# Development of New Earthquake Response Analysis for Infrastructures
# 社会基盤構造物の次世代地震応答解析手法の開発

Leader of Project: Hiroshi Mutsuyoshi(Professor, Faculty of Engineering)
プロジェクト代表者：睦好宏史（工学部・教授）

## 1 Introduction

The behavior of pile foundation during earthquake ground motion has an important effect on the overall structural behavior. Recent researches have shown that non-linearity of soil and soil structure interaction has significant effect on the seismic behavior of the structures, especially those constructed on the soft soil [1]. Moreover, observations of damages in the pile foundations in recent earthquakes have stressed the necessity of detailed study on performance of pile under seismic loading.

There have been number of studies carried out on small scaled concrete piles embedded into model ground [2-3]. However, it is well known that the mechanical behavior of concrete members is influenced by its scale. Hence, considering the complexity of the interaction between a pile and the supporting soil, analysis of experimental data from the load testing of full-scaled piles in the field gives better understanding of the actual behavior of piles during earthquakes. Valid verification of present analytical tools cannot be made without well documented data from the testing of the instrumented piles in the field. There are very limited studies on the behavior of piles based on full scale testing [4].

This paper presents the results of a lateral loading test conducted on full-scaled concrete piles embedded into the ground. The research aims to study the non-linear behavior of the concrete pile-soil interaction during ground motion. One directional monotonic loading and reversed cyclic loading tests were carried out on two test piles. Particular emphasis of the testing was given on depth-to-maximum-moment, magnitude of local deformation upon formation of a plastic hinge in the pile and characterization of local inelastic deformation.

## 2 Experimental Program

The experimental program consists of lateral loading test on two full scaled precast prestressed concrete piles embedded into the ground. One pile was subjected to monotonic loading and the second pile was subjected to reverse cyclic loading. Bending test was also conducted on the specimen with similar cross section as the test piles.

### 2.1 Test Pile Details

Test piles used for monotonic testing and reversed cyclic testing have same specifications. Both of the piles are hollow prestressed concrete piles of 30cm diameter and 6cm thickness. Six prestressed steel bars (PC bars) of 7mm diameter were used for longitudnal reinforcement and spirals of 3mm diameter and 100mm pitch were used for confining the concrete Fig 1(a). Strain gages were attached to the PC bars in top 12m section of the test piles as shown in Fig. 1(b). Whereas, for the bottom 14m sections of the piles, strain gages were not attached.

Compressive strength of the concrete was $f_c' = 69$MPa and yielding stress of longitudinal steel was $f_y = 1325$MPa. Effective prestress on the concrete was 5 MPa.

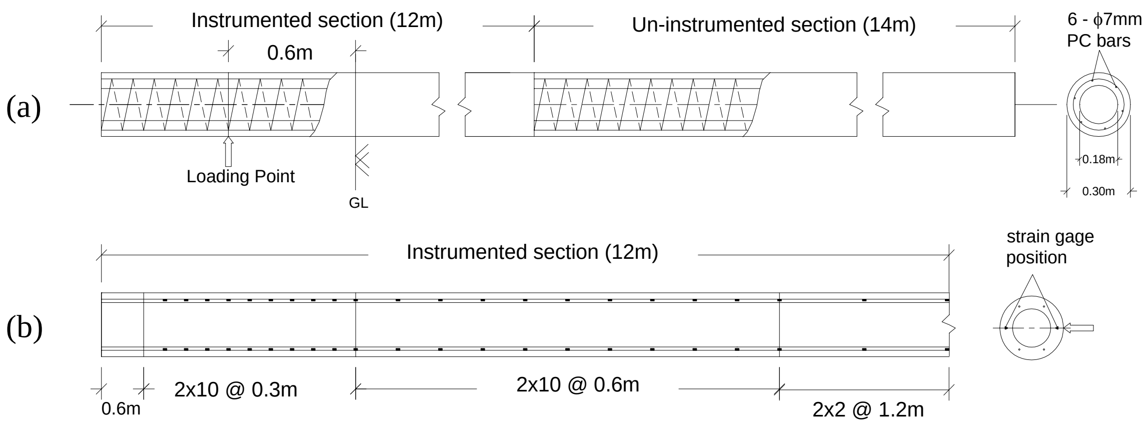


Fig.1 (a) Test pile details and (b) position of the strain gages

Test piles were setup in the following manner: i) drilling was carried out using 45cm diameter auger up to the depth of 20m ii) bentonite-cement paste was poured into the drilled hole to stabilize the soil and for easy penetration of the pile iii) 14m un-instrumented section of the pile was inserted and iv) end of 12m instrumented section was welded to the top of the 14m section and was embedded. Test piles were embedded up to 24.8m from the ground level (GL), where sand layer exists. The height of the head of the pile was 1.2m and the height of the loading point was 0.6m from the ground level. The reaction frames were setup on six reaction piles as shown in Fig 2.

The reaction piles were driven up to the depth of 10m. Displacement transducers were used to measure horizontal displacement of the piles at loading point. Experimental setup and instrumentation were done according to JSF standards [5].

### 2.3 Subsurface Investigation

Standard penetration test (SPT) was carried out at the experimental site to investigate the relevant soil parameters along and beyond the test pile depth. NSPT values obtained from the test are shown in Fig. 3 along with the soil type.

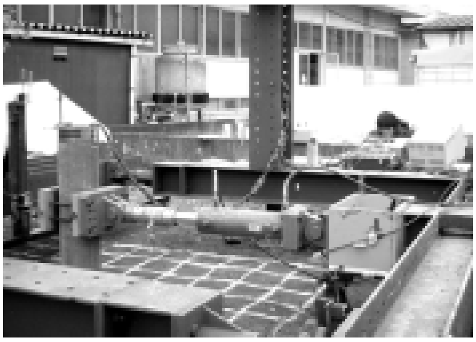

Fig.2 Experimental setup

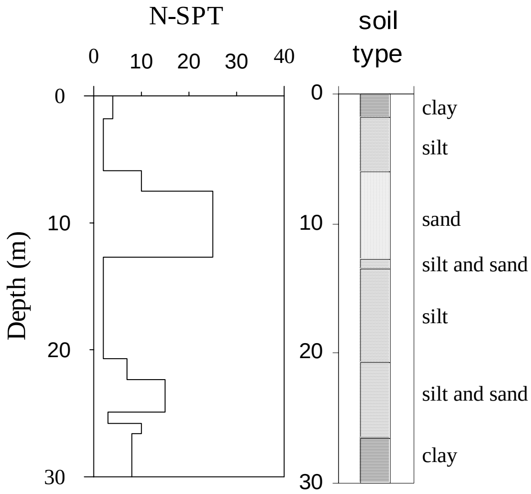


Fig.3 SPT test results

### 2.4 Loading Pattern

One dimensional monotonic loading was applied to SP1 and reversed cyclic loading was applied to SP2. In both the cases, loads were applied continuously and hence the effect of creep was not taken into consideration.

## 3. Observation and results

### 3.1 Damage Pattern

Occurrence of maximum bending moment and plastic hinge were below the ground level for both the specimen.

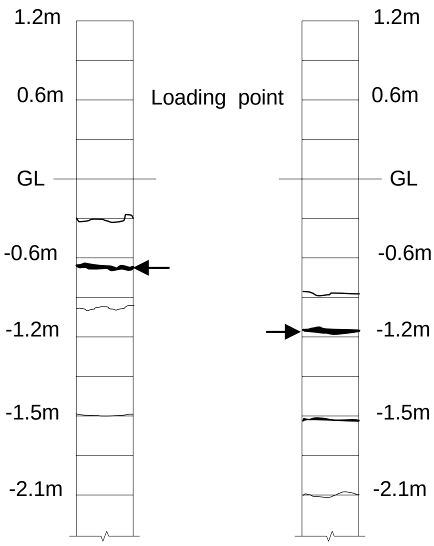


Fig.4 Crack pattern in (a) monotonic loading (b) reversed cyclic loading

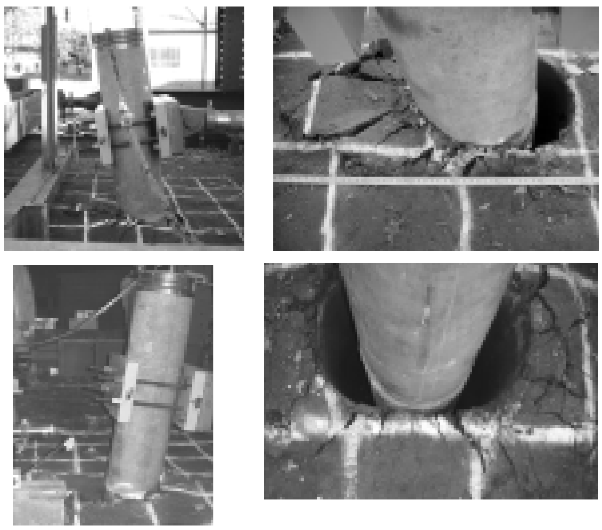

Fig.5 Soil deformation in (a) monotonic loading (b) reversed cyclic loading

No damage was observed above the surface of the ground. Flexural failure was observed in both cases. Failure occurred due to the breaking of the tension reinforcement and then crushing of the concrete in compression. Damaged in the piles below the ground surface was examined by digging trench around the piles after completion of the tests. The damage pattern in the test piles are shown in Fig 4. In the specimen SP1, plastic hinge was formed at the depth of 0.6m (2D) from GL. Three PC bars in tension side were broken and concrete was crushed in the compression side. Whereas, in the specimen SP2, plastic hinge was observed at the depth of 1.2m (4D) from GL. From the experiment, it was observed that depth of plastic hinge increased in the reversed cyclic loading compared with the monotonic loading. This is due to the decrease in the soil resistance caused by cyclic loading. Moreover, cracks were distributed in the wide range along the pile in specimen SP2 compared to SP1.

The movement of the soil after the loading in case of SP1 and SP2 are shown in Fig. 5. In monotonic loading, cracks were observed in soil in passive deformation side up to 0.6m distance from the test pile, whereas in the active deformation side, 10cm gap was observed in soil. In the reversed cyclic loading, cracks were observed up to 0.6m distance from the pile surface on each side and 15cm gaps were formed in soil in each side.

### 3.3 Restoring force and displacement relationship at pile head

Load-displacement relationships at the pile head for SP1 and SP2 are shown in Fig. 6. Here, the restoring force refers to the reaction at the pile head due to the applied displacement. In the case of monotonic loading, SP1, yielding of the pile occurred at $V_y$ = 44kN and maximum load achieved was $V_u$ = 51kN. Here the yielding of the specimen is defined as the yielding of longitudinal bars. The maximum displacement at the failure was 160mm. For reversed cyclic loading, SP2, yielding of PC bars occurred at depth of 1.2m from GL at load of $V_y$ = 28kN in the face A, where as in the face B first yielding occurred at height of 1.2m at $V_y$ = 30.5kN load. Failure of the pile occurred by breaking of the PC bars in the face B at the maximum displacement of 170mm.

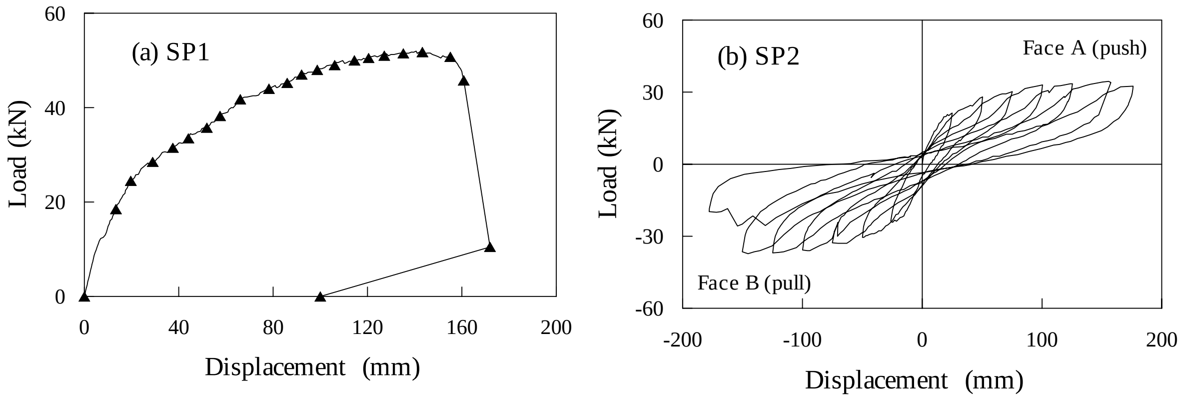


Fig.6 Restoring force – displacement curves (a) monotonic (b) reversed cyclic loading

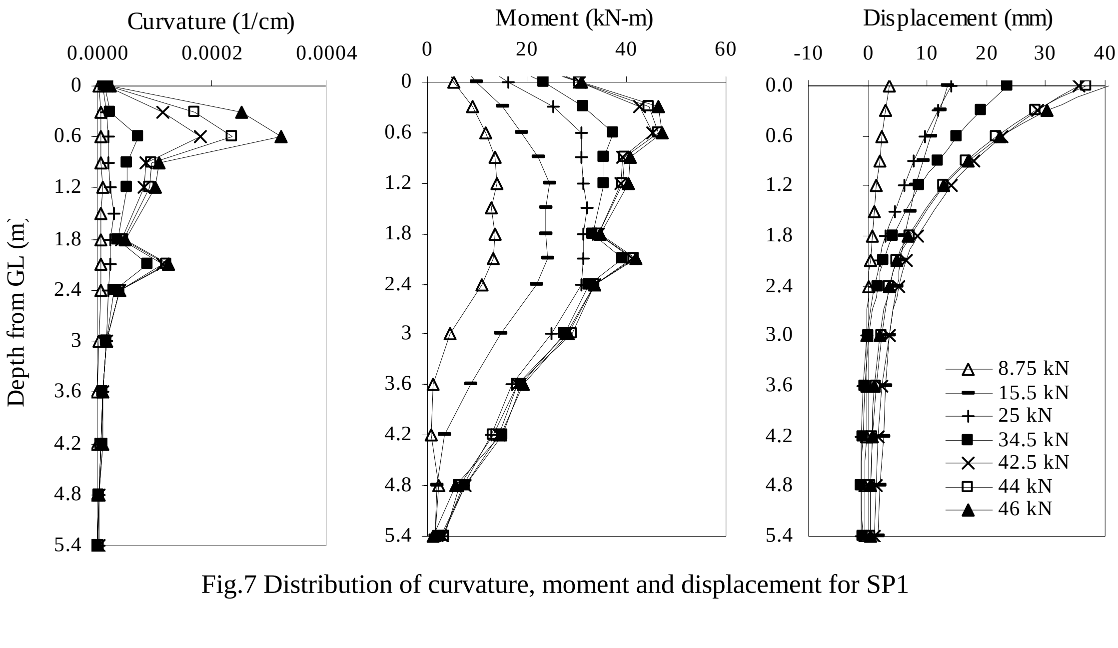


Fig.7 Distribution of curvature, moment and displacement for SP1

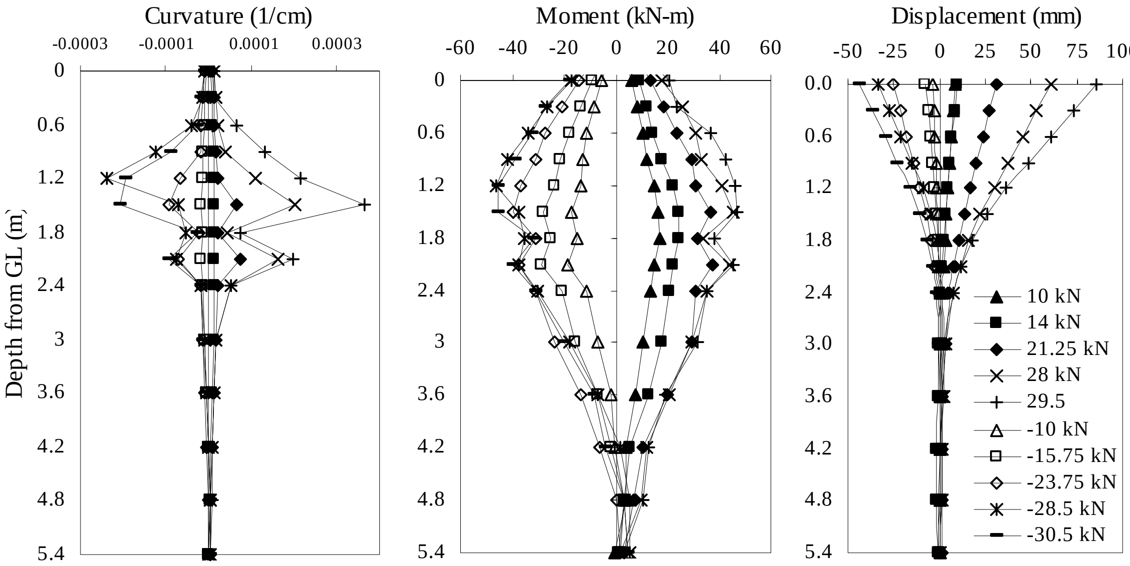


Fig.8 Distribution of curvature, moment and displacement for SP2

3.3 Curvature Distribution and equivalent plastic hinge length

Magnitude of the local deformation upon formation of a plastic hinge is important in characterization of the inelastic response of piles. Local-deformation can be expressed in terms of curvature distribution along the length of the pile. Curvature distributions along both of the piles were calculated from strain data and are shown in Fig. 7 and Fig. 8. Although the measured curvature showed considerable variation, the region of maximum flexural deformation was fairly well defined.

For specimen SP1, maximum curvature was measured at the depth of 0.6m, where the damage of the pile was also observed. In specimen SP2, maximum curvature was observed at the depth of 1.5 m from GL, however, the maximum damage in the pile was observed little bit higher at the depth of 1.2m.

Moment distribution were calculated along the pile from curvature data using the moment curvature curve obtained from the beam test conducted on the specimen with same section as test piles. Horizontal displacement along the pile depth were obtained from double integration of the curvature data. Cubic spline function was used to approximate the scattered curvature data before integration.

For SP1, maximum bending moment was observed at the depth of 0.6m from the GL. And for SP2, maximum bending moment was observed at 1.5m from GL. For cyclic loading, the shifting down of the plastic hinge location can have occurred due to reduced stiffness of the soil due to the repeated cyclic loading. Distribution of bending moment and horizontal displacement along the pile lengths are shown in Fig 7 and Fig. 8.

4. Conclusions

Considering the complex phenomena of pile-soil interaction during earthquakes, analysis of experimental data from lateral load testing on a full scale piles embedded into the field gives better understanding of the actual behavior of piles. Results of an experimental program on lateral loading test on single full scaled piles embedded into the ground are presented in this paper. Local deformations in the piles were studied from the distribution of curvature. Plastic hinge was formed at 0.6m (2D) depth from GL for the monotonic loading where as at 1.2m (4D) for the reversed cyclic loading. The lowering of the plastic hinge occurrence in the case of reversed cyclic loading is due to the decrease in the soil resistance caused by the repeated cyclic loading. The experimental data will be used as the base for further analytical study of soil structure interaction.

6. References


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