# OBSERVATIONS OF EARTHQUAKE RESPONSE BEHAVIORS OF FOUNDATION PILES FOR ROAD BRIDGE


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## SUMMARY

Observations of earthquakes have been carried out on a road bridge supported by piles on whose surface dynamic strain gauges were attached. The earthquake responses of piles extending through soft soil deposits are investigated. According to distribution diagrams of maximum axial strains and bending strains along the pile,the amplitude of axial strains decreases gradually along the pile from the upper end of it. It is also found that the large amplitude of bending strains occurs at the upper end and the lower end of the pile, while the bending strain is small in the middle part of the pile.


## INTRODUCTION

Pile foundations have been used frequently for the support of structures. However, the behaviors of pile foundations during earthquakes have not been sufficiently understood up to now.

The piles resist the seismic load which is forced through the ground around the pile due to the upward propagation of shear waves and the horizontally propagation of surface waves. The seismic loads produce the stresses along the pile and piles are deformed subjected to these stresses.

What is of importance in earthquake-resistant design of pile foundations is to know how the distribution of the deformation or the stresses along the pile will be occurred. Furthermore, it is important to clarify what are the principal factors causing stresses and strains in the pile.

The authors carried out earthquake observations at a road bridge constructed in the city of Fujisawa, Kanagawa Prefecture, in order to clarify the dynamic characteristics of the foundation pile of the bridge. This paper considers the behaviors of piles in soft soil deposits is examined with the use of the observed records.

## SOIL CONDITION AND OUTLINE OF EARTHQUAKE OBSERVATIONS

As shown in Fig. 1, a width of the bridge is 10.75 m and total length is 484.8 m, and it is composed of three different types of plate girders.

The soil condition is represented by the back marsh of the stream running between Piers P6 and P7 and consists of dilluvial deposits of cohesive soil and fine sand upon which extremely soft alluvial strata of humus and silt are deposited as shown in the soil exploration results given in Fig. 1.


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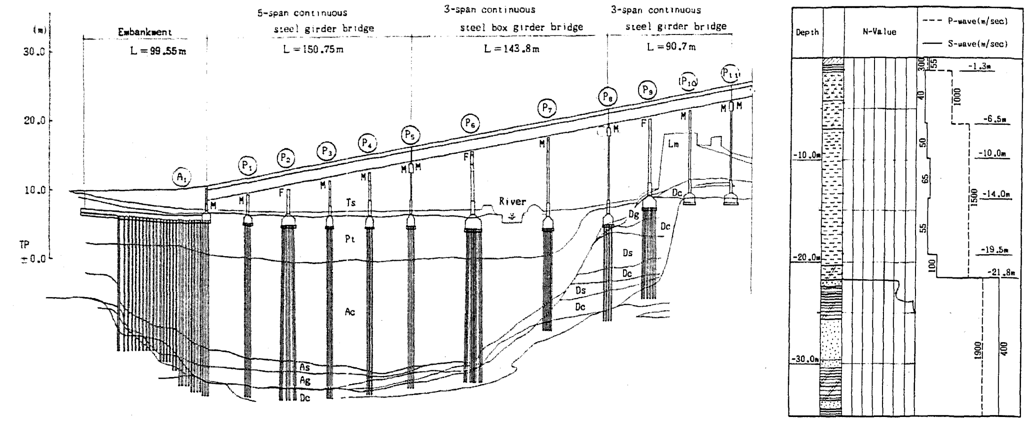
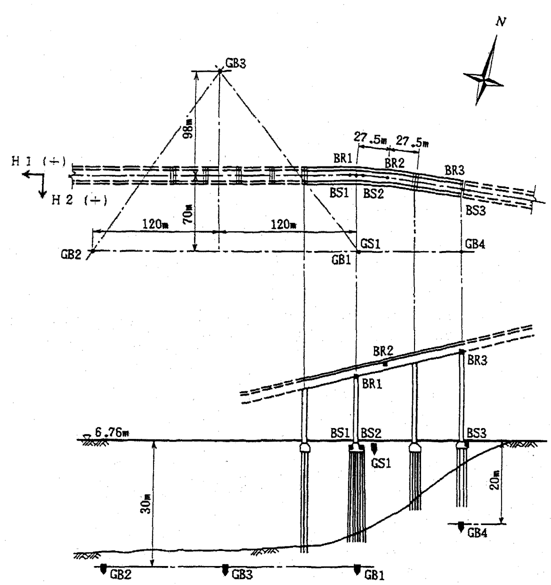



Fig. 1 Soil conditions

Earthquake observations have been made upon installation of accelerometers and strain meters as shown in Figs. 2 and 3. The accelerometers are of a servo type. A total of eleven units were installed with one unit (GS1) at the ground surface, four units (GB1 - GB4) at the bearing substratum, three units (BS1 - BS3) at footings, and three units (BR1 - BR3) at piers and a girder.

The strain meters were set at foundation piles of the Pier P6 which is of fixed-shoe type. Pier P6 is supported by 64 (8 rows x 8 rows) steel pipe piles ($\phi$ = 600 mm, L = 22 m, vertical pile t = 9 mm, batter pile t = 12 mm),



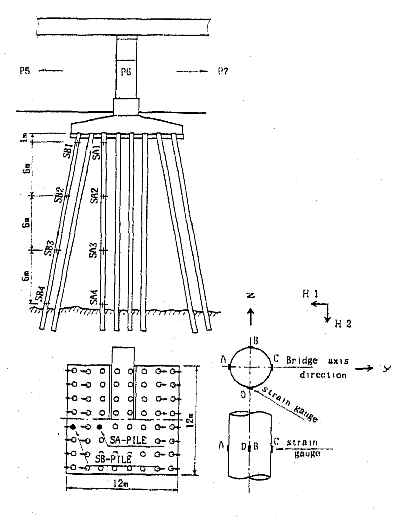




Fig. 2 Installation of accelerometers Fig. 3 Installations of strain meters

and the ends of the piles are adequately embedded in the bearing substratum. A total of 32 strain meters of strain gauge type were installed on one vertical pile and one batter pile at four different cross sections (SA1 ∿ SA4, SB1 ∿ SB4), with four points at each cross section on vertical direction.

Since beginning of earthquake observations in April 1981 a total of twelve earthquake records have been obtained.

## EARTHQUAKE RESPONSE BEHAVIOR CHARACTERISTICS OF PILES BASED ON OBSERVED RECORDS

Axial strain $\varepsilon_N$, bending strain $\varepsilon_{M_y}$ about axial direction of the bridge (Direction H1), and bending strain $\varepsilon_{M_z}$ about the direction perpendicular to the bridge axis (Direction H2) were obtained by the calculation formula shown below from the records, $\varepsilon_A$, $\varepsilon_B$, $\varepsilon_C$ and $\varepsilon_D$, of the four strain meters at each cross section.

$$\varepsilon_N = (\varepsilon_A + \varepsilon_B + \varepsilon_C + \varepsilon_D)/4$$

$$\varepsilon_{M_y} = (\varepsilon_B - \varepsilon_D)/2$$

$$\varepsilon_{M_z} = (\varepsilon_A - \varepsilon_C)/2$$

However, at the measuring cross section SB1 of the batter pile, records of the strain meters C and D were not obtained because of poor connections, therefore $\varepsilon_N$, $\varepsilon_{M_y}$ and $\varepsilon_{M_z}$ for SB1 are missing.

The results of analyses of Earthquake records No.12 (August 8, 1983, Kanagawa-ken Seibu Earthquake, M = 6.0, D = 20 km, Δ = 42 km) are reported here. A part of the observed records from this earthquake is shown in Fig. 4.

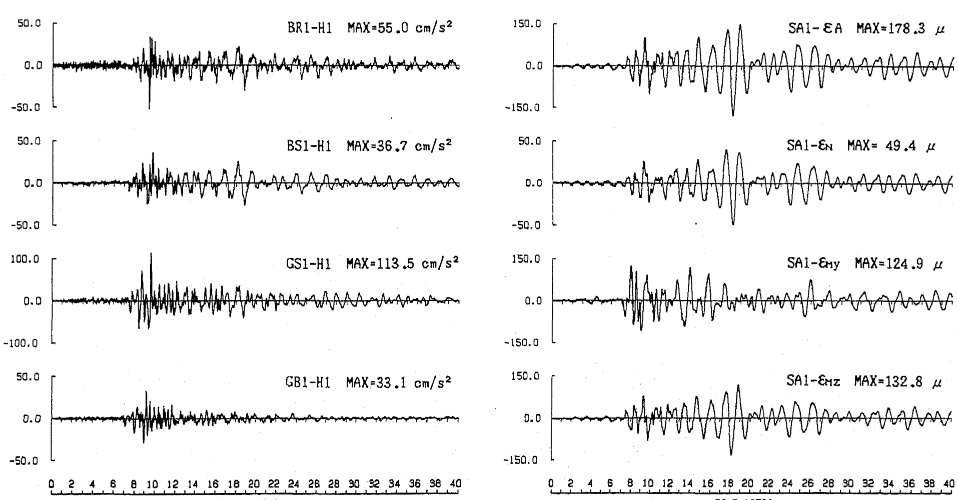



Fig. 4 Observed records from earthquake No.12

The maximum accelerations at the ground surface and the crown of Pier P6 in Direction H1 were 113.6 cm/sec$^2$ and 55.0 cm/sec$^2$, respectively, and the maximum value of dynamic strain of a pile was 178.3 μ at SA1-A.

In Figure 5, the power spectra for axial and bending strain along the pile are shown. From Fig. 5, since shapes of the spectra are practically unchanged in the direction of depth even though amplitudes of the spectra differ, it may be seen that both axial strain and bending strain along the pile are produced more or less by the same periodic characteristics.

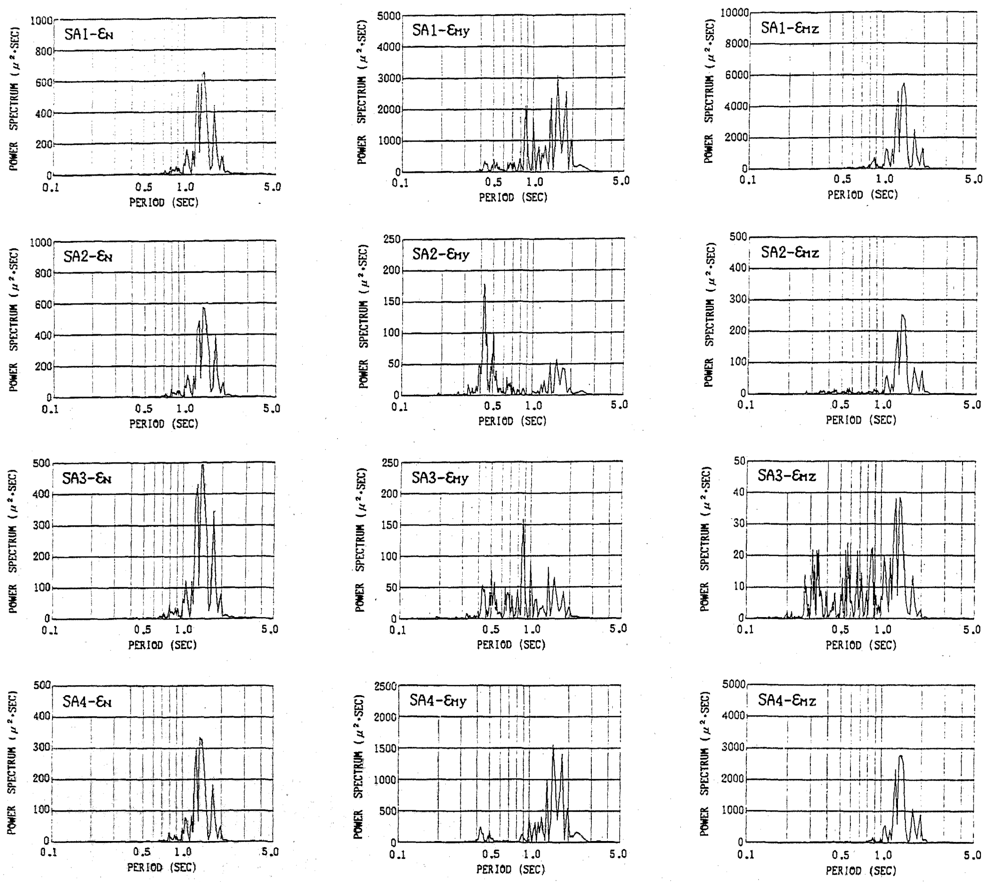



Fig. 5 The power spectra for axial ($^{\varepsilon}N$) and bending strain ($^{\varepsilon}M_y$, $^{\varepsilon}M_z$) along the pile

In order to investigate the correlations between records of strains produced at the various parts of piles, the cross-correlation coefficients of the strain records of SA2 to SA4 were calculated in relation to SA1 for axial strain and bending strain, respectively. The results are given in Fig. 6, and the respective correlation coefficients for axial strain and bending strain give extremely high values. It can be understood from this that piles do not vibrate locally and independently in the direction of depth.

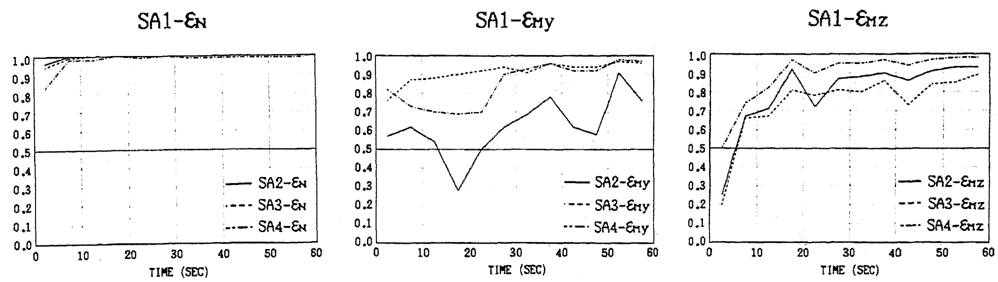



Fig. 6 Time variation of the maximum values of the cross-correlation coefficients of the strain records of SA2 to SA4 in relation to SA1

Figure 7 shows the time-variations of strain distributions of piles during 5 seconds at which the largest strain was produced at the upper end of the pile. It may be seen from this that a large bending strain is produced at the upper end of the pile, and bending strain is large at the lower end also. Furthermore, in the distribution diagram of bending strains in the axial direction of the bridge, the depth at which bending strains of vertical and batter piles become zero differ, and this can be a unique characteristic.

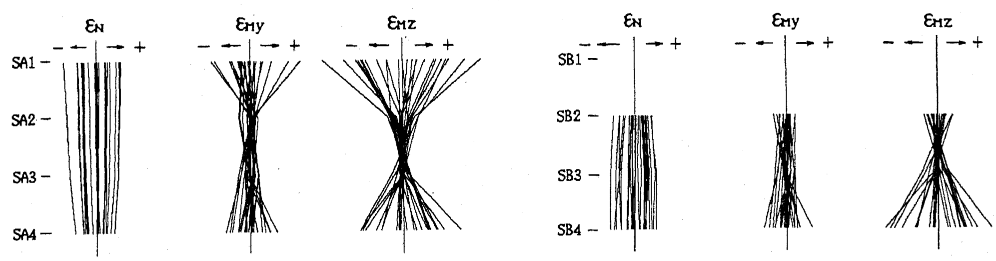



Fig. 7 Time-variations of strain distributions of piles for 5 sec.

Figure 8 shows the power spectra of accelerations observed at the ground and the pier. Comparing the power spectra of accelerations shown in Fig. 8 and strains of piles shown in Fig. 5, it is possible to examine the factors causing the strains along the piles. From the comparisons, it may be seen that the spectra for axial strain $\varepsilon N$ of both vertical and batter piles are closely similar to the spectrum for acceleration (BS1-H1) of the footing in Direction H1. Bending strains $\varepsilon M_y$ and $\varepsilon M_z$ are similar to the spectra of acceleration (BS1-H2) of the footing in Direction H2 and acceleration (BS1-H1) of the footing in Direction H1, respectively. From further investigation of the cross-correlations of the above, the result of extremely strong correlation was shown in Fig. 9. It can be considered from this that strains of piles of Pier P6 during earthquake are produced greatly governed by acceleration of the footing, i.e., by the inertia forces of the superstructure.

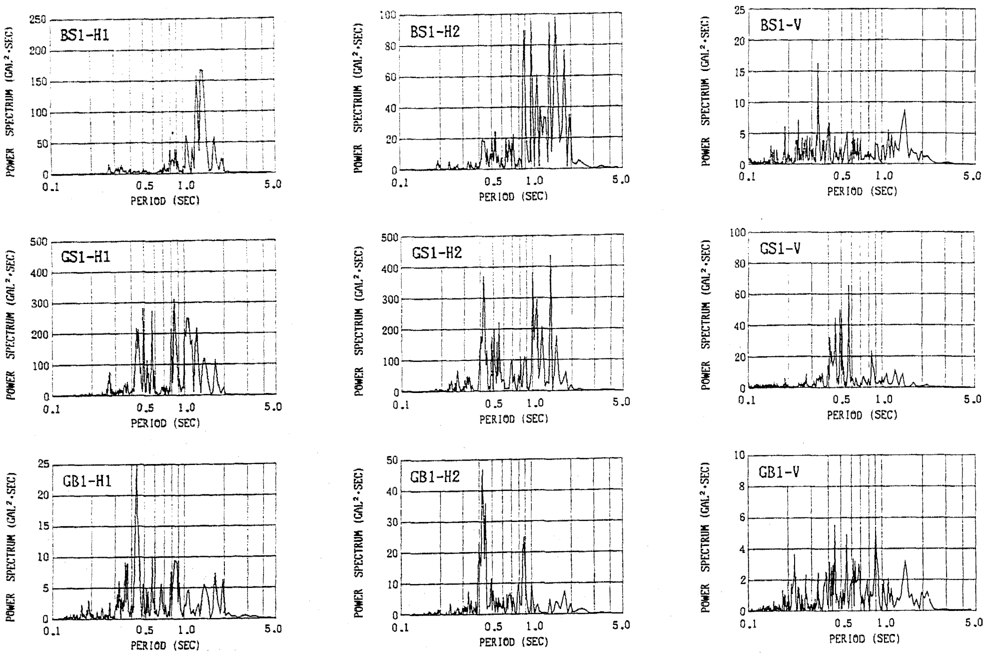



Fig. 8 The power spectra of accelerations (GB1, GS1, BS1) observed at the ground and the pier

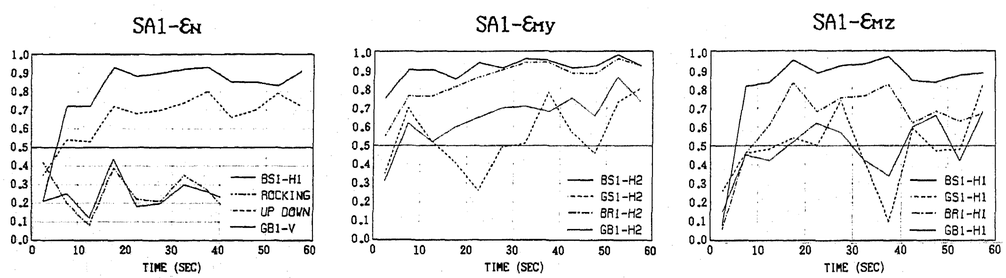



Fig. 9 Time-variations of the cross-correlation coefficients of the acceleration records of the ground and the pier in relation to the strain records of SA1

Next, the strain distribution of piles was examined at the time when the accelerations in Directions H1 and H2 of the footing of Pier P6 become maximum. The distribution diagram at the time is shown in Fig. 10. When the acceleration in Direction H1 becomes maximum, the axial strains of the vertical pile are in compression, and those of the batter pile are in tension. This trend is seen more or less throughout the records of this earthquake, and similarly seen in other earthquake records also. Furthermore, it can be seen

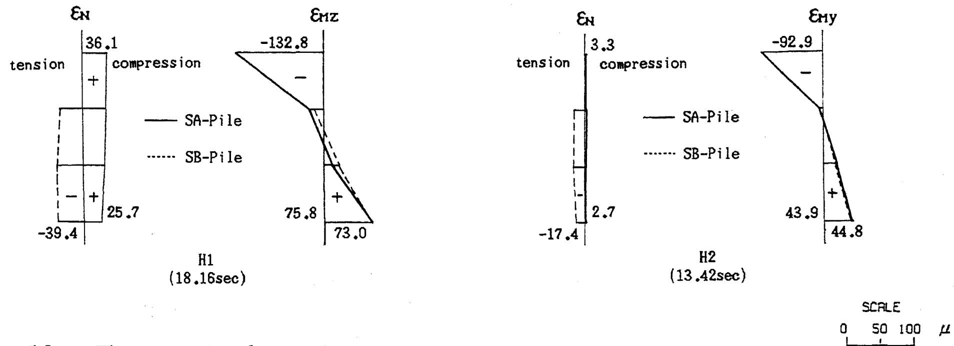



Fig. 10 The strain distribution of piles at the time when the acceleration (BS1) of the footing becomes maximum

that the distribution shapes of bending strains of vertical and batter piles resemble each other relatively well in Direction H2, but in Direction H1 these are fairly different.

Thus, it is thought that the differences in the behavior of the piles in the axial direction of the bridge is probably due to the difference of the structural type. However, a large difference in the behaviors of the piles cannot be seen in the direction perpendicular to the bridge axis. It is found that the behavior of the batter pile is the same as that of the vertical pile for a direction perpendicular to the inclination. Therefore the batter pile can be modeled as a vertical pile in the seismic design of the batter pile for the direction perpendicular to the inclination.

## ASEISMIC EFFECTS OF FOUNDATION PILES

In order to examine the aseismic effects of foundation piles, calculations were made for transfer functions between the surface (GS1) and the base (GB1), and between the P6 footing (BS1) and the base. Figure 11 shows the mean transfer function obtained by averaging all records. It is understood from this that amplifications between the footing and the ground are small in both directions of the bridge axis and the perpendicular to it. The amplitude of accelerations on the foundation is about 0.2 to 0.5 times that on the ground.

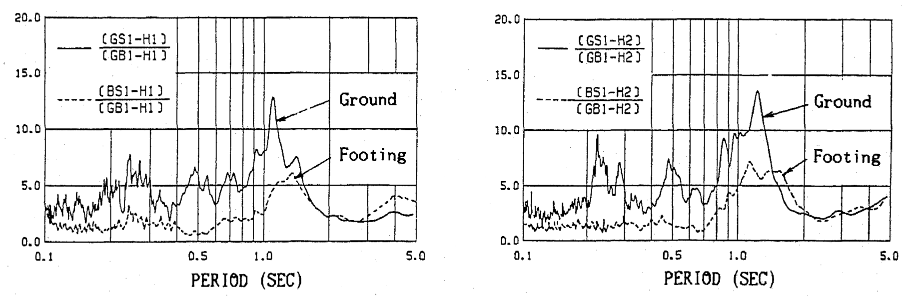



Fig. 11 Transfer function between the surface (GS1) and the base (GB1), and between the P6 footing (BS1) and the base

From the mean transfer function shown in Fig. 11, it is found that the amplification of the footing is larger than that of the ground surface at around 1.6 sec. This increase is considered to be caused by the inertia force of the superstructure.

## CONCLUSIONS

Dynamic characteristics of foundation piles were examined based on observed records of earthquake No.12, and the following conclusions are drawn:

(1) Axial strains decrese gradually in the directon of depth in vertical piles, while in batter piles axial strains differ from those in vertical piles.

(2) Bending strains are large at the upper and lower ends of piles, while they are small at intermediate sections. The distribution of bending strains for vertical piles in the direction perpendicular to the bridge axis is exactly the same as that for batter piles. However, in the axial direction both distributions differ fairly in each other. Batter piles are all inclined in the direction of the bridge axis, and it may be considered that behaviors of batter piles are similar to those of vertical piles in the direction perpendicular to the bridge axis.

(3) In general, it is found that behaviors of piles during earthquake are governed by both the inertia forces of the superstructure and the behaviors of the ground, but the influence of the ground is small from these observation results.

Since the number of earthquake records is still small and the each record is low acceleration level,pile behaviors under major earthquakes cannot be examined with present records. Earthquake records will be gathered further and more advanced studies will be carried out at the same time.

## ACKNOWLEDGEMENT

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