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RESPONSE BEHAVIOR OF RC PILES UNDER SEVERE EARTHQUAKE

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SUMMARY

In this paper, restoring force characteristic of RC pile-soil system is considered experimentally and analytically, aiming at the establishment of the evaluation method of the effect of the behavior of RC pile-soil system on that of pier body and entire system of RC bridge under seismic excitation. Several lateral loading tests of RC piles, which placed in soil box filled with dry sand, are performed. Considering lateral restoring force at pile top, deformation of pile bodies and passive earth pressure on the surface of pile, some results are derived as follows; the stiffness of pile and ground affects on the location of plastic hinge, the settlement of ground surface is observed due to reversed cyclic loading, and soil particles around pile body are compacted by the deformation of pile. In addition, 3-dimensional finite element analyses are conducted in order to consider the application of proper method to evaluate the interaction between pile and soil. Consequently, large hysterisis loop measured in the experiment cannot be expressed by the method. It is very important to estimate the damping characteristic of the system for the evaluation of seismic behavior, therefore the hysterisis model of soil under large deformation and the model which can relates the phenomena between pile and ground under earthquake should be developed.

INTRODUCTION

In Japan, RC highway bridge piers are designed based on the concept that pier should be damaged earlier than foundation, therefore the horizontal capacity of pier should be higher than that of foundation [Kawashima (1997)]. But the 1995 Hyogo-ken Nanbu Earthquake had brought about a serious damage to many RC structures, especially there are a lot of RC bridge piers with their body damaged as well as their piles of foundation underground. This fact tells that not only response behavior of pier body but also that of pile foundation affects on the seismic behavior of entire bridge system, therefore, the reliable performance evaluation method of the behavior of bridge pier under seismic excitation should be developed as soon as possible.

There are a lot of examples of the trials to evaluate a response behavior of bridge pier, foundation and ground entire system using mass-spring model, frame model and FEM model [Penzien et al. (1964), Toki et al. (1986), Hirao et al. (1997), Maki et al. (1998,1999)]. In many of them, the application of suggested evaluation method is discussed whether analytical result has an agreement with the real damage by modelling an actually damaged structure. Although a difficulty of an evaluation of analytical propriety is a matter of common knowledge, whether each possible phenomena under real earthquake are expressed by proper method should be checked in detail. The objective of this paper is to clarify a response behavior of RC pile under severe earthquake and to develop a reliable performance evaluation method of the seismic behavior of RC structure entire system. In order to realise this objective, some loading tests and 3D FEM analyses are performed on static restoring force characteristics of RC rectangular piles in model ground [Takano et al. (1999), Maki et al. (1999)].

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LATERAL LOADING TEST OF RC PILE

Summary of Experiment

Generally, deformation of pile under seismic loading is determined by shear deformation of ground itself induced by bedrock acceleration, and by inertial force caused by response of superstructure. Regarding former, some static and dynamic test using shear deformable box [Chen et al. (1997a, 1997b)], and latter, lateral loading test at pile top with fixed boundary ground [Fukuda et al. (1997)]. Moreover, the vibration test can consider both effects as stated above [Makris et al. (1997)]. The loading test performed in this paper belongs to latter, and it models horizontal load at pile top induced by inertial force of superstructure. In addition, instead of circular cross section of pile and rotation fixed pile top in real situation, rectangular section and rotation free pile top are applied in our experiments below.

Figure 1 shows the experimental set-up for loading tests of RC pile. RC pile specimen is set in soil box (152cm x 100cm x 160cm) before making model ground. Model ground is consist of dry sand (Gifu sand), which has almost uniform diameter distribution, being fallen by gravity from constant height, and is not artificially compacted in order to have an agreement of the ground condition between each experimental cases. Then lateral load is carried out at pile top by actuator. The features of each specimens and experimental conditions are tabulated in Table 1. Four cases of tests are performed with changing the existence of ground, the type of loading and the amount of longitudinal reinforcement. Specimen has 10cm x 10cm rectangular cross section, and D6 or D10 deformed bars are used for longitudinal reinforcement and 3.2mm diameter steel wire for lateral reinforcement. Depth from the surface of ground to bottom of pile is 125cm and that from loading point to bottom of pile is 150cm. Some strain gauges are stuck on the surface of longitudinal reinforcement in order to measure vertical curvature distribution, and also some earth pressure cells are put on the surface of the specimen to measure active and passive earth pressure distribution.

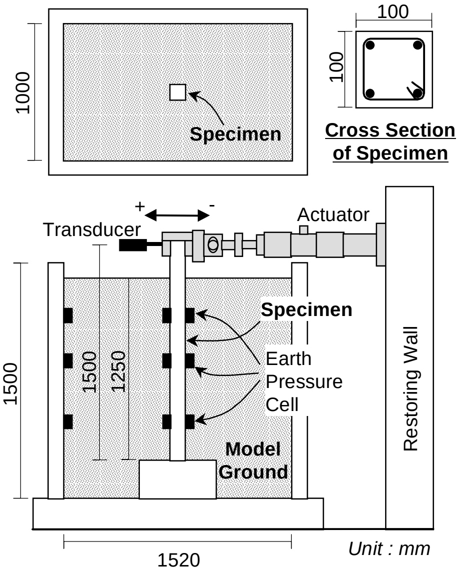


Figure 1 : Experimental Set Up

Table 1 : Experimental Cases

No.	Longitudinal Reinforcement	Concrete Strength (MPa)	Ground	Loading Type
SP-1	D6	41.9	none	Monotonic
SP-2	D6	44.2	Gifu Sand	Monotonic
SP-3	D6	45.3	Gifu Sand	Reversed Cyclic
SP-4	D10	43.0	Gifu Sand	Reversed Cyclic

Experimental Results

Relationship between Lateral Restoring Force and Lateral Displacement at Pile Top

Skeleton curves of relationships between lateral restoring force and displacement at pile top in all cases are shown in Figure 2, and hysterisis curve of SP-3, the case of reversed cyclic loading, is shown in Figure 3. It can be seen from Figure 2 that the difference between SP-1 and SP-2 comes from the existence of ground due to restoring force of ground. The effect of loading condition is that yield point of specimen can obviously be recognised at displacement of 40mm in the curves of SP-3 and SP-4, although not clearly in SP-1 and SP-2. Restoring force hysterisis curve is expressed by tri-linear type as can be seen in Figure 3, but restoring force at pile top drops radically in each cycle just after starting unloading from maximum displacement and large residual displacement occurs. This phenomenon is caused by the occurrence of restoring force of soil in opposite direction, i.e. active earth pressure, due to sand flows into a gap between pile and ground. From Figure 4, which shows the variation of equivalent damping coefficient calculated from each hysterisis loop, it can be recognised that 0.2 at yielding, 0.3 of SP-3 and 0.25 of SP-4 at final cycle are reached. Above-mentioned restoring force of soil in opposite direction acts on pile as damping force causes a high damping.

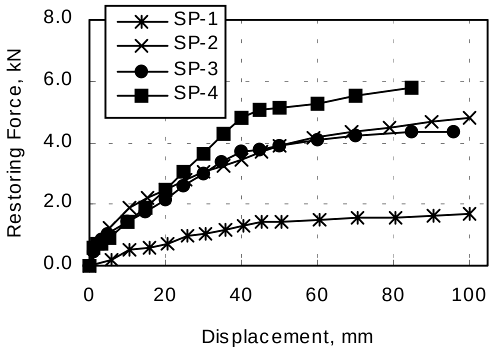


Figure 2 : Skeleton Curves of All Specimens

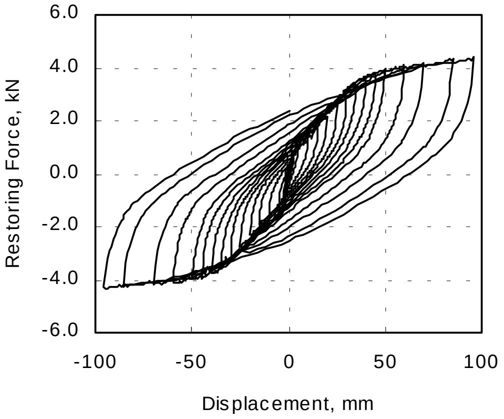


Figure 3 : Hysterisis Curve of SP-3

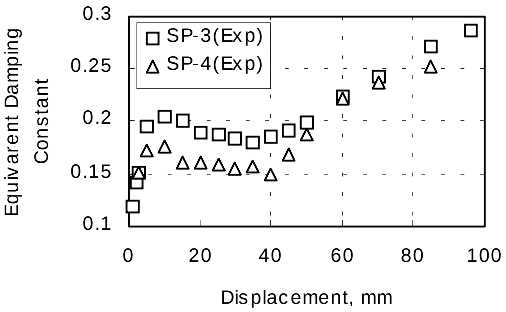


Figure 4 : Equivalent Damping Coefficient of SP-3 and SP-4

Distributions of Cracking and Curvature of Specimen

Figure 5 shows the crack distributions of each specimen after test. A large crack is occurred at the bottom of the pile in SP-1, otherwise in SP-2 many cracks are distributed on all over surface of the pile and the widest crack is observed at G.L.-60cm. In SP-3, a serious damage is occurred in the range from G.L.-30cm to G.L.-60cm. Compared with SP-2, some difference from loading type can be observed. This phenomenon is brought about by the compaction of soil particles due to reversed cyclic loading. Details are stated in the next section. In SP-4, which has large amount of longitudinal reinforcement, the range of large cracks is located from G.L.-50cm to G.L.-70cm which shifts deeper compared with SP-3. This means that deformation of pile in ground varies due to stiffness of pile body.

Figure 6(a) and 6(b) show the curvature distributions calculated from the measured data of the strain of longitudinal reinforcement. Figure 6(a), which is of each case at 50mm pile top displacement, has an agreement with crack distributions in Figure 5. Regarding SP-1 as the case that pile is placed in no stiffness ground, it is confirmed that the stiffer the surrounding soil, the shallower the location that plastic hinge occurs shifts. Also, by comparing SP-3 and SP-4, the stiffer the pile is, the deeper the location of plastic hinge shifts. Therefore, the position of plastic hinge generated by pile top loading is affected by the ratio of stiffness of pile body and surrounding soil. Figure 6(b) shows the variation from 10mm to 50mm pile top displacement of SP-3. From this figure, with increase of amplitude of pile top displacement, maximum curvature location shifts gradually deeper. This is caused by progress of soil deformation around pile body due to pile deformation.

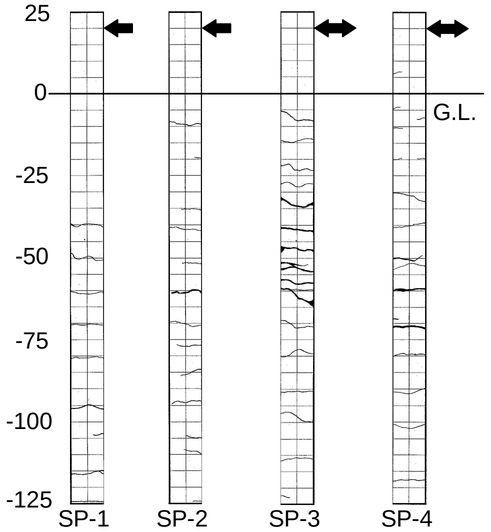
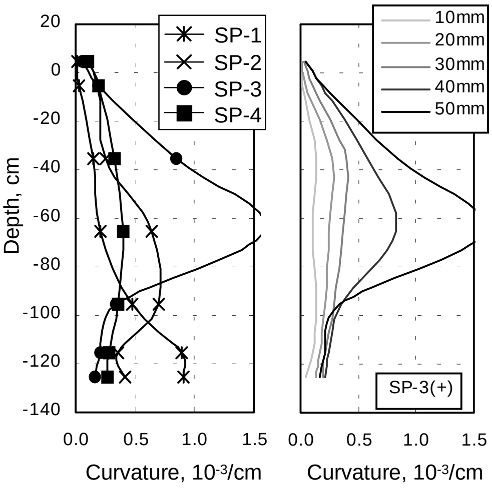


Figure 5 : Crack Distributions



(a)50mm Disp.(Exp) (b)SP-3(Exp)

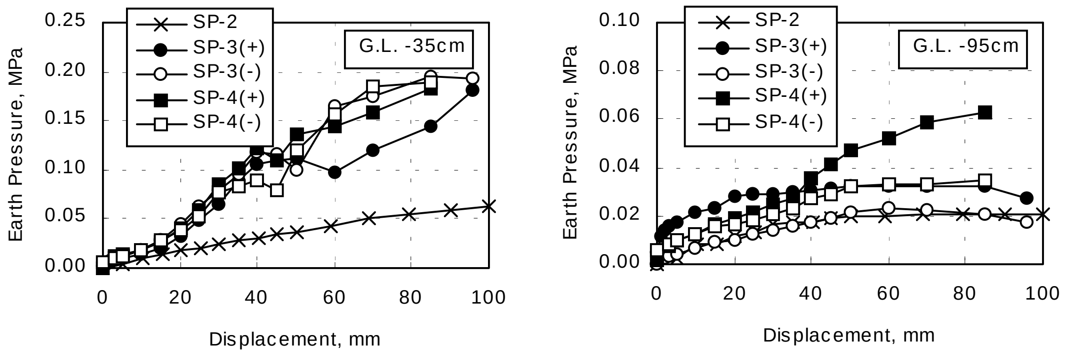
Figure 6 : Curvature Distributions

Deformation of Ground and Passive Earth Pressure

A remarkable phenomenon at ground surface around pile body in the cases of SP-3 and SP-4, reversed cyclic loaded specimens, is the cone-shaped settlement as shown in Figure 7. This settlement gradually becomes large with increase of pile top displacement amplitude, and finally reached its radius of about 15cm. Diagonal slip surfaces appear from the corners of specimen, and upheaval at the passive side and settlement at the positive side occur. This phenomenon causes the compaction of soil particles around pile body in the case of reversed cyclic loading, and the difference of deformation between SP-2 and SP-3. By the way, there are some trials to theorise soil passive wedge as observed in this experiment [Ashour et al. (1998)].

Figure 7 : Photo of Ground Surface around Pile

Figure 8(a) and Figure 8(b) show the skeleton curves of hysterisis of passive earth pressure measured by earth pressure cells. They set at G.L.-5cm, G.L.-35cm, and G.L.-95cm on both side of pile body, but at G.L.-5cm, earth pressure couldn't be measured due to the cone-shaped settlement shown in Figure 7. Comparing SP-2 and SP-3, higher passive earth pressure acts to SP-3 than to SP-2, since soil deposit becomes dense with loading due to the compaction by reversed cyclic loading, as mentioned above. In early stage of loading, i.e. until 40mm of yield displacement, there is no remarkable difference between the results of SP-3 and SP-4, but after yielding, passive earth pressure increases more rapidly in SP-4 than SP-3. This is caused by the difference of deformation in ground due to stiffness of pile body, as stated in section 2.2.2. Additionally, at G.L.-35cm in both cases, after a few decreases around 40mm of yield displacement, passive earth pressure increases again, but the tendency like this is not observed at G.L.-95cm and it keeps constant except for the positive side of SP-4. Considering this phenomenon with the results in section 2.2.2, it is due to that plastic hinge appears at around G.L.-60cm. Because after yielding, lateral displacement of pile at G.L.-35cm shallower than the plastic hinge location is less than before yielding, passive earth pressure becomes low at that depth. But, because at G.L.-95cm deeper than the plastic hinge location, lateral displacement is not vary comparing before and after yielding, earth pressure keeps almost constant. With further increase of lateral displacement amplitude at pile top, the increment of restoring force after yielding force is distributed above plastic hinge, therefore passive earth pressure at G.L.-35cm starts increasing again.



(a) at G.L.-35cm **(b) at G.L.-95cm**

Figure 8 : Skeleton Curves of Hysterisis of Passive Earth Pressure v.s. Pile Top Displacement

DIMENSIONAL FINITE ELEMENT ANALYSIS

Analysing Method and Models

The establishment of reliable analytical method is necessary in order to evaluate the seismic safety of entire structural system. In this research, 3-dimensional finite element analyses are perform so as to consider whether or not existing analytical method can express the result of performed experiment mentioned in the previous chapter. COM3, the 3-D FEM program to analyse RC structure, which is developed by university of Tokyo [Okamura et al. (1990)], is used for analyses in this paper. Pile specimen and model ground is divided into elements as shown in Figure 9. RC pile is modelled by 3-noded 3-D RC beam elements and ground is modelled by 20-noded 3-D solid element. For material model of each components, 3-dimensional elasto-plastic constitutive model of RC, which, hysterisis model for compression which can express the behavior of reinforced concrete under loading, unloading and reloading, hysterisis model for tension which considers the tension stiffening effect, and hysterisis model for steel which relates unloading-reloading behavior and bauschinger effect, are assembled, is applied for RC beam element [Tsuchiya et al. (1998)], and Osaki model, which can be applied for sandy and cohesive soil, is used for the material model of solid element [Osaki (1980)]. Details are explained in references.

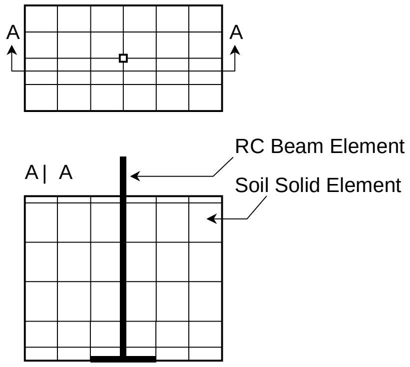


Figure 9 : Finite Element Idealization of Pile-Soil System

Analytical Results

Relationships between restoring force and lateral displacement at pile top are illustrated in Figure 10-12. Figure 10 shows those of SP-1 and SP-2, Figure 11 shows skeleton curves of SP-3 and SP-4, and Figure 12 shows hysterisis curve of SP-3. From these results, this program can express the curve of monotonic loading and the skeleton curve of reversed cyclic loading, but it describes smaller hysterisis loops compared with experimental results. The variations of equivalent damping coefficient calculated from experimental and analytical hysterises of SP-3 and SP-4 are shown in Figure 13. It can be acknowledged from this figure that hysterisis damping of the system is evaluated as a half of the measured result. The causes of these results are considered to be the compaction of soil particles around pile body in the experiments. Therefore, the material model of soil can be applied for simple soil element, and it is necessary to install the additional model which can relates the soil-structure interaction, caused by the existence of structure, such as the compaction effect in our experiment. In the future, in order to apply this method for evaluation of seismic behavior of structural system, it is indispensable to estimate the hysteritic-damping characteristic of the system accurately.

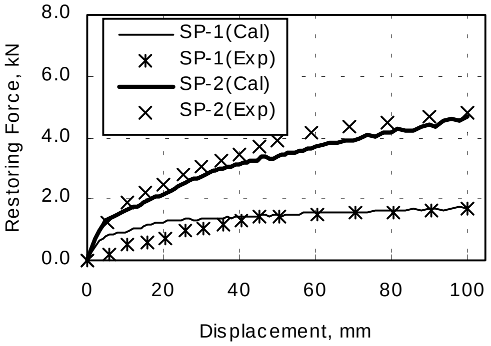


Figure 10 : Relationships between Restoring Force and Lateral Displacement at Pile Top

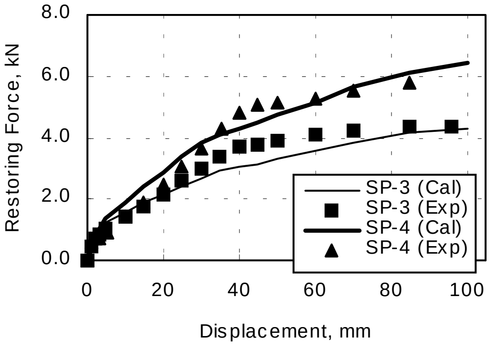


Figure 11 : Skeleton Curves of SP-3 and SP-4

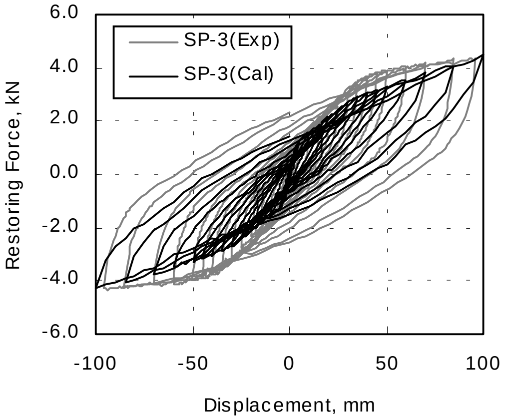


Figure 12 : Hysterisis Curves of SP-3

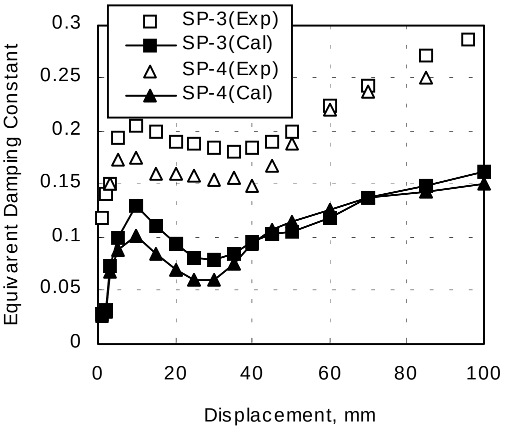
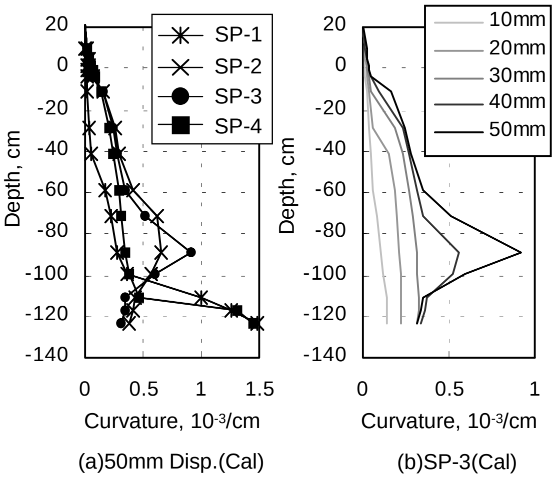


Figure 13 : Equivalent Damping Coefficient

Figure 14(a) shows the curvature distributions at 50mm pile top displacement in each case, and Figure 14(b) shows the variation of curvature distribution of SP-3 from 10mm to 50mm pile top displacement. A good agreement with experiment is achieved in the cases of SP-1 and SP-2, but the curvature maximum depth is lower than the plastic hinge locations of SP-3 and SP-4. Same tendency can also be recognised in Figure 14(b). Additional phenomenon occurs between pile and ground due to reversed cyclic loading, and that this phenomenon is not evaluated accurately causes the disagreement between the results of experiments and analyses. Considering these results, the phenomena may occur in real cases as follows; first, loose ground made of dry sand is compacted by the reversed cyclic deformation of pile, and secondary, the compacted soil ground has small restoring force after large deformation, and finally, the settlement of sand provides the opposite-directed large restoring force in the active side of pile. Consequently the restoring force at pile top rapidly decreases when unloading. This characteristic causes a large damping effect of the pile behavior under reversed cyclic loading. In order to express these experimental results analytically, the appropriate model which can relates above-mentioned phenomena should be applied, and further consideration is needed, including the hysteritic model of soil under large deformation and the model of boundary between pile and ground.



(a)50mm Disp.(Cal) (b)SP-3(Cal)

Figure 14 : Curvature Distributions calculated from Analyses

CONCLUSIONS

In this paper, some loading tests and analytical considerations are performed on the restoring force characteristic of pile-soil system, aiming at the establishment of the evaluation method of seismic behavior of the structure-pile-soil entire system. Derived conclusions are listed as follows.

Pile placed in soil ground has higher restoring force than that of pile body itself due to the effect of earth pressure. In addition, the location of plastic hinge shifts according to the ratio of stiffness of pile and ground.

Under reversed cyclic loading, passive earth pressure becomes high with the increase of displacement amplitude. This is caused by the compaction of soil particles around pile body, and the restoring force of compacted soil ground may provides the remarkable progress of damage of pile.

Regarding the restoring force characteristic of RC pile, applied analytical method can express the skeleton curve of force-displacement relationship at pile top, but cannot produce the large hysterisis loop measured from experiments. This is because the model, which expresses the compaction effect, as stated above, is not installed in the used analytical method. In order to establish the reliable evaluation method of seismic behavior of the structural system in the future, the damping characteristic of the system should be accurately estimated, and the material model of each component and the model, which can relate the phenomena between pile and ground, should be developed.

In order to complete the development of evaluation method, further investigation is needed on the restoring force characteristic of RC pile, such as the difference between static and dynamic response behavior, the effects of strain rate dependence and frequency dependence, and so on.

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REFERENCES

Ashour, M., Norris, G. and Pilling, P. (1998), "Lateral Loading of a Pile in Layered Soil using the Strain Wedge Model", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol.124, No.4, pp.303-315

Chen, L.T., Poulos, H.G. and Hull, T.S. (1997a), "Model Tests on Pile Groups subjected to Lateral Soil Movement", Soils and Foundations, Japanese Geotechnical Society, Vol.37, No.1, pp.1-12

Chen, L.T. and Poulos, H.G. (1997b), "Piles subjected to Lateral Soil Movements", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol.123, No.9, pp.802-811

Fukuda, H. et al. (1997), "Lateral Loading Tests on the Model Pile in a Large Scale Shearing Pit (Part 1-3)", Summaries of Technical Papers of Annual Meeting of the Architectural Institute of Japan, pp.525-530 (in Japanese)

Hirao, K., Sawada, T., Nariyuki, Y. and Sasada, S. (1997), "Effect of Foundation Interaction on Reduction Factor of RC Piers", Seismic Design Methodologies for the Next Generation of Codes, A.A.Balkema, Rotterdam, pp.359-370

Kawashima, K. (1997), "The 1996 Japanese Seismic Design Specifications of Highway Bridges and the Performance Based Design", Seismic Design Methodologies for the Next Generation of Codes, A.A.Balkema, Rotterdam, pp.371-382

Maki, T., Mutsuyoshi, H. and Takano, K. (1998), "Response Analysis of Reinforced Concrete Pier Considering Nonlinearity of Ground", Transactions of the Japan Concrete Institute, Vol.20, pp.125-130

Maki, T., Takano, K. and Mutsuyoshi, H. (1999), "Response Analysis of Reinforced Concrete Pier with Pile Footing Considering Non-linear Soil", The 7th East-Asia Pacific Conference on Structural Engineering & Construction, Kochi, Japan (under Printing)

Maki, T., Mutsuyoshi, H. and Takano, K. (1999), "Restoring Force Characteristic and Deformation of RC Pile in Ground", Proceedings of the 25th JSCE Earthquake Engineering Symposium, pp.565-568 (in Japanese)

Makris, N., Tazoh, T., Yun, X. and Fill, A.C. (1997), "Prediction of the Measured Response of a Scaled Soil-Pile-Superstructure System", Soil Dynamics and Earthquake Engineering, Vol.16, pp.113-124

Okamura, H. and Maekawa, K. (1990), Non-linear Analysis and Constitutive Models of Reinforced Concrete, Gihodo, Tokyo

Osaki, Y. (1980), "Some Notes on Masing's Law and Non-linear Response of Soil Deposits", Journal of the Faculty of Engineering, The University of Tokyo(B), Vol.XXXV, No.4

Penzien, J., Scheffey, C.F. and Parmelee, R.A. (1964), "Seismic Analysis of Bridges on Long Piles", Journal Engineering Mechanics Division, ASCE, EM3, pp.223-254

Takano, K., Maki, T. and Mutsuyoshi, H. (1999), "The Cyclic Loading Test and 3D FEM Analysis on the RC Pile-Soil System", Proceedings of the Japan Concrete Institute, Vol.21, No.3, pp.1273-1278 (in Japanese)

Toki, K. et al. (1986), "Research on Seismic Design Method of Bridge Foundation", Research Report of Disaster Prevention Research Institute of Kyoto University, No.86-2 (in Japanese)

Tsuchiya, S., Fukuura, N. and Maekawa, K. (1998), "Dynamic Response of RC Piers applied with Multi-Directional Forces using 3-Dimensional FEM Analysis based on Fiber Model", Proceedings of the JCI Symposium on Deterioration of Concrete Members in the Plastic Yielding Stage under Cyclic Seismic Overload, pp.359-368 (in Japanese)