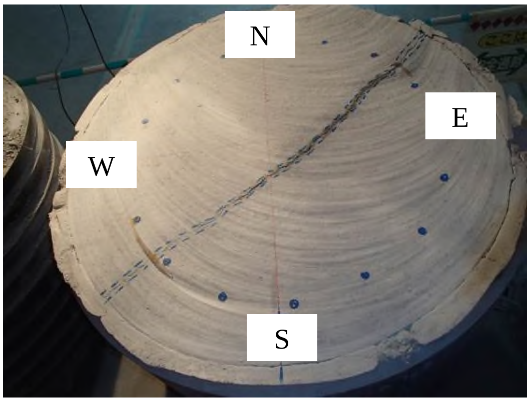
(d) After removing cover concrete of pile head (D-5)

Photo 2 – Type B); Bending failure of pile

Type C) Shear failure

Shear failure was observed in 9 piles. The failure can be grouped into two types; long shear span type and short shear span type. Photo 3 shows the long shear span type shear failure and Photo 4 shows the short shear span type. Additionally, Photo 5 shows an example of combined type with Type B) and Type C) failures. The long shear span type of failure had a shear crack of approx. 3-meter depth, whilst the short shear span type a crack of about 1-meter depth. The long shear span type was observed only on one pile. This pile is one of four piles located at C-4 right below to shear wall receiving a relatively large axial load and it is assumed that fluctuating axial to the pile during earthquake was large relatively.

(a) After removing surface concrete (C-4)



(b) Cross-section of pile (C-4)

Photo 3 – Type C); Shear failure (Long shear span type)


(a) After removing surface concrete (D-7)


(b) After removing cover concrete of pile head (D-7)

Photo 4 – Type C); Shear failure (Short shear span type)


(a) After removing surface concrete (D-7)

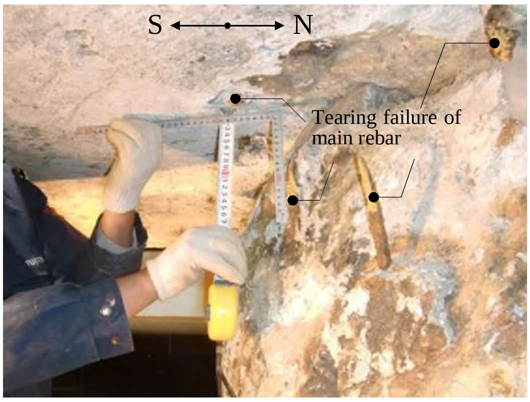

(b) After removing cover concrete of pile head (D-7)

Photo 5 – Combined type with Type B) and Type C); Shear failure after bending yield

Type D) Slip failure at the pile head joint

Slip failure at the pile head joint was observed in 4 of 8 piles with relatively small axial load. Photo 6 shows an example of Slip failure. The horizontal gap between pile and pile cap caused by the slip was about 70 mm along N-S direction as shown in Photo 6 (b); the direction of slip of the pile was north relative to the upper structure. Local bucklings of main rebars caused by the slip were found. Some tearing failures of the main rebars were also found at the pile head joint. The range of damaged concrete was about 20 to 40 cm from the top of the pile.


(a) After removing surface concrete (Z-5)



(b) Investigatin of damaged pile (Z-5)

Photo 6 – Type D); Slip failure at the connection

4. Consideration

4.1 Distribution of damaged piles

The distribution of damaged piles is summarized in Fig. 5. Table 3 shows the summary of the ratio of the numbers and notes of damaged piles. The most common type of damage was bending failure at pile head joint with far fewer instances of other types of damage. This type was seen all over the site. Slip failures at pile head joint were found at area of small axial load (supported the basement floor only).

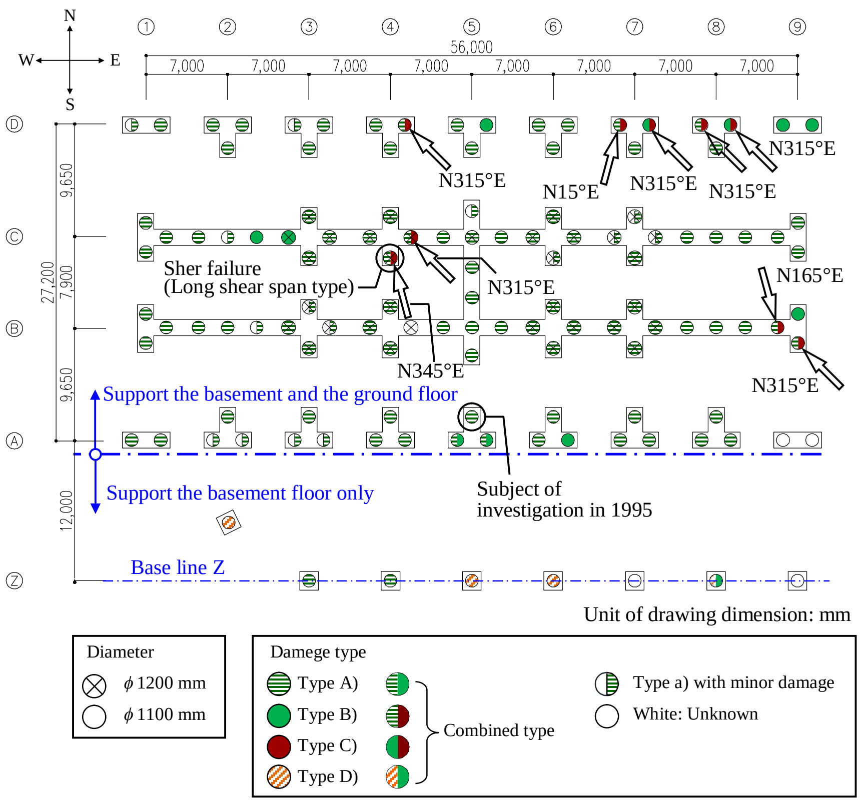


Fig. 5 – Distribution map of damaged piles

Table 3 – Summary of the ratio of the damaged piles

Type of damage		Number of piles	Ratio (Among 124 piles)	Note
A)	Bending failure at pile head joint	107	86.3 %	・ Most common type of damage. ・ Local bucking at the pile head joint was found. ・ Seen all over the site.
B)	Bending failure of pile	11	8.9 %	・ The degree of the cover concrete damage was relatively severe. ・ Local buckling of main rebar was found longer than found for Type A).
C)	Shear failure	9	7.3 %	・ This failure can be grouped into two types; the long and the short shear span type. ・ Seen as a combined type with type A) and type B).
D)	Slip failure at the pile head joint	4	3.2 %	・ Seen at relatively small axial load. (Area of the basement floor only).

4.2 Shear failure

4.2.1 Estimation of direction of shear force

The primary direction of shear force for the piles during earthquake was estimated by considering the shear crack. Because the shear crack relates to the horizontal force as shown in See Fig. 6.

The direction of horizontal force estimated by the shear cracks are shown in Fig. 5 as arrow symbols. The dominant direction of horizontal force was north-west. It is assumed that the most common direction of shear force estimated by shear crack was N315°E although a few shear cracks of pile with different angles were also observed.

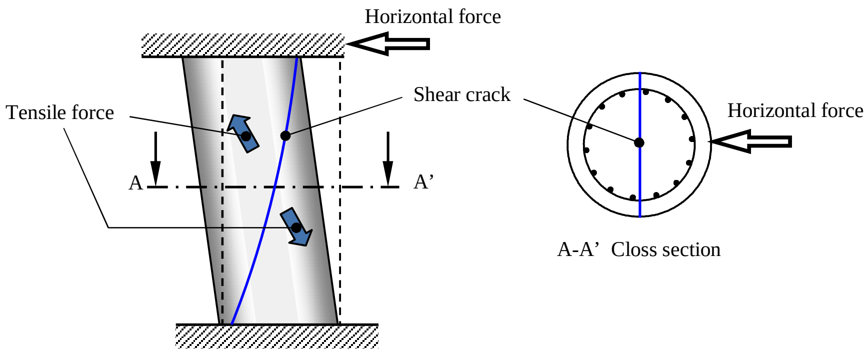


Fig. 6 – Direction of shear force

4.2.2 Primary direction of ground motion

The primary direction of ground motion at the building site was estimated from the record observed at the nearest observation point. The location of the building site, the nearest observation point and the seismic fault are shown in Fig. 7. Based on record from the nearest observation point, the primary direction of ground motion are shown in Fig. 8. The range of estimated shear force direction considering the shear cracks are also shown in Fig. 8.

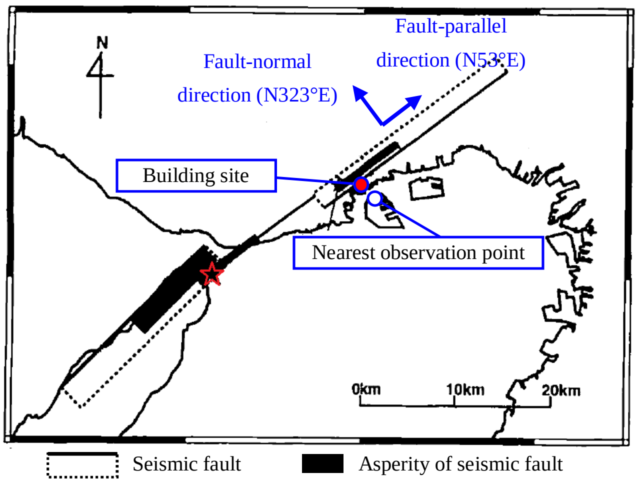


Fig. 7 – Location of the building site, the nearest observation point and the seismic fault [2]

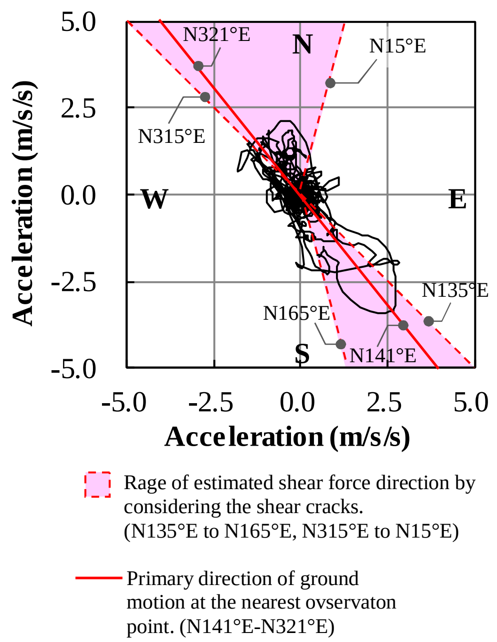


Fig. 8 – Acceleration of the nearest observation point

Refering to Fig. 8, it can be seen that the primary direction of ground motion was estimated to be N141°E-N321°E direction. This direction was nearly equal to the fault-normal direction (N323°E ; as shown in Fig. 7, direction normal to the strike direction of the seismic fault). On the other hand, the range of estimated primary shear force direction by considering the shear crack was N315°E to N345°E. The Primary direction of ground motion generally matched the direction of horizontal force estimated by the shear cracks.

4.3 Bending failure and Slip failure at the connection

The factors causing the bending failure and slip failure at pile head joint were considered. At the time this building was constructed (1973), pile foundations were only designed for vertical loads based on the Common Specifications of Construction Work in Japan (1969 edition) [3]. Therefore, the pile head parts seem not to have been embedded in the upper concrete. Fig.9 shows the assumed detail of pile head at the time. Because of this detail of pile head, it can be considered that the bending failures at pile head joint were observed on many piles and the slip failures were observed in the case of small axial loads. In the case of the detail as Fig. 9, the leveling concrete between pile and upper concrete was weak against bending compressive force, so that the main rebars at the pile head joint received large tensile stress.

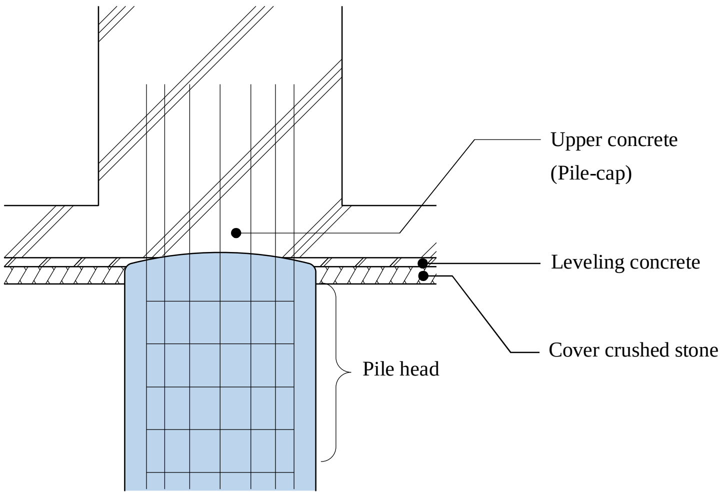


Fig. 9 – Assumed detail of pile head
based on the Common Specifications of Construction Work (1969 edition)

5. Conclusion

This paper reports on cast-in-place reinforced concrete piles from the 8-story steel reinforced concrete structure building that were damaged by the 1995 Hyogo-ken Nanbu Earthquake. Damage to the piles was observed 18 years after the earthquake and an extensive and detailed investigation of the damage was carried out. The types and causes of the damage were considered. The following conclusions were made:

1) Damage was observed to almost all the piles.
2) The damage to piles was classified into four types; bending failure at pile head joint, bending failure of pile, shear failure, and slip failure at the connection. More than 80% were bending failures at the connection, this is consistent with the result of past investigation in 1995.
3) The slip failures at the pile head joint were observed at area of small axial load.
4) The dominant direction of horizontal force estimated from the shear crack of the piles was N315°E. Additionally, the primary direction of ground motion at the building was N141°E-N321°E. These two directions generally agreed with the primary direction of ground motion recorded at a nearby observation point.
5) It can be concluded that the design method of piles based on the specifications in use in Japan at the time of construction of this building led to the damage of some piles.

Acknowledgements

The authors acknowledge the generous support of Ministry of Land, Infrastructure and Transport of Japan for writing this paper.

6. References

[1] Architectural institute of Japan, Kinki Branch (1996): Report of investigation on damage to building foundation due to the 1995 Hyogo-ken Nanbu Earthquake. (in Japanese)

[2] K. Kamae and K. Irikura (1998): Source Model of the 1995 Hyogo-ken Nanbu Earthquake and Simulation of Near-Source Ground Motion, Bulletin of the Seismological Society of America, Vol. 88, No. 2, pp. 400-412, USA.

[3] Building and Repairing Department, the Ministry of construction (1969): Common Specifications of Construction Work of Japan (1969 edition). (in Japanese)