13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1628

EFFECT OF CONFINING SOIL PRESSURE ON RESPONSE BEHAVIOR OF RC PILES UNDER GROUND

Takeshi MAKI[1] and Hiroshi MUTSUYOSHI[2]

SUMMARY

The objective of this paper is to clarify the ductile behavior of reinforced concrete piles under ground by considering the effect of surrounding soil pressure on the ductility of RC piles. First, the effect of local confining pressures at plastic hinge on ductility of flexural RC beams was considered experimentally and analytically. It was clarified that soil pressures at a localized plastic hinge restrain the spalling of cover concrete, which results in improving ductility and relieving a reduction of restoring force due to buckling of longitudinal reinforcements. In addition, the effect of surrounding soil pressures on response behavior and damage of RC piles subjected to the horizontal cyclic loads at pile head was experimentally investigated. In the case of lateral loading at pile head, gap can arises between pile and soil, which causes no or less confining pressures. Therefore, the so-called confining effect due to surrounding soil pressures cannot be expected when pile is subjected only to inertial horizontal force at pile head.

INTRODUCTION

The recent seismic design methodologies of reinforced concrete structures based on the structural performance evaluation increase the necessity to develop the analytical method, which can precisely evaluate overall responses of structures including their foundations and surrounding soil. Seismic performance of RC structures can be influenced by not only the structural details of superstructure but also those of foundation located under ground [1]. The current JSCE code prescribes that it is desirable to conduct a dynamic response analysis of RC structure-foundation-soil entire structural system in the process of seismic performance verification. However, the response behavior of foundation strongly depends on the properties of surrounding soils, which cause nonlinear external distributed forces on pile's surface during an earthquake. The seismic behavior of pile foundation including its surrounding soil has been qualitatively clarified, but the effect of surrounding soil pressure on the pile's surface, resulting in working as a confining stress of RC pile, has not yet been evaluated. If the confining effect of soil pressure is taken into account in the seismic design process, more efficient seismic design of RC structural system will be realized. Therefore, such effect is desirable to be automatically simulated by the applied analytical method in the performance verification process.

---

[1] Research Associate, Saitama University, Japan, E-mail: maki@mtr.civil.saitama-u.ac.jp
[2] Professor, Saitama University, Japan, E-mail: mutuyosi@mtr.civil.saitama-u.ac.jp

The objective of this paper is to clarify the response behavior of RC piles under ground, by considering the effect of surrounding soil pressures on the ductility of RC piles, especially focusing on buckling of longitudinal reinforcement and spalling of cover concrete of the flexural members. First in this paper, the results of cyclic loading tests and analyses of RC flexural beams with and without confining pressures at their plastic hinge regions are reported. Then, the results of cyclic loading tests of RC model piles under ground are discussed.

CYCLIC LOADING TESTS OF RC BEAMS

Experimental Program

The objective of the loading tests was to evaluate the effective confining stress level on the flexural ductile behaviors of RC members [2][3]. **Figure 1** shows the concept of RC beam tests discussed in this chapter. The similar moment distribution as that of pile subjected to horizontal inertial force at pile head can be realized in two-point loading test of simple beam as shown in the figure. Experimental setup is illustrated in **Figure 2**. Simply supported beams with 2.1m span length under constant (2MPa) axial compressive stress were tested and two-point cyclic displacements were applied through a loading actuator at a center of the beam specimen with 300mm spacing.

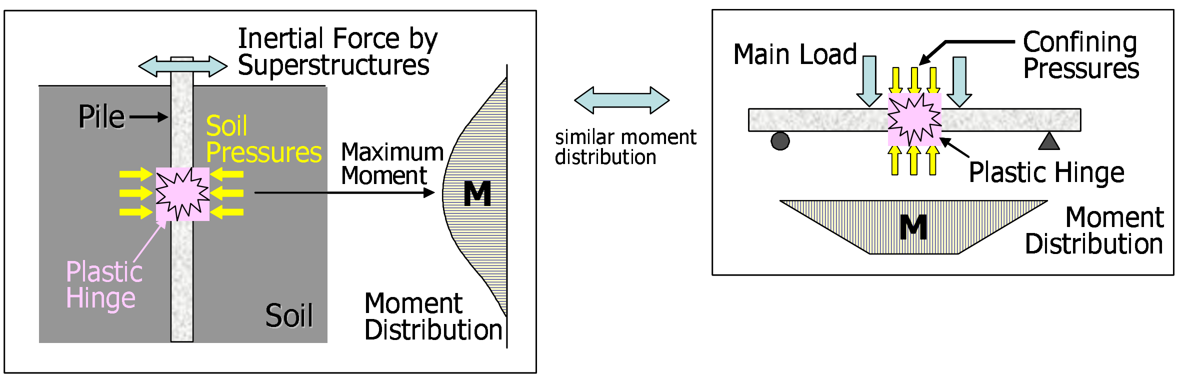

Figure 1: Modeling of RC Pile by RC Beam Test

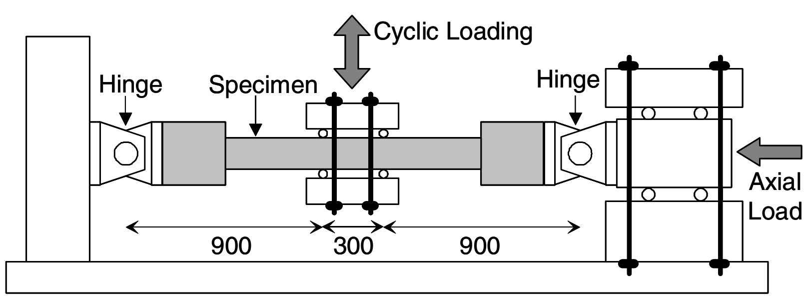

Figure 2: Loading Setup for RC Beams

Table 1 shows typical characters of three experimental cases, and **Figure 3** shows the details of the specimens tested in the experiments. Each specimen had 150*150mm square cross section. The deformed bars of 6mm diameter (D6) were placed as longitudinal reinforcement with the cover thickness of 15mm from the specimen surface to the center of the bars; accordingly, the effective depth of the beams was 135mm and the longitudinal reinforcement ratio was 1.13%. For lateral reinforcement, the deformed bars of 3mm diameter (D3) were arranged with 75mm spacing in all specimens. At the center in span of the beams, the lateral reinforcement spacing was 150mm, as shown in **Figure 3**, resulting in the buckling of longitudinal reinforcement could be locally induced. Compressive strength of concrete was around 50-55MPa.

Table 1: Experimental Variables and Specimens

Case	Cross Section (mm)	Longitudinal Reinf. Ratio (%)	Cover Thick-ness (mm)	Effective Depth (mm)	Lateral Reinf. Spacing (mm)	Confinement Type
A-1	150 x 150	1.13 (8-D6)	15	135	75	No confinement
A-2						Styrol Only
A-3						Rubber + External Rods

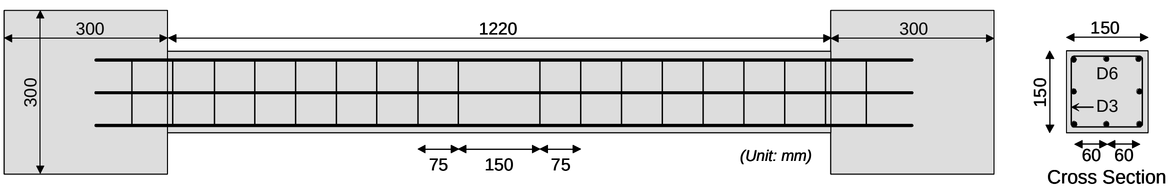

Figure 3: Specimen Details

In this experiment, two types of confining method were adopted, using styrol form and rubbers with external rods. These confining methods are illustrated in **Figure 4**. Confinement was given in plastic hinge region between two loading points. In these confined regions, the spacing of lateral reinforcement was 150mm. The reason why Styrol or Rubber was adopted as confining material, was to give a relatively low confining stress, compared with a stress induced by a steel jacket or FRP wrapping, commonly used for seismic strengthening of RC columns. In the case of rubber confinement (A-3), 200kPa of initial stress was introduced by controlling screws of external rods. Consequently, A-2 could be low-confinement case and A-3 be relatively high-confinement case. Passive confining stress was measured by small pressure cells located between specimen's surface and confining material.

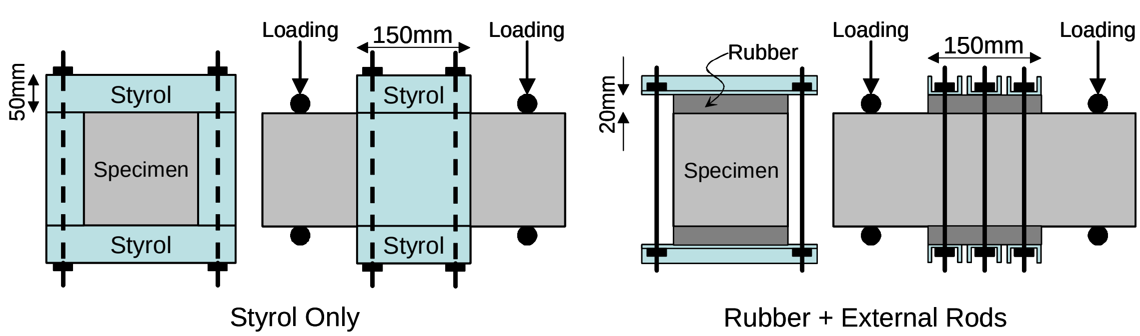

Figure 4: Confinement Types in Plastic Hinge Regions

Test Results

Obtained vertical load and displacement skeleton curves are shown in **Figure 5**. In this figure, vertical displacements are normalized by yield displacement of each specimen, and the effect of geometrical nonlinearity is eliminated. From these results, ductility was slightly improved due to confining stresses. In the case A-3, 200kPa of confining stress was kept until 50mm of vertical displacement, and then increased to around 300kPa with the increase of displacement amplitude. This confining stress of 200-300kPa might be effective on the buckling behavior of longitudinal bars and the spalling of cover concrete because the buckling was observed at the different location as shown in **Figure 6**.

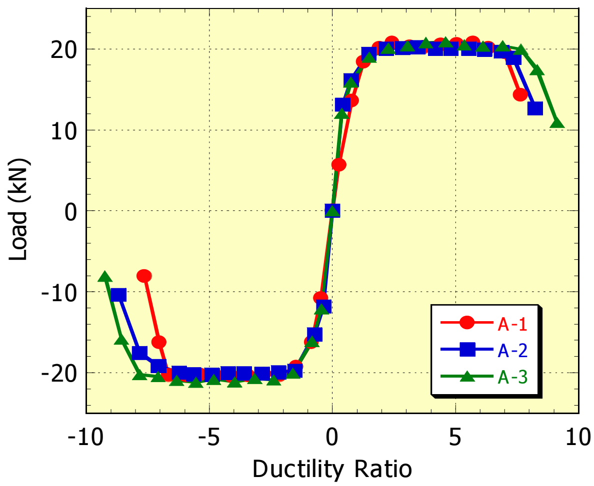

Figure 5: Vertical Load and Displacement Relationships

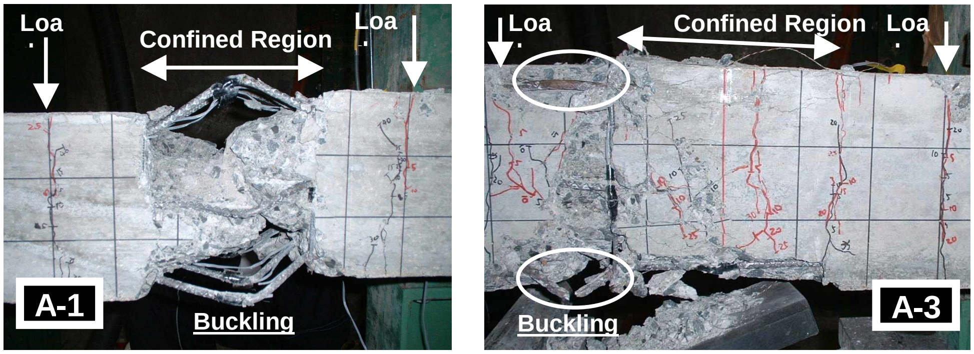

Figure 6: Ultimate State of A-1 and A-3 Specimens

The buckling of longitudinal bars could be observed at the center of the specimens (150mm stirrup spacing region) in A-1 and A-2, as intended localization of nonlinear behavior. However in A-3, buckling was not occurred in the large spacing region but in the next 75mm spacing region, as shown in **Figure 6**. In order to evaluate the effective confining stress quantitatively, further investigations are needed for various types of cross section, amount and locations of longitudinal bars, and spacing of stirrups.

ANALYTICAL INVESTIGATION ON EFFECT OF CONFINING PRESSURES

Analytical Model

In order to clarify the mechanism of confining effect on ductility of RC members, analytical investigations were conducted by using 3-dimensional finite element analysis program COM3, which was developed by Prof. Okamura and Maekawa, and their colleagues in University of Tokyo [4][5]. The nonlinear path-dependent type constitutive law of reinforced concrete was installed in the program, and the applicability for static/dynamic analysis of various types of RC structures has already been verified in these ten years [5]. The constitutive law of reinforced concrete installed in this program includes the elasto-plastic and fracture model, tension stiffening/softening model for concrete, and nonlinear reinforcing bar model including Bauschinger effect and stress release paths due to buckling. Accordingly, these constitutive models can be applied for the analysis of nonlinear post-peak behavior of RC members. By using this method, analytical simulations of cyclic behavior of RC beams discussed in the previous chapter were conducted.

Figure 7 shows the finite element modeling of RC beam used in the investigations. 20 nodes 3D solid elements with nonlinear constitutive laws of concrete and reinforcement were applied for RC region, while elastic elements were used for loading plates. **Figure 8** illustrates the loading position of confining pressures in plastic hinge region of RC beam specimens. The constant confining pressure of 0.0 N/mm^2 or 0.5 N/mm^2 was applied to the elements between the two loading points, as shown in the figure.

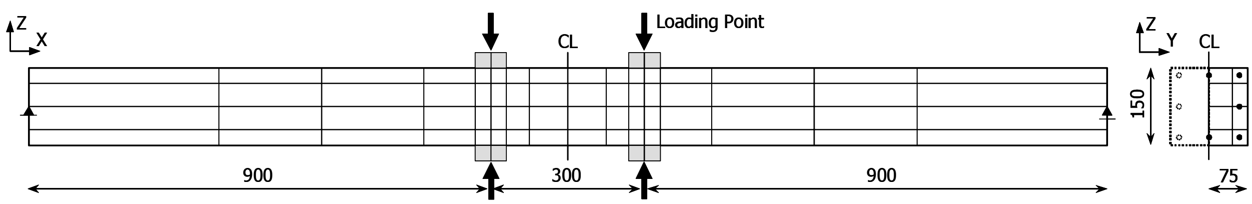

Figure 7: Finite Element Modeling for RC Beam Specimen

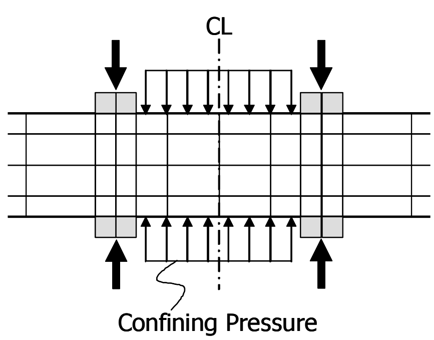

Figure 8: Loading Position of Confining Pressure

Analytical Results

Figure 9 shows the load-displacement hysteresis curves of no confining specimen, which were obtained experimentally and analytically. These results indicate the applicability of applied method to the subsequent analytical investigations. **Figure 10** shows the comparison of load-displacement skeleton curves of unconfined and confined beams. It can be observed that the ductility of flexural RC member can be improved by the constant confining pressure applied in plastic hinge region. **Figure 11** illustrate the stress-strain curves of longitudinal reinforcements in plastic hinge regions. The decrease of compressive stress due to buckling can be observed in both cases, however, the remarkable increase of compressive strain was restrained in confined specimen. This fact indicates that the applied confining pressure in plastic hinge region restrains lateral strain increase of cover concrete (it might induce the spalling of cover concrete), which results in the gradual progress of lateral deformation of longitudinal reinforcement.

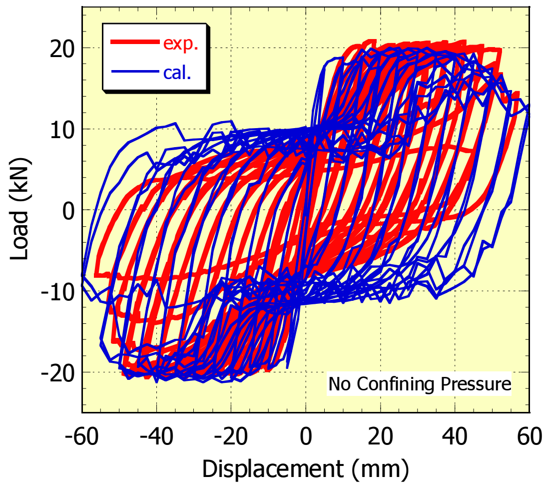

Figure 9: Load-Displacement Hysteresis Curves

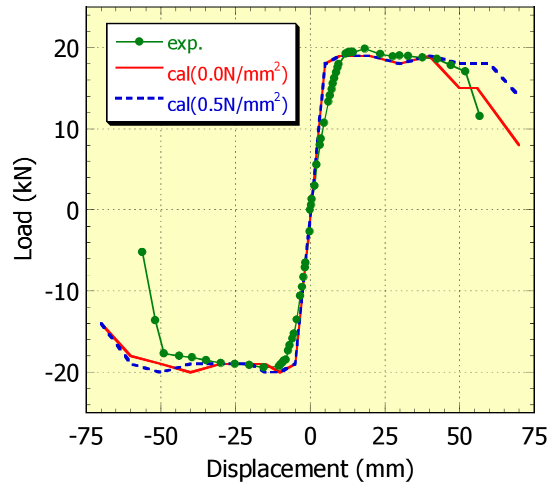

Figure 10: Comparison of Skeleton Curves

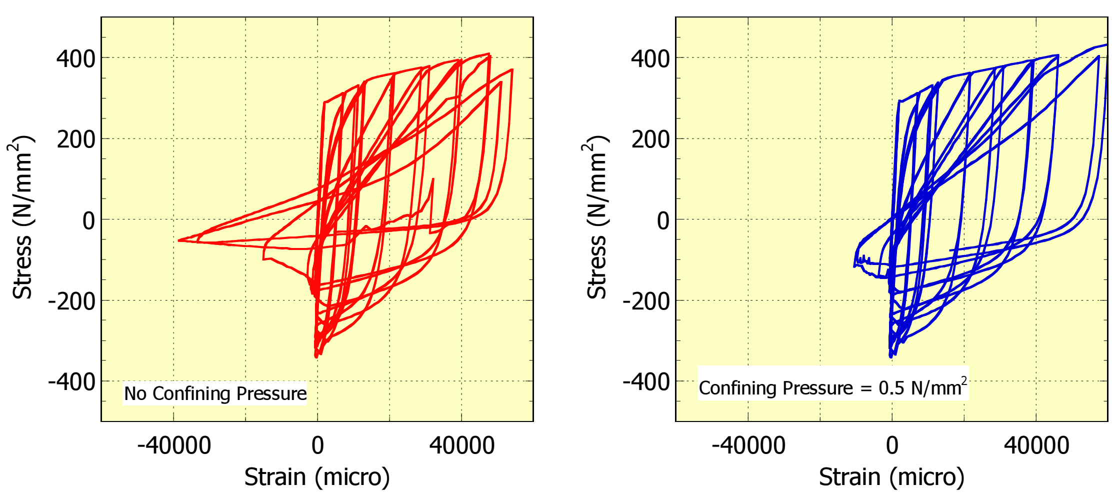

Figure 11: Stress-Strain Hysteresis Curves of Longitudinal Reinforcement

LATERAL CYCLIC LOADING TESTS OF RC PILES UNDER GROUND

Introduction

In the previous chapter, it was experimentally and analytically clarified that the confining pressures applied in plastic hinge region improve the ductility of RC members. The confined member cannot avoid the buckling of longitudinal reinforcements at confining pressure level of $0.5N/mm^2$ as applied in this study, whereas the relatively gradual decrease of restoring force can be realized rather than unconfined RC members. However, soil pressures acting on the pile surface will vary during earthquake, due to the irregular deformations of piles and surrounding soils. In this chapter, the effect of soil pressures on the response behavior is investigated, by conducting the lateral cyclic loading tests of RC pile under ground, in order to consider the effects of various soil pressure levels on the flexural behavior of piles under horizontal cyclic loads applied at pile head [2][3]. The experimental data will be utilized for the subsequent analytical investigations.

Experimental Setup and Variables

Figure 12 shows the loading setup for RC piles. Pile specimen was fixed to the bottom of the rigid soil box, and the box was filled by wet sand around the specimen. The soil was sufficiently compacted by using concrete blocks and the consolidation state of soil was almost constant for all the test cases. The void ratio of the compacted soil was about 0.7 and it may correspond to the relative density of around 80%. The horizontal cyclic displacements were applied at the top of the specimen under constant vertical load of 20kN (axial stress of 2MPa).

6mm diameter deformed bars (D6) were used for longitudinal reinforcement with cover thickness of 15mm, and 3.2mm diameter deformed bars (D3) were used for lateral reinforcement with 100mm spacing. Cross sectional detail is also shown in **Figure 12**. The specimen had sufficient shear capacity compared with flexure, but it may seem that the spacing of 100mm was relatively too large for conventional RC members. The reason of this arrangement detail is that the buckling of longitudinal bars is intended to occur easily even under low confining pressures. Soil pressure cells were attached to the pile surface for measuring soil pressure acting on the pile, and the deformations of the specimens were measured by the strain gauges attached on the longitudinal reinforcement. Compressive strength of concrete was around 50-55MPa.

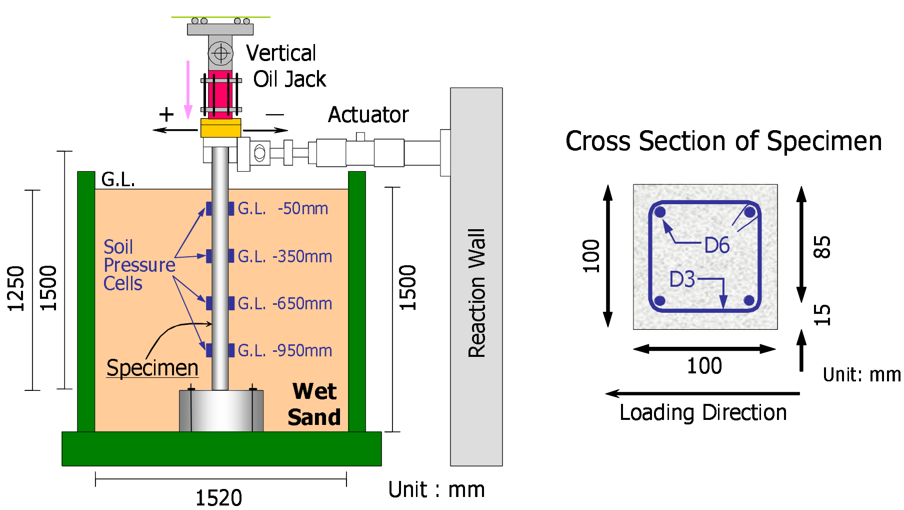

Figure 12: Loading Setup and Cross Sectional Detail

Table 2 shows the test variables of this experiment. As stated in the previous section, the objective of this experiment was to consider the effect of different soil pressure level. Therefore, the loading history was chosen as the experimental variable. The case P-0 was intended to check the soil pressure levels by using steel elastic specimen having the same initial flexural stiffness as that of RC pile specimens, and loading history was changed for other three RC pile cases. In the case P-3, one-side cyclic displacements were applied until the amplitude of 60mm, and then reversed cyclic displacement was applied from the amplitude of 65mm and larger.

Table 2: Loading Setup and Cross Sectional Detail

Case	Pile Specimen	Loading Pattern	Amplitude Increment
P-0	Steel	Reversed Cyclic	5 mm
P-1	RC (100 x 100mm)		
P-2			15 mm
P-3		One-Side Cyclic	5 mm

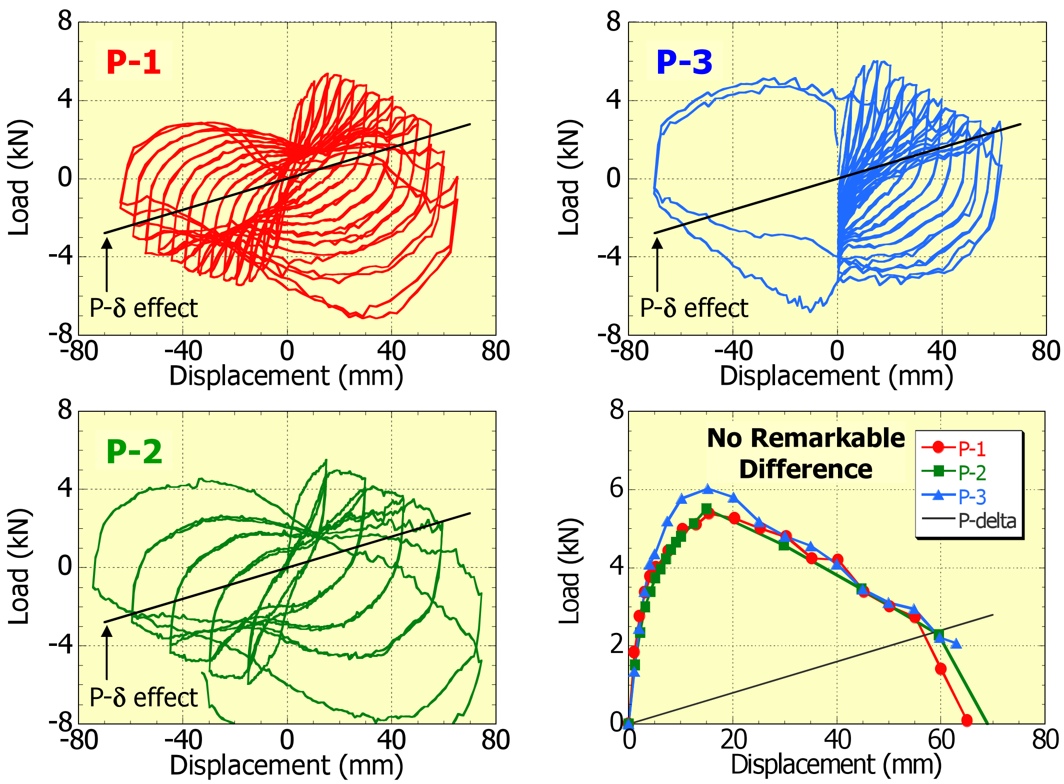

Figure 13: Horizontal Load and Displacement Relationships of RC Pile Cases

Test Results

Horizontal load and displacement relationships of P-1, P-2 and P-3 are illustrated in **Figure 13**. The dotted line in each figure indicates the load due to P-δ effect with the plastic hinge location at G.L.-250mm,which was assumed from the crack distributions shown in **Figure 14**. No remarkable differences could be observed in the load-displacement curves of the piles subjected to the different loading histories. The buckling of longitudinal bars occurred at the depth around G.L. -250mm when the horizontal displacement was around neutral in the 60mm amplitude cycle for P-1 and P-2, whereas for P-3 in 65mm reversed cyclic loop, which was its virgin negative loading cycle.

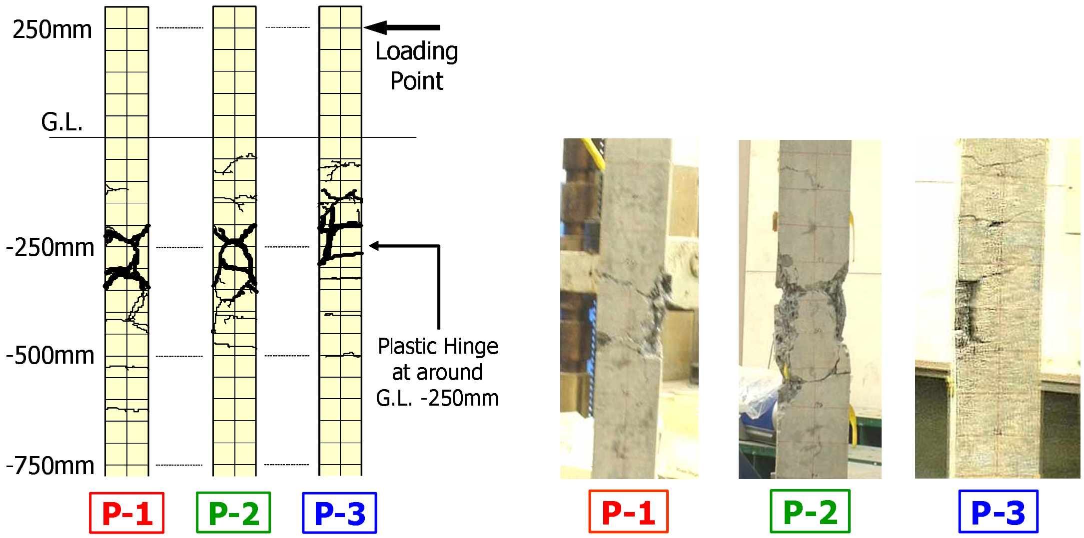

Figure 14: Crack Distributions and Damage States of Specimens

Figure 15 shows the variations of soil pressures at the depth of -50mm and -350mm. The plastic hinges of the pile were located between these two points. Soil pressures at G.L.-350mm (deeper than hinge location) decreased after the yielding of pile specimens, whereas the pressures at G.L.-50mm kept increasing. Soil pressure level at the plastic hinge location might be around 200-300kPa in each case.

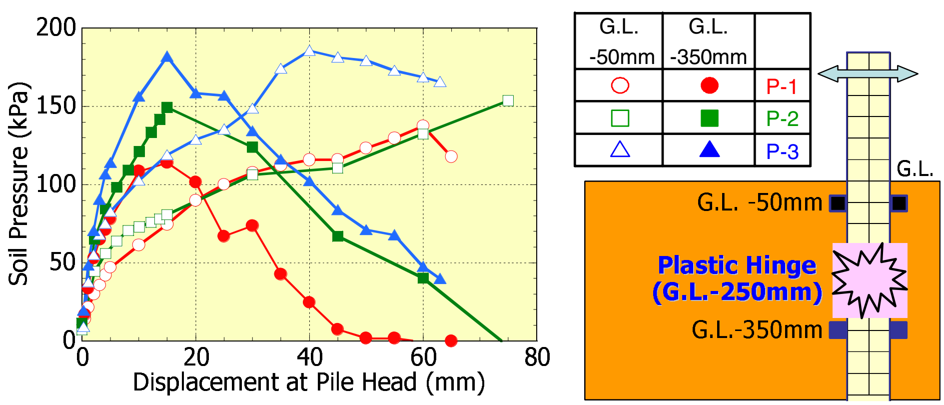

Figure 15: Soil Pressure Variations

During the loading tests, gap was found between the specimen and surrounding soil, as shown in **Figure 16**, which resulted in no confining stress onto the specimen at the horizontal displacement of around neutral. Therefore, same as could be observed in the beam tests, the buckling of longitudinal reinforcements occurred at the displacement concerned. From these experimental results, it can be concluded that no or little effect of confinement by surrounding soil on enhancing the flexural behavior of RC piles can be expected when the pile is subjected only to the horizontal inertial force at pile head. Further investigations are needed, especially analytical studies, in the case of the pile subjected to the lateral soil movements or in the complex mode including both actions.

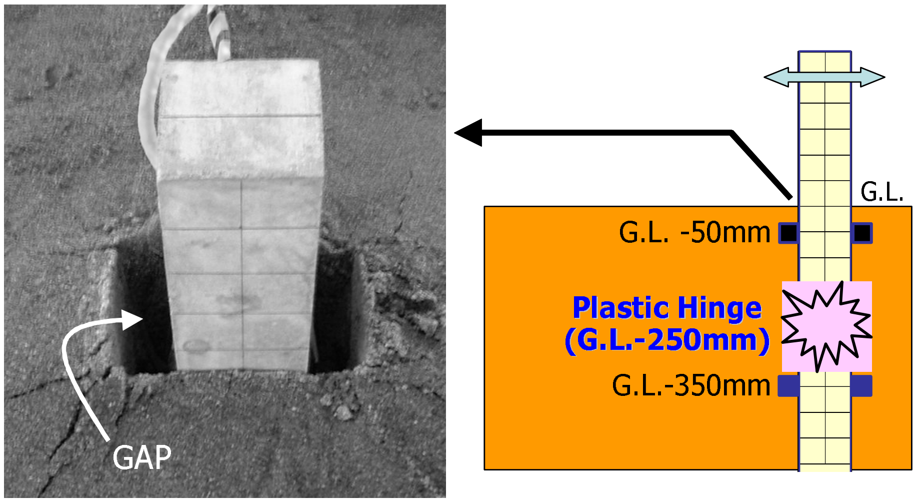

Figure 16: Remarkable Gap between Pile and Soil

CONCLUSIONS

The objective of this paper is to clarify the effect of confining stress of soil on the flexural behavior of RC piles under ground, and the cyclic loading tests of RC beams and piles were conducted, with the additional analytical investigations. Followings are the summary of this research.

From the results beam loading tests, 200-300kPa of confining stress might be effective on the enhancing of the flexural behavior of RC members, a little improvement of ductility of the beam could be confirmed from the experiment. Further investigations are needed considering the stirrup spacing and the reinforcement arrangement. From the results of subsequent analytical works, confining pressures in plastic hinge region restrain the spalling of cover concrete, which results in the gradual progress of lateral deformation of longitudinal reinforcement, relative to unconfined members.

From the results of pile loading tests, the measured soil pressures were around 200-300kPa similar to the results in beam tests, but no confining effect on the flexural behavior of RC piles could be observed, due to the buckling of reinforcing bars occurs at around the neutral displacement at pile head, which resulted in no or little confining stress acted on the pile surface. Therefore, no confining effect can be expected when the pile is subjected only to the horizontal force at pile head.

The flexural behavior of RC piles in complex mode including both horizontal force at pile head and lateral soil movements may as well be investigated using the analytical method that can automatically consider the varying confining stress, such as the finite element method.

ACKNOWLEDGEMENTS

The FEM program COM3 used in this research was offered by Prof. Koichi MAEKAWA in University of Tokyo, Japan. His kind cooperation is gratefully acknowledged. This research was executed with the support of Industrial Technology Research Grant Program in 2002 from New Energy and industrial Technology Development Organization (NEDO) of Japan.

REFERENCES

1. Maki, T., Takano, K. and Mutsuyoshi, H. (1998). "Response Analysis of Reinforced Concrete Pier Considering Nonlinearity of Ground." *Transactions of the Japan Concrete Institute*. Vol.20, 125-130.
2. Maki, T., Okitsu, M., Nakamura, M. and Mutsuyoshi, H. (2003). "Effect of Confining Soil Pressure on Ductility of RC Piles under Ground." *Proceedings of The 9th East Asia-Pacific Conference on Structural Engineering and Construction*. Bali, Indonesia, included in CD-ROM.
3. Maki, T., Okitsu, M., Nakamura, M. and Mutsuyoshi, H. (2003). "Effect of Surrounding Soil Pressures on Ductility of RC Piles under Ground." *Proceedings of The 27th JSCE Earthquake Engineering Symposium*. Osaka, Japan, included in CD-ROM. (written in Japanese)
4. Okamura, H. and Maekawa, K. (1991). *Nonlinear Analysis and Constitutive Models of Reinforced Concrere*. Gihodo-Shuppan, Tokyo, Japan.
5. Maekawa, K., Pimanmas, A. and Okamura, H. (2003). *Nonlinear Mechanics of Reinforced Concrete*. Spon Press, New York, USA.