SEISMIC PERFORMANCE OF BRIDGE FOUNDATION WITH HINGE AT PILE HEAD

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Abstract

This paper describes a series of dynamic centrifugal experiments of bridge foundation models with hinge at pile head. Hinge connecting method for pile head is considered to reduce the response of the pile and to improve seismic performance of pile foundation even in the liquefiable ground during earthquakes. The experiment pointed out that method reduced the bending moment of the pile by approximately 30%, the rotational angle of the pile by approximately 50%, the axial force on the drawing side by approximately 30%, and the axial force on the forcing side by approximately 70%, although it increased the horizontal displacement of the superstructure by approximately 30%. The experimental study indicates the possibility of applying the hinge connecting method to liquefied ground.

1. Introduction

Bridge foundations must be designed to support upper structures adequately against large-scale earthquakes. In the case of pile foundations constructing at soil liquefaction prone area, large sectional force used to be developed at the pile head and at the boundary of liquefied layers because of the reduction of subgrade reaction due to the occurrence of liquefaction. For this reason, it is sometimes necessary to take such measures as increasing the number of piles, the pile diameter, and the amount of reinforcement. That may cause the foundation design extremely uneconomic.

On the other hand, a new type of pile foundation in which stress release mechanism is installed at the pile head in order to reduce sectional force is interested in this study. That type of foundation, in comparison with conventional type, could realize much reduction of construction cost in addition to secure the required seismic performance at the same time. As the stress release mechanism, it will be needed to come up with several methods to positively reduce the degree of fixation at the pile head, e.g. by connecting the pile head with a hinge or a roller, and by conducting other semi-rigid connection. Feasibility of pile foundation with stress release mechanism has been studied actively especially among the architectural group[1)], and in some cases research result has already been put into practical use. In the civil engineering field, however, research is still on-going stage and the applicability of the new technique is currently being studied[2)].

This paper describes a series of dynamic centrifugal experiments of bridge foundation models with hinge at the pile head. Superstructure-ground-foundation systems were

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modeled for the experiments. The dynamic response characteristic of the hinge connection was identified in comparison with the conventional rigid connection. Emphasis was placed on the effectiveness and applicability especially to the liquefiable ground.

2. Numerical Analysis using Beam on Winkler Foundation Approach

Numerical analysis was made in order to identify the relationship between the pile head connecting condition and the bending moment/ displacement distribution. Analysis was made using beam on Winkler foundation approach. **Fig.1** shows the analytical solution of displacement $u\ (z)$/ bending moment $M\ (z)$ distribution developed at pile, when a horizontal force P acts on the head of a pile that is supported by ground with subgrade reaction coefficient k_H and that has a flexural rigidity EI and semi-infinite length of diameter D. β is a coefficient as expressed in Eq. (1).

$$\beta = \sqrt[4]{\frac{k_H D}{4EI}} \qquad (1)$$

In terms with a pile foundation that has the hinge at its head, following characteristics can be pointed out.

a) Non-dimensional bending moment has a maximum value of 0.64 at a non-dimensional depth of $\beta z=\pi/4$. The maximum bending moment occurs at deeper point however the value decreases as approximately 2/3 comparing with that of a pile with rigid connection.

b) Horizontal displacement at the pile head increases as approximately twice comparing with that of a pile with rigid connection.

The analytical solution should identify qualitative trends although these results are not necessarily generated correctly because of a finite length of the pile, existence of resistance at footing face, nonlinearity of subgrade reaction, existence of pile group efficiency and other factors. When a construction method for reducing the degree of fixation of the pile head is applied, the amount of horizontal displacement at the pile head ought to be checked carefully because the relative displacement between adjacent substructures must be strictly managed.

3. Experimental Bridge Model

The experimental bridge model is a set of substructure and surrounding ground[3)] that is a component of a continuous steel girder bridge with a pier height of 12.2m. The foundation consists of an 8.5m*8.5m footing and 3*3 array cast-in-place piles with a pile diameter of 1.2m. Assumed bridge is a continuous steel girder bridge with the earthquake shear force distribution structure. Longitudinal direction was interested in this study. For the simplicity, one substructure as a part of the continuous bridge is modeled because it is difficult to reproduce the response characteristics of continuous girder bridge with above mentioned specific bearing systems in the experiment.

In a dynamic centrifugal experiment, data equivalent to the experimental result for a full-scale model could be obtained if N-times centrifugal acceleration acts upon a 1/N-scale model. Experimental conditions were defined taking into account the following matters in terms with the similarity law.

a) Mass and barycentric position of the upper-structure. The mass was determined to be equivalent to the weight of the girder under the Level 2 Earthquake. Its barycentric position was determined to be same as the position where an inertial force acts.

b) Mass and stiffness of the bridge pier. The stiffness was determined to be secant stiffness at yield.

c) Width, thickness and mass of footing

d) Diameter, placement space, length and flexural rigidity of pile. Flexural rigidity was determined to be a value before cracking.

e) Thickness of ground, liquefaction resistance and coefficient permeability of liquefied layer (G.L.-5 to -13m). The relative density of the sandy layer was determined so that a shear stress ratio of R_{L20} (at which an experimental sample reaches a total amplitude strain of *DA*=5% after 20 repetitions) was equal to the cyclic triaxial compression strength ratio R_L, estimated from an N value.

On the basis of these definitions, natural vibration characteristics of the bridge and the ground, liquefaction resistance of the sandy layer, the sectional force developed at foundation and other related factors become almost equal to those of an actual bridge.

The experimental model was scaled at 1:70 as shown in **Fig.2**. As described above, two types of pile models were adopted, i.e. a pile with hinge at pile head and a pile with rigid connection with footing. The experiment was conducted on a 70G centrifugal force field using the large dynamic geotechnical centrifuge at the Public Works Research Institute. A ground model was prepared in a laminar box, in which the ground consists of a dry sandy layer of relative density D_r=60%, a saturated sandy layer of *Dr*=60%, a normally consolidated clay, a saturated sandy layer of *Dr*=85% and a saturated sandy layer of *Dr*=90%. Only the sandy layer of *Dr*=90% was prepared by compaction method, and the other sandy layer was prepared by air pluviation method, where Toyoura-sand was used for every sandy layer. The clay layer was consolidated with escalated load in the gravity and centrifugal fields, where kaolin clay was used for the clay layer. The saturated sandy layer of *Dr*=60% where liquefaction was estimated to occur was saturated with a metlose solution that had 70 times viscosity of water.

An aluminum pipe with an outer diameter of 16mm and a thickness of 1.5mm was used as the model pipe. One end of the model pipe was embedded in the bearing stratum. The pile head was connected rigidly to the footing or connected with a hinge. As a hinge, a universal joint was formed by combining an 11mm diameter ball with a spherical support. The ball and the support were adjusted by a moderate force that did not cause any friction or looseness. The bridge pier model which weight was equivalent with that of the superstructure was placed on the footing.

Fig.2 and **Fig.3** show the sensor configuration. For piles No.1, 2, 4 and 5, only bending strains were measured. For pile No.7, both bending strain and axial strain were measured.

Fig.4 shows the input motion applied to the shaking table which was obtained after multiplying the amplitude of the base waveform by 0.7, where a ground motion at bedrock observed by the Kobe Marine Observatory[4)] was adopted as the base waveform. Values in this report, hereinafter, are all converted to the actual scale.

4. Dynamic Response of Ground and Bridge Pier

Dynamic response characteristics of the ground were studied. **Fig.5** shows time histories of acceleration, excessive pore pressure and relative displacement in horizontal direction, where all sensors were placed enough apart from the foundation model and assumed to be independent from the response of structure. In determining a time history of displacement, measured acceleration waveforms were Fourier-transformed and numerically integrated in a frequency-domain with a high-pass filter of approximately 0.1Hz. Displacement values shown in this report were all calculated in the same way. The dynamic response of ground in both cases were almost same with each other, although a little difference was shown in the time history of excessive pore pressure measured at the saturated sandy layer of *Dr*=85% and *Dr*=90%.

The excessive pore pressure in the liquefied layer (P1-1, P1-2) had almost reached an initial load pressure σ'_{v0} approximately 8.5 seconds after the beginning of excitation, whereas the acceleration decreased rapidly in the shallower layers than the liquefied layer. Consequently it could be found that the liquefaction occurred at approximately 8.5 seconds after the beginning of excitation.

As shown in **Fig.5**, the ground acceleration decreased in accordance with the propagation of shear wave, i.e. acceleration was smaller in the clay layer (A1-4) than that in the sand layer of *Dr*=85% (A1-5), and smaller in the liquefied layer (A1-3) than that in the clay layer. This is why the rising component wave was difficult to be transferred through two adjacent layers in which there was much difference of shear stiffness and impedance ratio. As shown with the time history of ground displacement, large displacement tends to be developed in the layer shallower than those adjacent boundaries.

Fig.6 shows the time history of horizontal acceleration developed at the top of pier model. There was only a little difference between two cases although acceleration developed at the bridge model with rigid connection at pile head was estimated to be bigger than that at the bridge model with hinge in which it would be difficult to transfer seismic force from the pile head to the footing. Consequently, it can be studied that the connecting conditions at pile head have little influence to the dynamic response characteristic of whole bridge model.

Above mentioned result does not mean that the hinge connection did not work in this experiment. **Fig.7** shows the distribution of maximum bending moments developed at several piles. Large bending moment acted on the rigidly connected pile head, where bending moment acted on the hinge connection smoothly approached zero. It reveals that the hinge worked properly.

5. Dynamic Response of Footing and Piles

Dynamic response characteristic of bridge foundation during an earthquake depends on the external force, i.e. inertial force of superstructure and ground deformation around footing and piles. Influence of these external forces to the response characteristic of foundation was compared in this section. Here, the lateral displacement of ground surface developed around the footing and the inertial force transferred from the bridge pier were almost same in both cases as referred in **Fig.5** and **Fig.6**.

Fig.8 shows a phase relationship between a bending moment and an acceleration developed at the top of pier or a lateral displacement developed at the ground surface. Bending moment described in this figure in each case was observed at the depth where a maximum bending moment was observed. In both cases, a relationship between the ground surface displacement and the pile's bending moment shows better linearity than that between the pier acceleration and the pile's bending moment. On the basis of this finding, it can be pointed out that the dynamic response characteristic of pile foundation depends on the ground deformation rather than the inertial force of superstructure.

In addition, **Fig.9** shows time histories of the relative displacement between the footing and the shaking table in both cases. Those time histories show good agreement with that of relative displacement between the ground surface displacement and the shaking table in terms of the shape and the amplitude of the waveforms as shown in **Fig.5**. That means the displacement of footing depends on the lateral displacement of surrounding ground, and also indicates that the ground deformation has a dominant effect on the response of the pile foundation.

6. Effects of Connecting Condition at Pile Head

The maximum bending moment developed at pile, as shown in **Fig.7**, was 6.3MN・m (G.L.-4.55m at the pile head) in the case of rigidly connected pile head, and 4.5MN・m (G.L.-17.5m in the clay layer) in the case of hinge connection. That means the hinge connection of the pile head reduced the bending moment by approximately 30%. In the case of bridge foundation with hinge at pile head, generally speaking, the maximum bending moment has a tendency that the depth is deeper and the value is smaller comparing with the bending moment developed in the case of bridge foundation with rigid connection at pile head.

Fig.10 shows a time history of a relative displacement of the footing and surrounding ground surface. There was a clear difference and is consistent with the explanation described in section 2, i.e. the difference between two types of connecting condition reached 5cm (approximately twice) at most.

On the other hand, regarding the total performance of a whole bridge, it is more important to discuss a lateral displacement of a superstructure resulting from a total displacement of the pile foundation and the pier. **Fig.11** shows a relative displacement of the superstructure and the ground surface. The figure shows that the difference between the maximum displacement values in the two cases was 3cm (approximately 1.3 times) at most. The lateral displacement of superstructure did not necessarily increased twice although the lateral displacement of footing increased twice in the case of hinge connection. This is because, as mentioned later, locking movement of footing is relatively difficult to be occurred with hinge connection at pile head comparing with the rigid case.

Fig.12 shows a time history of a rotational angle of the footing. Those values were calculated based on the measured vertical accelerations by accelerometers installed at both ends of the footing. The rotational angle of the footing in the case of hinge connection was small at almost all times, and the maximum angle was approximately 50% of that in the case with the rigid connection at pile head.

Fig.13 shows a phase relationship between axial force and axial displacement (positive on the tension side) developed at the pile head. The axial force variation and the axial displacement were small in the case with hinge connection at pile head. Considering the fact that the axial force before excitation calculated from the weight of superstructure was approximately -1.9MN, it can be pointed out that the difference of the axial force variation between two cases was relatively large. In the case of hinge connection, the maximum axial force was reduced by approximately 30% on tension side and by approximately 70% on compression side alternatively. Regarding the axial force variation, small variation on tension side contributes to stabilize M-ϕrelationship of the pile, and small variation on compression side contributes to prevent yielding of the pile foundation system.

The difference on the axial force variation and the rocking behavior between two cases can be explained as follows. **Fig.14** illustrates the balance of the rotational moment acting on the footing during an earthquake. When an inertial force from a superstructure provides a clockwise moment to a footing, as shown in a deformation mode of a pile, also clockwise moment develops as a reaction at a pile head, and promotes a rotational behavior of footing. In the case of a rigid connection, therefore, large axial force is to be developed at the pile head in order to balance the rotational moment acting on a footing. In the case of a hinge connection, on the other hand, axial force of a pile becomes smaller because there is not any clockwise moment develops at a pile head.

Smaller the axial force variation, smaller the axial displacement of the pile. And thus smaller the axial displacement of the pile, smaller the rotational behavior of the footing. Consequently, the bridge foundation with hinge connection at pile head is pointed out to be effective for reducing the rocking behavior of the footing. In addition to this fact, the axial force of pile is not produced by the ground deformation in the case of hinge connection. Therefore, foundation with hinge connection at pile head is more effective for reducing the axial force variation and the rotational behavior of the footing if the ground deformation is more dominant comparing with the inertial force from the superstructure.

7. Conclusions

Conclusions obtained can be summarized as follows;

1) Dynamic centrifugal experiment was conducted using two cases of bridge foundation models set on a liquefiable ground, i.e. foundation with rigid connection and hinge connection at pile head. In this experiment, the ground deformation rather than the inertial force from superstructure had a dominant effect on the response of the pile foundation.
2) The foundation with hinge connection at pile head had reduced the maximum bending moment of pile by approximately 30%, the maximum rotational angle of footing by approximately 50%, the maximum axial force on tension side by approximately 30% and the maximum axial force on compression side by approximately 70%, comparing with the foundation with rigid connection.
3) The foundation with hinge connection had increased the horizontal displacement of the superstructure by approximately 30%, comparing with the foundation with rigid connection.
4) In the case that the horizontal displacement of the superstructure is acceptable to some extent, the hinge connection at pile head seems to be quite effective for reducing the construction cost of the foundation, securing the seismic safety as well as the rigid connection.
5) The foundation with hinge connection at pile head is more effective for reducing the axial force variation and the rotational behavior of the footing especially in the case the ground deformation has dominant effect comparing with the inertial force from the superstructure, for instance foundation set on the liquefiable ground or the soft cohesive ground.

References

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3) Japan Road Association, 6. Design Calculation Example for Unstable Ground in Earthquakes, Materials Concerning Seismic Design for Road Bridges, 1997 (in Japanese)
4) Ground Vibration Division, Public Works Research Institute, Seismic Design of Underground Structures against Large-scale Earthquakes, Research Report of Ground Vibration Division, No.22, 2001 (in Japanese)

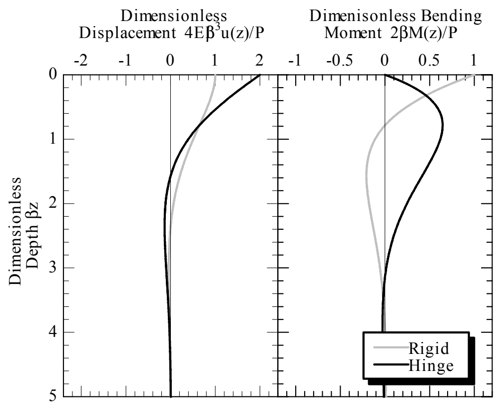
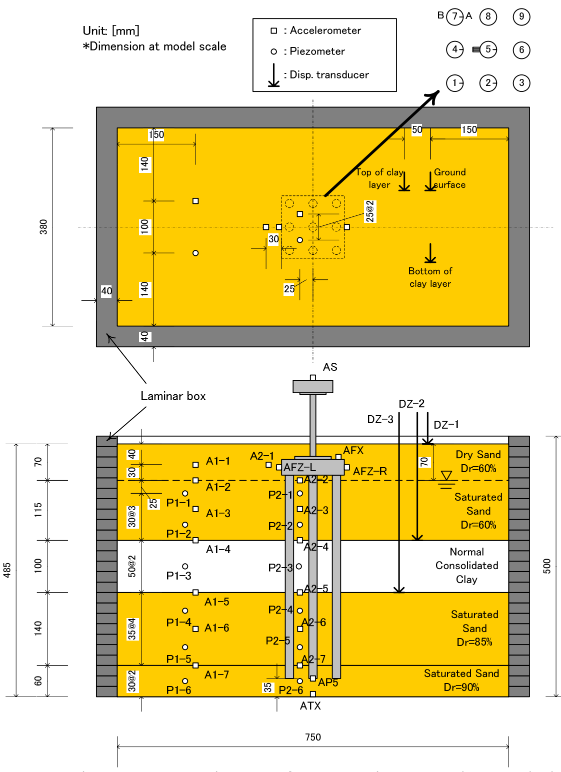


Fig.1 Analytical Solutions of Pile Displacement and Bending Moment



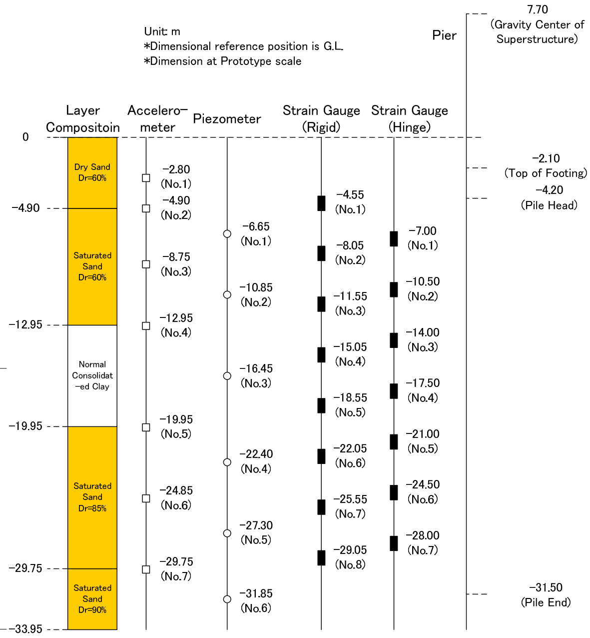


Fig.2 Overview of Experimental Model

Fig.3 Sensor Configuration

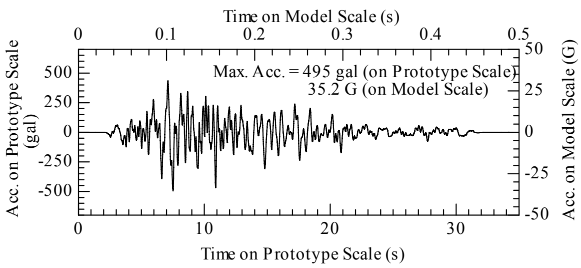


Fig.3 Input Waveform

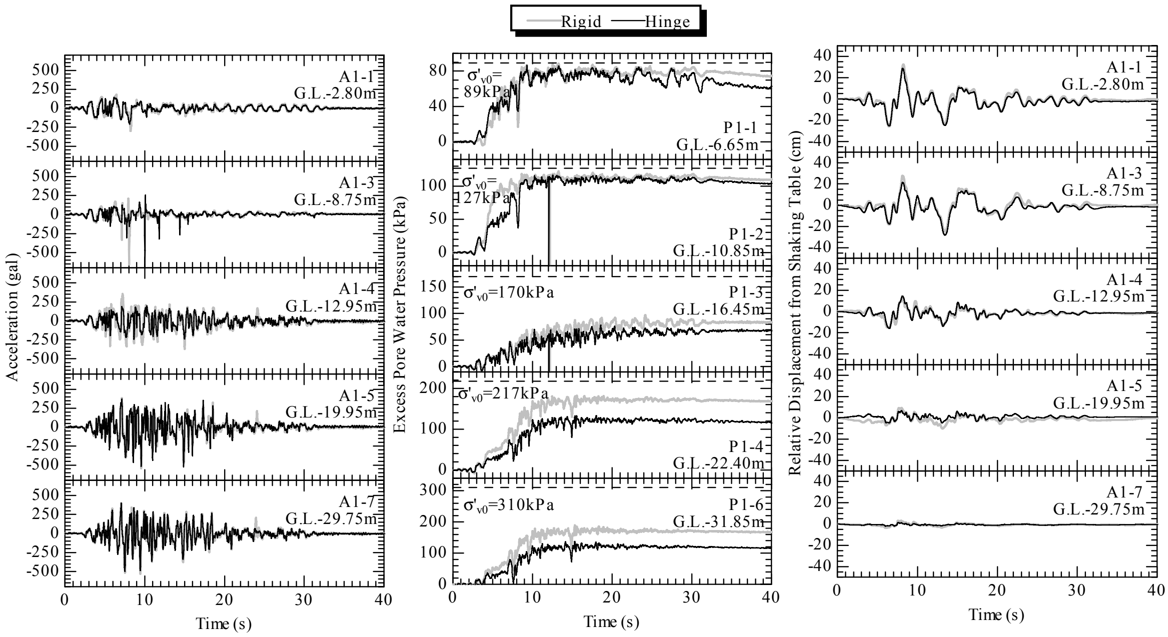


Fig.5 Acceleration, Excess Pore Water Pressure and Surface Displacement

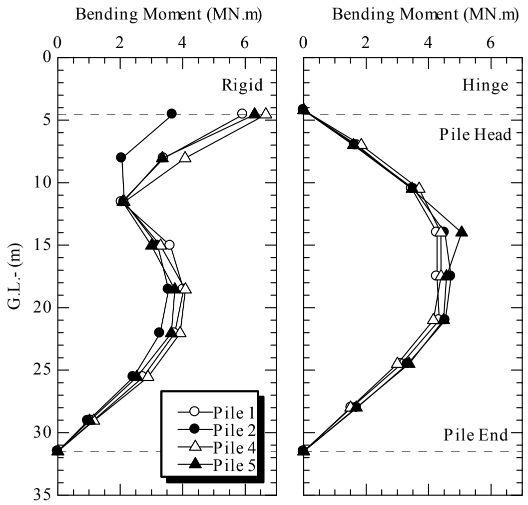


Fig.7 Maximum Bending Moment of Piles

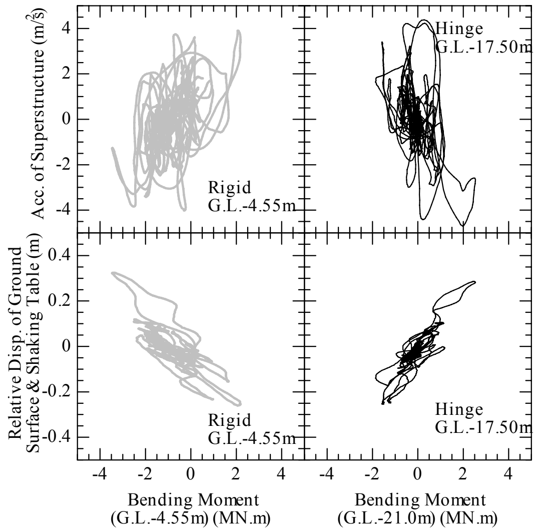


Fig.8 Phase Relationship
Bending Moment ~ Ground Disp./ Pier Acc.

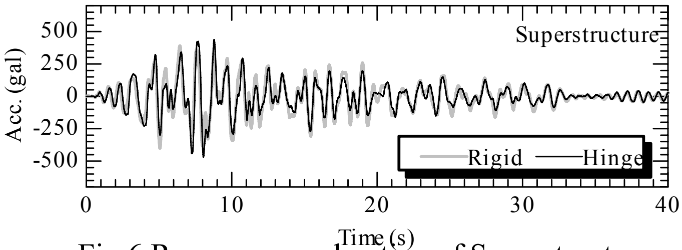


Fig.6 Response acceleration of Superstructure

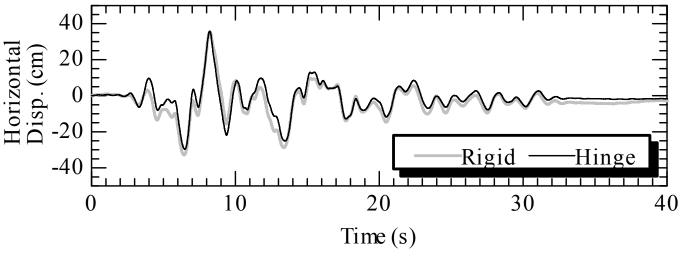


Fig.9 Relative Displacement of Footing and Shaking Table

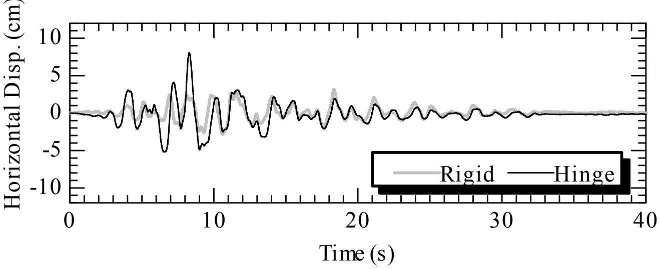


Fig.10 Relative Displacement of Footing and Ground Surface

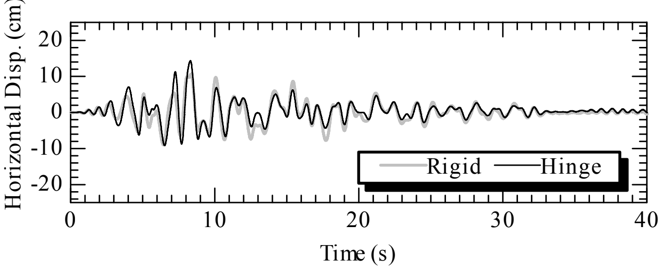


Fig.11 Relative Displacement of Superstructure and Ground Surface

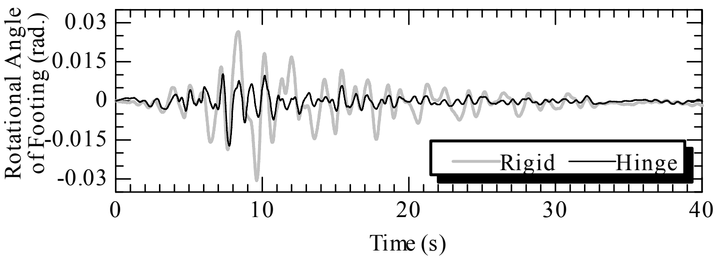


Fig.12 Rotational Angle of Footing

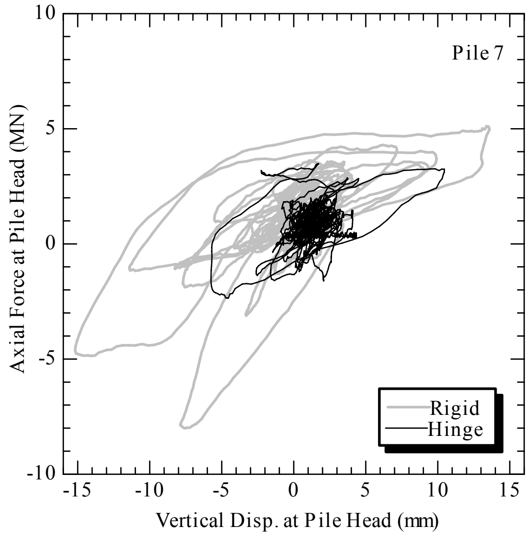


Fig.13 Relationship between Axial Force and Axial Displacement at Pile Head

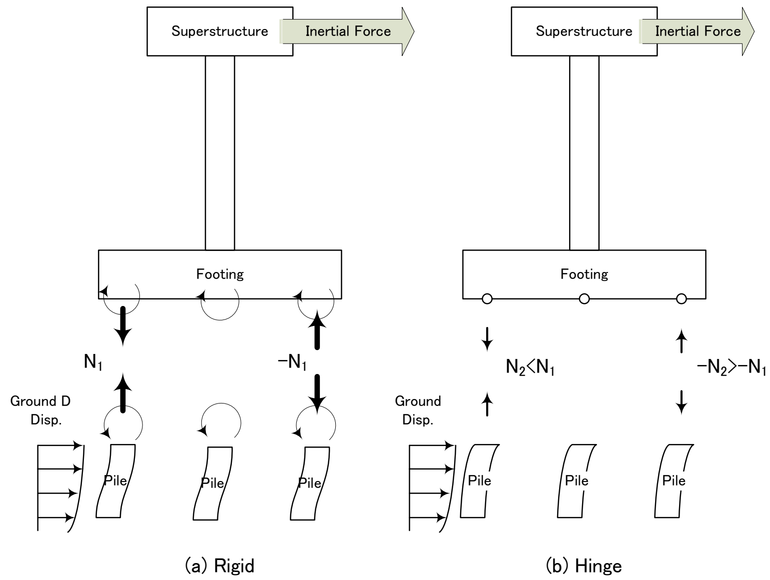


Fig.14 Variation of Sectional Force depending on Connecting Condition