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Full Length Research Paper

Static and dynamic response analysis of reinforced concrete piles

I. Ezz El-Arab[1]* and T.Maki[2]

[1]Structural Engineering Department, Faculty of Engineering, Tanta University, Egypt.
[2]Arab Center for Engineering Studies (ACES), Soil Laboratory, United Arab Emirates.

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In order to clarify restoring force and deformation characteristics of reinforced concrete (RC) pile – soil system, static and dynamic loading tests were conducted for RC piles in dry sandy soil. It was clarified that, within the range of the tests, the restoring force at pile head can be determined from the maximum damaged depth of the pile which depends on the relative stiffness between the pile and its surrounding soil. Additionally, it was observed in the dynamic loading tests that the loading velocity has a small effect on the restoring force of the pile. The derived results from these tests can be used to establish an accurate evaluation method for seismic performance of RC structures.

Key words: Dynamic and static analysis, reinforced concrete piles, dry sand, restoring force.

INTRODUCTION

Due to any seismic excitation, many engineers and researchers worked out to study and analyze the behavior of damaged reinforced concrete (RC) structures. Lysmer et al. (1999). reported that the response of a superstructure is usually influenced by behavior of the structure foundation and its surrounding soil.

The present design Specifications of Highway Bridges (1996) states that a bridge pier should be designed to have a lower horizontal capacity than its foundation. Conversely, according to the pre-mentioned studies, an accurate evaluation of the entire system's response, including the superstructure, foundation and the surroundding soil, should be conducted instead of obtaining the individual response of the structural components. Therefore, in order to establish such an overall evaluation method of the entire system's response due to seismic attack, a set of reversed cyclic and dynamic loading tests was conducted for piles inside a model soil. There are few experimental results of RC piles, presented by Fukui et al. (1998) and Fukuda et al. (1997). As a consequence, the result of the current experimental program of piles is of high importance in clarifying the interaction between the foundation and its surrounding soil.

EXPERIMENTAL PROGRAM

Experimental loading setup and specimen variables

Figure 1 shows the experimental loading system. RC pile specimens were fixed to a steel box. The steel box was filled by dry sand. Two types of soil conditions were considered (loose and dense). Horizontal displacements were applied to the specimens through a loading actuator that resulted in rotations of the piles at their connections to the attached pile heads. Deformations and strains of the concerned parts of the specimens were measured by the use of strain gauges and earth pressure cells attached to the piles' surfaces.

Eight specimens were tested in the current experimental program. The test variables included the pile's material (steel, RC), shape (square, circular), soil stiffness (loose, dense) and loading type (monotonic, reversed cyclic and dynamic loading). Table 1 shows the experimental variables of the specimens. Details of cross sections of the RC specimens are shown in Figure 2. All the RC pile specimens have stirrups of φ 3.2 mm @100 mm.

Loading program

Both static and dynamic loading tests were conducted (Table 1). Figure 1 shows that stroke signals were dispatched from a computer

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*Corresponding author. E-mail: islamezzelarb@yahoo.com. Tel: +20101 999 87 52.

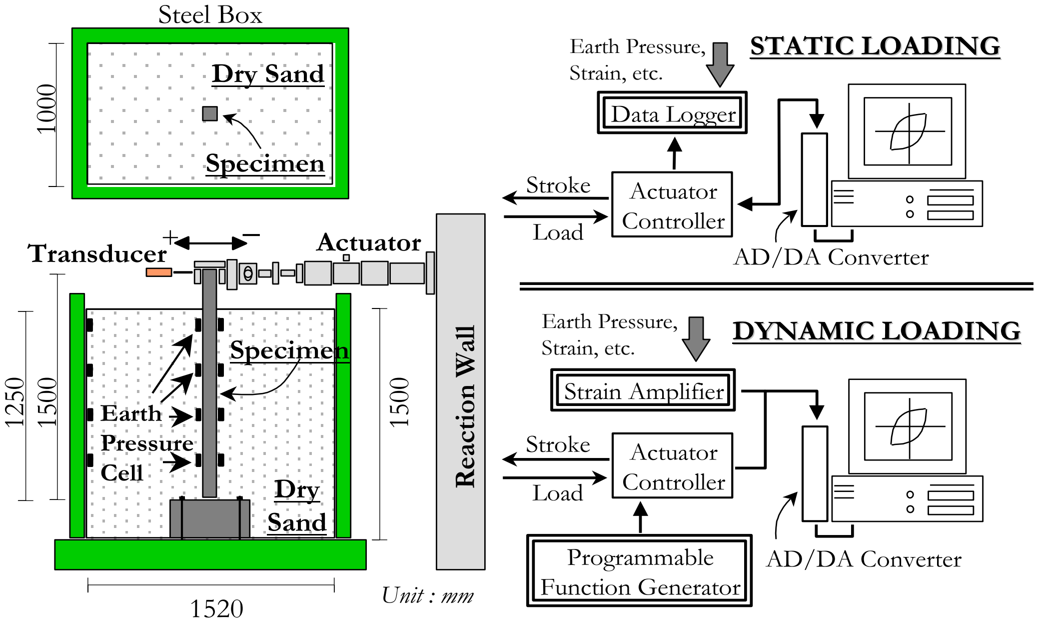

Figure 1. Experimental loading setup and system.

Table 1. Experimental variables of test specimens.

No.	Material	Shape	Reinforced	Soil condition	Loading type	Specimen name	Pile stiff.	Soil stiff.	Rel. stiff.
1	RC	Square	D6	None	Monotonic	RCR-N-M	------	------	------
2				Loose		RCR-L-M	------	------	------
3					Rev. Cyclic B	RCR-L-R	Mid.	Low	2
4				Dense	Rev. Cyclic A	RCR-D-R	Mid.	High	3
5					Dynamic	RCR-D-D	------	------	------
6			D10	Loose	Rev. Cyclic B	RCR2-L-R	High	Low	1
7		Circular	D6	Dense	Rev. Cyclic A	RCC-D-R	Low	High	4
8					Dynamic	RCC-D-D	------	------	------

Soil condition ... Loose: Relative density Dr=57.4%, Dense: Relative density Dr=72.6 ～ 80.4%; Concrete strength $f_c^{\prime}$ = 40,000 kN/m^2, steel yielding stress = 360,000 kN/m^2.

to the actuator while feedback stroke, load and different measured data were returned to the computer. For the reversed cyclic loading tests, both multiple integers of 5 and 10 mm displacement amplitude were considered in the cycles, respectively. For the dynamic loading tests, sine curve signals were dispatched at every 0.002 s from a program function generator and measured data were conveyed to the computer through a dynamic strain amplifier. Multiple integers of 10 mm displacement amplitude were used and number of repetition of each cycle displacement was 10 times in the dynamic loading tests. Since the velocity response at the ground surface has a constant value within an ordinary period's range, the applied wave's frequency was varied to keep a maximum loading velocity of 200 mm/sec in each cycle Clough and Penzien 1993, and and ProShake Cer. 1.1).

RESULTS OF REVERSED CYCLIC LOADING TESTS

Restoring force – displacement relationships

John (1985); Chopra 1995 reported that the interaction between RC pile and its surrounding soil is dependent on their relative stiffness. For a quantitative evaluation of such an interaction, ranking values relative stiffness with

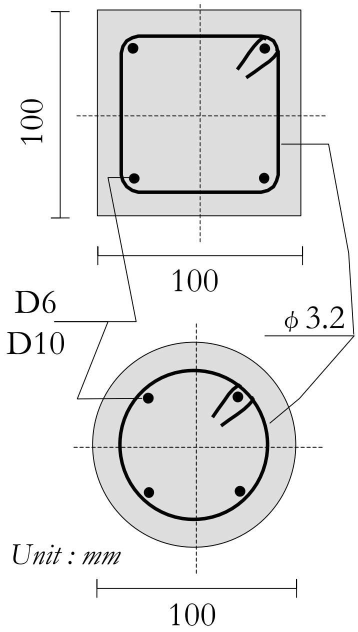

Figure 2. Cross sections of RC specimens.

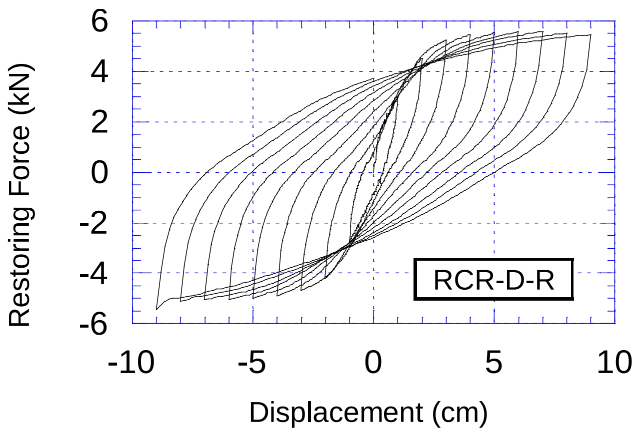

Figure 3. Hysteresis curve for RCR-D-R (No.8).

clear physical meaning should be adopted. Hereafter, a proposed ranking, shown in Table 1, is used for comparison between the cases. The smaller the ranking, the higher the relative stiffness between the pile and the soil results.

Figure 3 shows the relationship between the displacement and the restoring force of specimen RCR-D-R (No.4). It can be observed that a fat hysteretic behavior was obtained resulting in almost no pinching of the hysteretic loops. The residual displacement at each cycle, which can be defined as the displacement when the load degrades to become zero during unloading, was about 50% of the associated maximum displacement of the concerned cycle. A similar observation was reported by Maki and Mutsuyoshi (1999) for specimen RCR-L-R (No.3). Also, a similar behavioral tendency was found for specimens No.6 and No.7. Figure 4 shows the relationships between the plastic ratio and the equivalent-damping factor for four RC pile specimens. The equivalent damping factor of each specimen was calculated from the area of each cycle while the plastic ratio was defined as the ratio between the displacement (amplitude) to the yield displacement of each specimen. The yielding displacement is defined as the intersection between stiffness after cracking and stiffness after yielding of approximated tri-linear skeleton curves of the specimens. A maximum difference of about 5% was observed between the four specimens. It can be observed that a lower damping was found for the case of dense soil or low stiffness piles. The hysteretic damping was found to be high for a RC pile – soil system in cases of smaller relative stiffness between the RC piles and their surrounding soil.

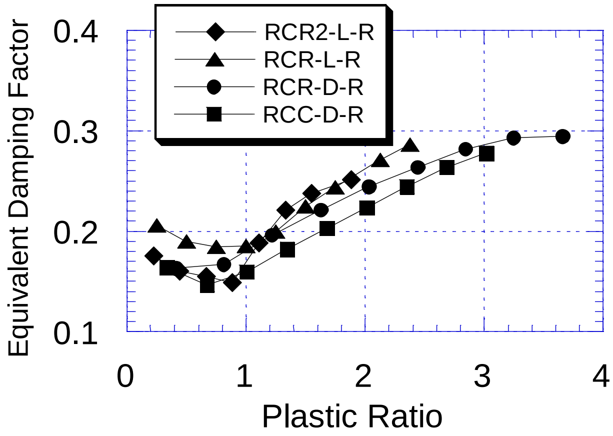

Figure 4. Equivalent damping factor.

The difference between the plastic ratio versus the restoring force of the RC piles surrounded by both loose and dense soils is shown in Figure 5a and b. Different plastic ratios of all specimens were observed as a result of the different input actuator displacements and the defined yield displacements. Different patterns of load increase were observed due to the soil compaction.

Nevertheless, it cannot be judged whether such differences are dependent on the soil condition or on the maximum plastic ratio.

Pile deformation and maximum damaged zones

Figure 6 shows the curvature distributions of the pile specimens along their depth at plastic ratios of 1.0 (μ=1.0). Each curvature was calculated from the recorded strains of the strain gauges attached to the longitudinal reinforcement. Maximum curvatures of the specimens

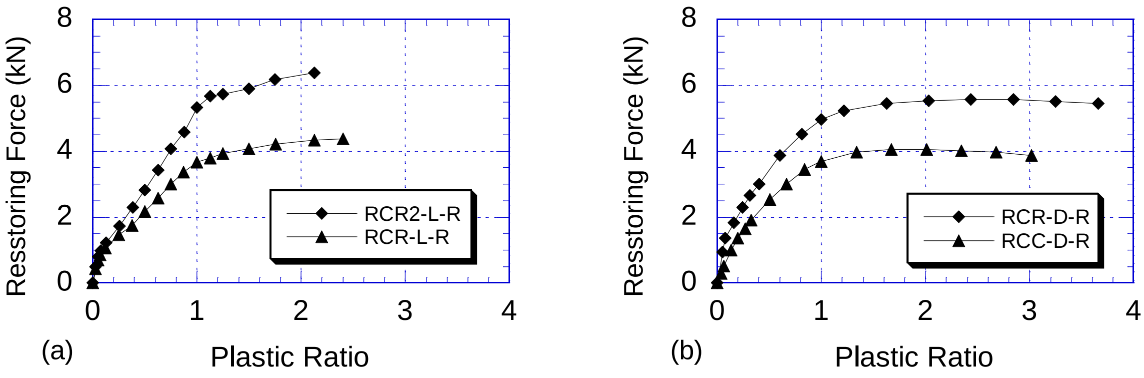

Figure 5. Skeleton curves for (a) loose ground and (b) dense ground.

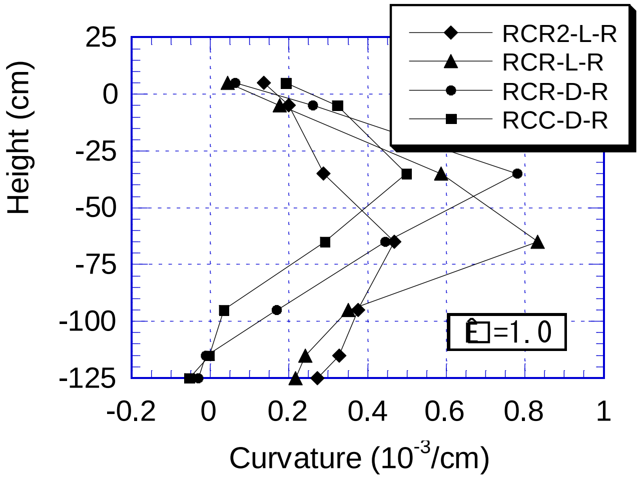

Figure 6. Curvature distributions.

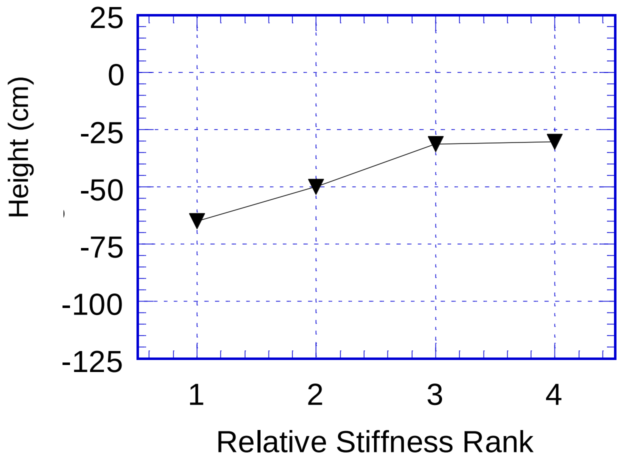

Figure 7. Variation of maximum curvature height of specimen RCR-L-R.

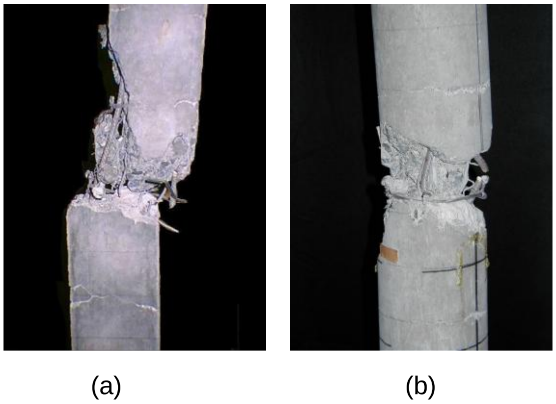
(a) (b)

Figure 8. Damage states for (a) square and (b) circular piles at maximum curvature displacement.

were recorded at depths ranging from -50 to -80 cm for the cases of pile specimens in the loose soil, while those depths were found to be from -20 to –50 cm for the cases of pile specimens in the dense soil. A comparison between specimens RCR-L-R and RCR2-L-R or between RCR-D-R and RCC-D-R shows that the curvature's increase expanded to lower levels in the case of stiffer piles (specimens RCR2-L-R and RCR-D-R). The heights at which zero curvatures were obtained was from between –100 to –115 cm in the cases of dense soil. Such an observation could be attributed to the observed shift of the maximum curvatures. Figure 6 shows the variation of height at which the maximum damages were obtained of the four specimens. In Figure 7, It can be clearly observed that the height of maximum curvature decreased as the relative stiffness increased.

DYNAMIC LOADING TEST RESULTS

Damage of piles after loading

The objective of conducting the dynamic loading tests was to clarify the effect of cycle repetition and loading

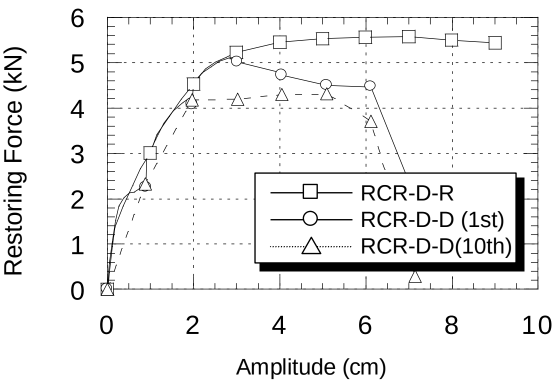

Figure 9. Skeleton curves under static and dynamic loading.

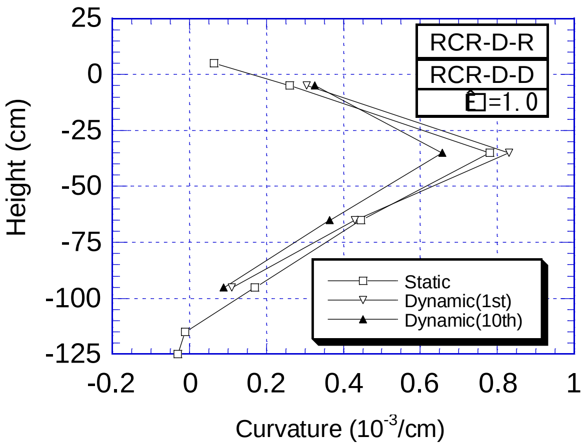

Figure 10. Curvature distributions.

velocity on the resulting restoring force characteristics. Similar to the static loading tests, two RC specimens (square and circular) were used. Hereafter, a focus on repetition showed a decrease from the static one at almost all the pile length. This can be attributed to the the behavior of specimen RCR-D-D was paid though a similar behavior was observed for specimen RCC-D-D. Both specimens reached the ultimate state at approximately the same displacement levels. Such a state was reached by cutting of the longitudinal reinforcement (Figure 8). A comparison between the ultimate states in the static loading tests and in the dynamic loading will be discussed next.

Restoring force – displacement relationships

Figure 9 shows a comparison between the skeleton (displacement – restoring force) curves of the dynamically tested specimens with those tested statically. Prior to yielding, no much difference could be observed while a decrease in the restoring force could be clearly observed and high strength degradation after a displacement of 60 mm was pronounced. In the range of the current experiments, the restoring force of the RC pile – soil system is independent on the loading velocity unless the yielding load has a slight high value at a velocity of 200 mm/s (Mutsuyoshi and Machida, 1985). Figure 9 shows that a decrease of about 10 to 20% due to the 10 repetitions at almost all amplitudes was observed.

Deformation of piles

Figure 10 shows a comparison between the curvature distribution of specimen RCR-D-R that was tested using cyclic loading and specimen RCR-D-D that was tested dynamically. A similar curvature distribution of the statistically tested specimen was observed for the 1st repetition of the dynamically tested specimen, which proves the fact that the restoring force is independent of the loading velocity. The curvature distribution in the 10th remarkable strains increase of the longitudinal reinforcement after yielding.

Conclusions

In order to study the restoring force characteristics of a RC pile – soil system, both static and dynamic loading tests were conducted. The following conclusions could be drawn:

1) The height about which maximum curvature and/or maximum damage of a pile is dependent on the relative stiffness between the pile and its surrounding soil. A quantitative estimation of such height is necessary to evaluate the restoring force characteristics of the RC pile – soil system.
2) The dynamic loading tests clarified that the loading velocity has a small effect on the restoring force in the range of the current tests.
3) A remarkable decrease of restoring force was observed in the dynamic loading tests, which was due to the repetitions in each cycle. This fact gives suggestions that such a decrease of restoring force should be considered in the seismic evaluation of actual structures.

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