International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

2001 - Fourth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

30 Mar 2001, 4:30 pm - 6:30 pm

Back-Calculated p-y Relation of Liquefied Soils from Large Shaking Table Tests

Kohji Tokimatsu
Tokyo Institute of Technology, Japan

Hiroko Suzuki
Tokyo Institute of Technology, Japan

Yasutusu Suzuki
Kajima Technical Research Institute, Japan

BACK-CALCULATED p-y RELATION OF LIQUEFIED SOILS FROM LARGE SHAKING TABLE TESTS

Kohji TOKIMATSU
Tokyo Institute of Technology
Meguro-ku, Tokyo, Japan

Hiroko SUZUKI
Tokyo Institute of Technology
Meguro-ku, Tokyo, Japan

Yasutsugu SUZUKI
Kajima Technical Research Institute
Chofu-city, Tokyo, Japan

ABSTRUCT

Time histories of the p-y behavior during soil liquefaction, defined as the relation between subgrade reaction and relative displacement between pile and soil, are back-calculated based on shaking table tests using a large-scale laminar box. The results show that, if the pile pushes the soil, the subgrade reaction is correlated with the relative displacement between pile and soil. In contrast, if the soil liquefies and pushes the pile, the subgrade reaction becomes correlated with the relative velocity between pile and soil. The p-y curve of loose sand shows stress-softening behavior after liquefaction, while the p-y curve of medium dense to dense sand shows stress-hardening behavior. The stress-hardening behavior tends to diminish with cyclic loading after liquefaction if the sand is not sufficiently dense or the input acceleration is high. The coefficient of subgrade reaction is affected by such factors as the pore pressure ratio, relative displacement, and soil density.

INTRODUCTION

The p-y behavior, defined as the relation between the subgrade reaction and relative displacement of soil and pile, is an important factor affecting the performance of soil-pile-structure interaction during soil liquefaction. Although many studies have been made on p-y behavior, most of them are concerned with soils under non-liquefied conditions. The p-y relation of sand during soil liquefaction has not been well understood, partly because of lack of the standard test procedure to determine it. Recently, Wilson (1998) back-calculated the p-y behavior by double differentiation of pile bending strain observed in centrifuge liquefaction tests. The number of strain measured in this study, however, appears insufficient to determine reliable soil resistance by double differentiation. Further studies are therefore required to obtain fundamental mechanism of soil-pile-structure interaction including p-y behavior in liquefiable soils. Along these lines, a soil-pile-structure interaction study is conducted using a large shaking table with dense instrumentation (Tamura et al., 2000). The object of this paper is to describe the p-y behavior of sand during soil liquefaction in large shaking table tests and to examine factors affecting the p-y behavior.

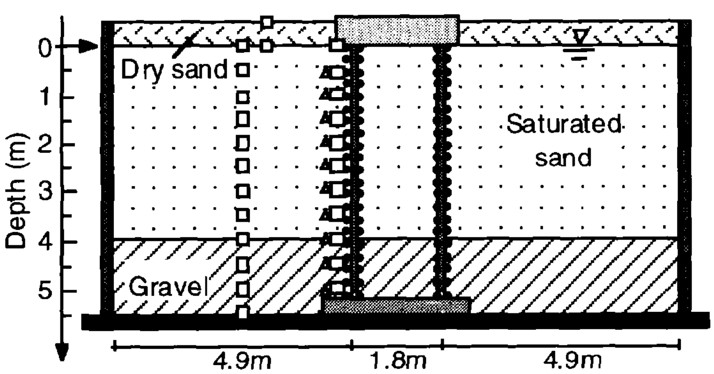

Fig. 1. Model layout

SHAKING TABLE TEST

Liquefaction tests were conducted on soil-pile-structure systems using the shaking table facility of National Research Institute for Earth Science and Disaster Prevention, STA. Figure 1 shows a soil-pile-structure system constructed in a

Table 1. Soil-pile-structure systems

Series ID.	Foundation Embedment	Super Structure & Natural Period	Soil Density
A1	No	No	Loose
AL	No	Yes (0.8s)	Loose
AS	No	Yes (0.2s)	Loose
BS	Yes	Yes (0.2s)	Loose
BL	Yes	Yes (0.8s)	Medium Dense
B1	Yes	No	Dense

stacked shear box 6 m high, 12 m long and 3.5 m wide. The soil profile in the shear box consisted of two layers: a liquefiable sand layer 4 m thick and an underlying dense gravelly layer about 1.5 m thick. A 2x2 pile group that supported a foundation of a weight of 16.7 kN was used throughout the study. All the piles had a diameter of 16.52 cm with a 0.37 cm wall thickness and their tips were connected to the container base with pin joints.

Table 1 summaries the six soil-pile-structure systems used. Series ID starting with A had a foundation without embedment, and B with embedment. Series ID containing 1 had the foundation only. Series ID containing S and L had a superstructure of a weight of 139.3 kN with an additional weight of 3.9 kN to the foundation. The natural periods of the structure for series S and L were 0.2 s and 0.8 s, respectively. The soil-pile-structure system was heavily instrumented with accelerometers, displacement transducers, and pore pressure and strain gages, such as shown in Fig. 1 for series B1. Series A1, AL, AS, and BS had a loose top layer, while series BS and B1 had medium dense and dense top layers, respectively. The water table was set at the bottom of the foundation for all tests.

An artificial ground motion called Rinkai was scaled and used as an input base acceleration to the shaking table. The soil-pile-structure system in each series was subjected to a series of shaking with a maximum input acceleration ranging from 30 to 600 cm/s^2. Accelerations and pore water pressures of the ground and the piles, and accelerations and displacements of the foundation and the superstructure as well as those of the shear box were measured during the tests. Bending strains at every 25 cm throughout all piles were also measured together with the rotation angles of their pile tips. The test results used in this study are those of A1 with a base acceleration of 120 cm/s^2 (A1-120), BL with 120 and 240 cm/s^2 (BL-120 and BL-240), and B1 with 120 cm/s^2 (B1-120).

The lateral pile displacement, y, and lateral subgrade reaction, p, during the test may be calculated, using simple beam theory given by the following equations:

$$M = -EI\frac{d^2y}{dx^2} \qquad (1)$$

$$\frac{d^2M}{dx^2} = -p \qquad (2)$$

in which EI is the flexural rigidity of the pile, x is the vertical distance along the pile, and M is the bending moment computed from the measured strain.

The double integration of bending moment with depth gives the pile displacement, y, and the double differentiation the subgrade reaction, p. In addition, the integration of accelerations of the soil and pile also yields the particle velocities and displacements as well as the relative values between the two. Since the pile displacement computed from the acceleration matches with that from the bending moment, the pile displacement, and relative displacement between soil and pile are computed from the acceleration recordings.

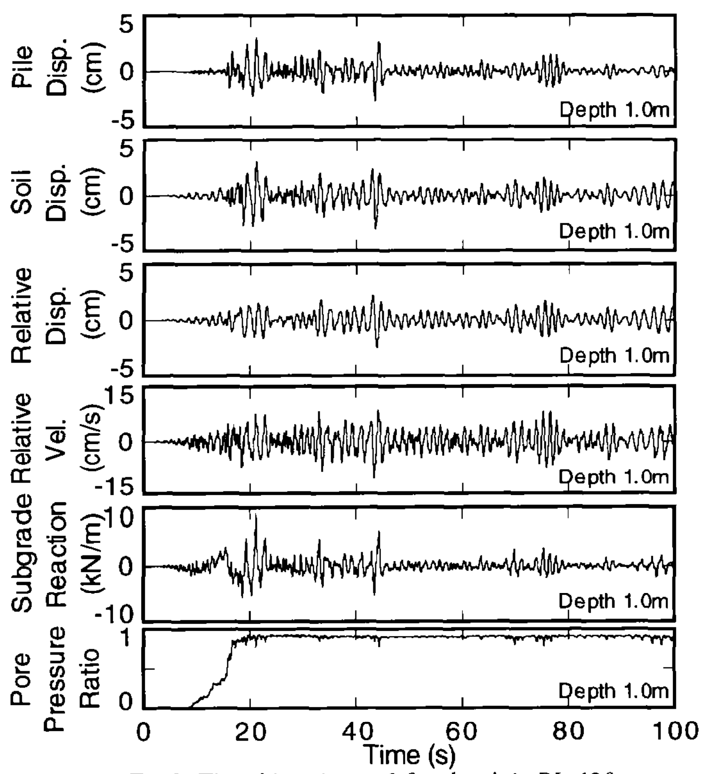

Fig.2. Time histories at 1.0m depth in BL-120

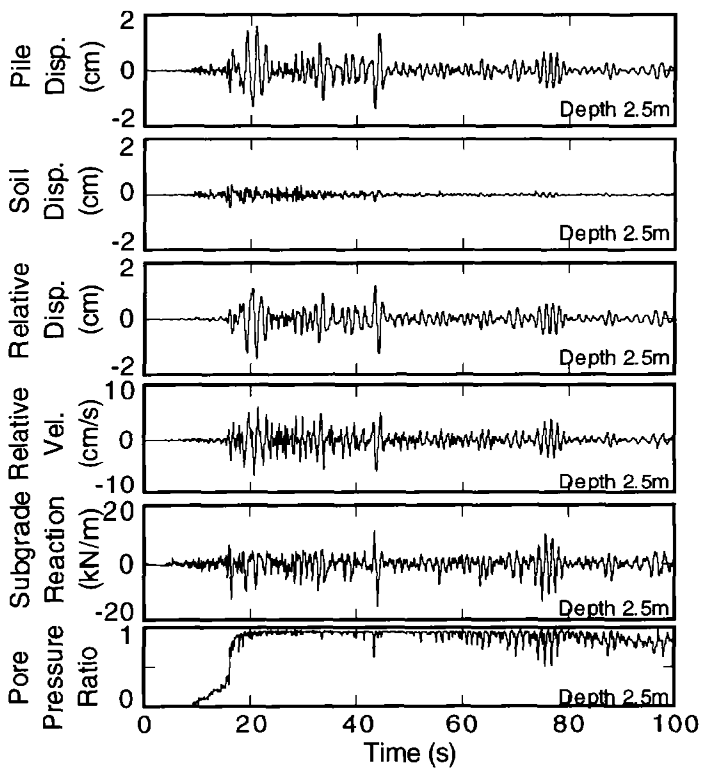

Fig.3. Time histories at 2.5m depth in BL-120

EVALUATION OF LATERAL SUBGRADE REACTION

Time histories of displacements of soil and pile, relative displacement and velocity between the two, subgrade reaction, and pore pressure ratio at depths of 1.0, 2.5 and 4.5 m in tests BL-120 are presented in Figures 2-4. At 1.0 and 2.5 m depths, the pore pressure ratio approaches 1 and liquefaction develops in about 18 s. At 1.0 m depth, the soil tends to displace more than the pile and tends to push the pile after liquefaction. At 2.5 m depth, on the contrary, the pile tends to displace more than the soil and tends to push the soil after liquefaction. At 4.5 m depth where liquefaction does not develop, the pile moves with the soil, producing a small amount of relative displacement. The subgrade reaction appears correlated with the relative velocity rather than the relative displacement at 1.0 m depth, while it appears correlated with the relative displacement at 2.5 and 4.5 m depths.

To examine the abovementioned trends, the relationships of subgrade reaction with relative displacement and velocity at depths of 1.0, 2.5, and 4.5 m in BL-120 are presented in Figures 5 and 6. In each figure, the relationships at the three depths are shown in three time periods, i.e., 0-20 s, 20-50 s, and 50-80 s. At a depth of 1.0m, the p-y relation becomes elliptical with time, and the subgrade reaction appears correlated with the relative velocity rather than the relative displacement after 20 s. This suggests that the soil may behave like a fluid when it liquefies and pushes the pile near the ground surface. In contrast, at 2.5 and 4.5 m depths, the subgrade reaction correlates with the relative displacement throughout the shaking.

At a depth of 2.5 m where liquefaction develops in about 20 s, the p-y relation in Fig. 5 shows cyclic degradation until about 20 s and then exhibits stress hardening in which the subgrade reaction increases sharply as the relative displacement exceeds

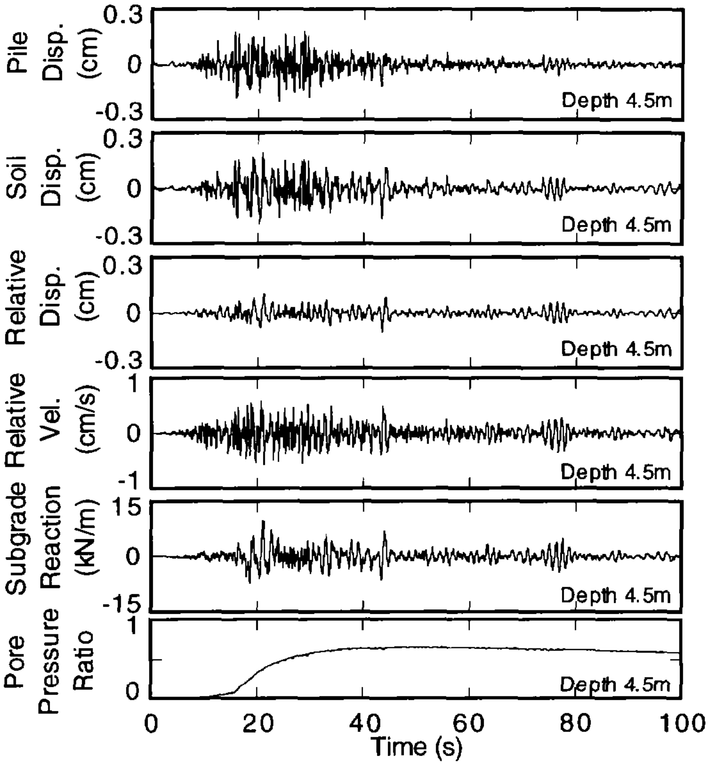

Fig.4. Time histories at 4.5m depth in BL-120

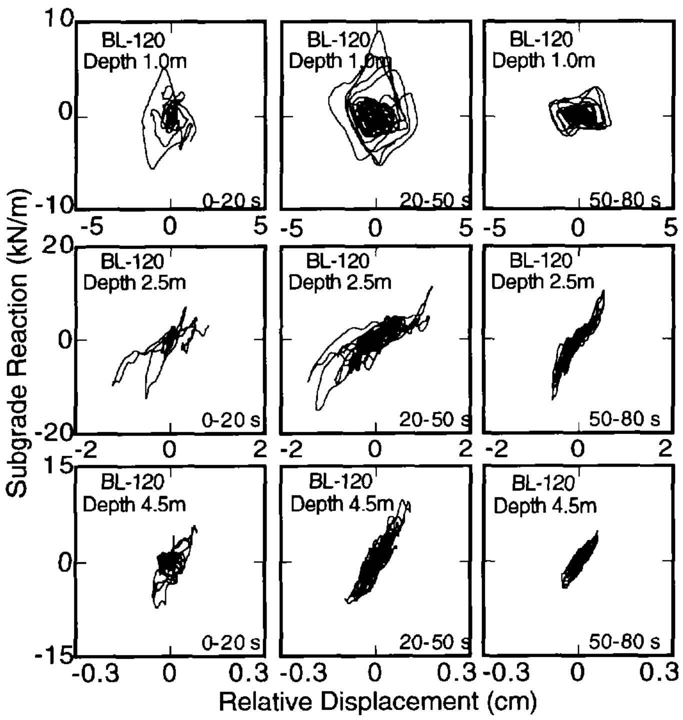

Fig.5. Relationships between subgrade reaction and relative displacement in BL-120

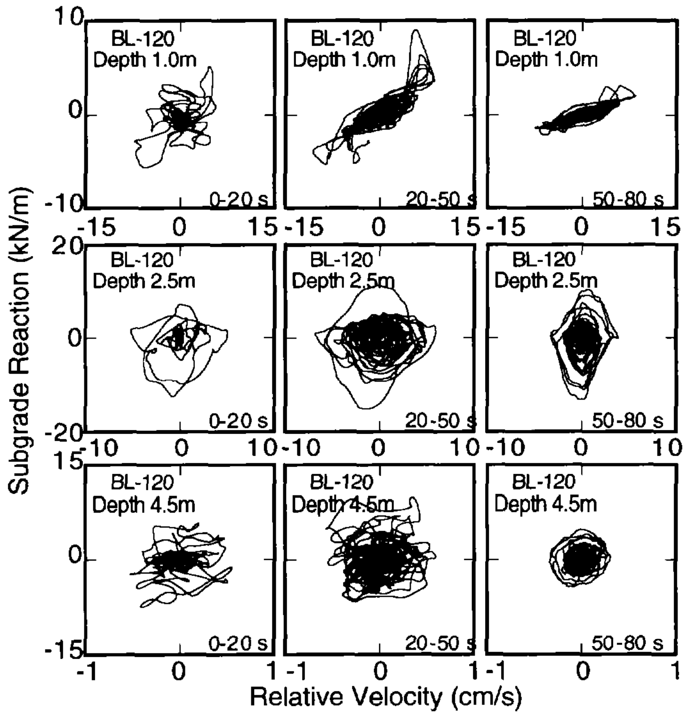

Fig.6. Relationships between subgrade reaction and relative velocity in BL-120

a certain limit, i.e., 0.5-1.0 cm. Probably, the dilatancy characteristics of soil near the pile reduce the excess pore pressure and increase the soil resistance with increasing relative displacement. At the depth of 4.5 m where liquefaction does not occur, the p-y curve does not degrade significantly throughout shaking.

Figure 7 shows the p-y relations at a depth 2.5 m in A1-120, B1-120 and BL-240. The density of the first layer is loose in Series A1, medium dense in Series BL, and dense in Series B1. A comparison of the p-y curves in A1-120 and B1-120 with those in BL-120 shown in Fig. 5 indicates that the p-y relation is strongly dependent on the soil density. Namely, the slope of the p-y relation gets sharp with increasing soil density. In addition, the p-y relation exhibits stress-hardening behavior as the soil density increases. The p-y relation in B1-120, in particular, shows no sign of cyclic degradation or softening, in which a very small relative displacement induces a large subgrade reaction.

A comparison of the p-y relations in BL-240 (Fig. 7) with those in BL-120 (Fig. 5) indicates that, if the input acceleration is doubled in BL-240, the p-y relation does not show the stress-hardening behavior. Probably, the high input motion in BL-240 produces extensive soil liquefaction, thereby suppressing the occurrence of dilatancy characteristics of soil near the pile.

The above results suggest that various factors such as soil density, pore pressure ratio, depth, and the intensity of soil liquefaction as well as relative displacement and velocity between soil and pile affect the p-y behavior.

COEFFICIENT OF LATERAL SUBGRADE REACTION

Factors Affecting Coefficient of Lateral Subgrade Reaction

Figure 8 compares the time histories of the coefficient of subgrade reaction at depths of 2.5 and 4.5 m in BL-120 and

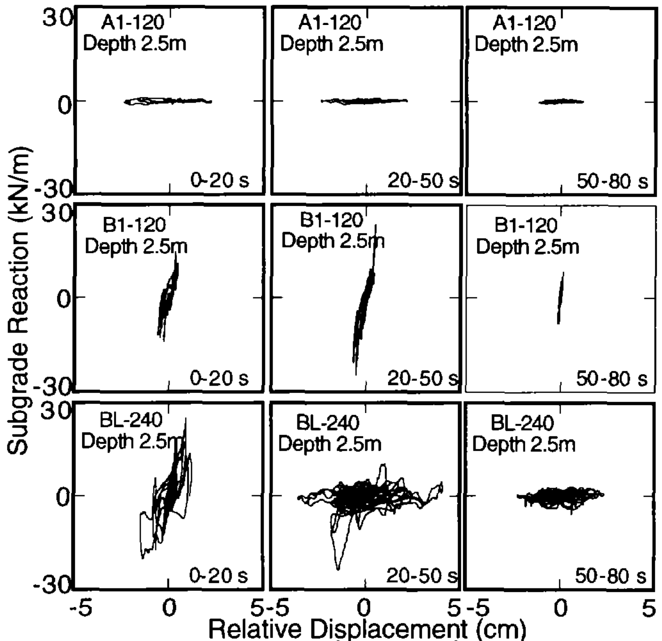

Fig.7. Relationships between subgrade reaction and relative displacement in A1-120, B1-120 and BL-240

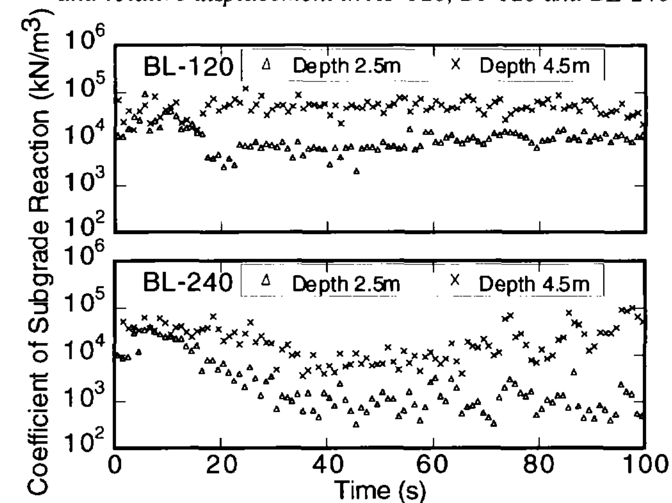

Fig.8. Change in coefficient of subgrade reaction with time in BL-120 and BL-240

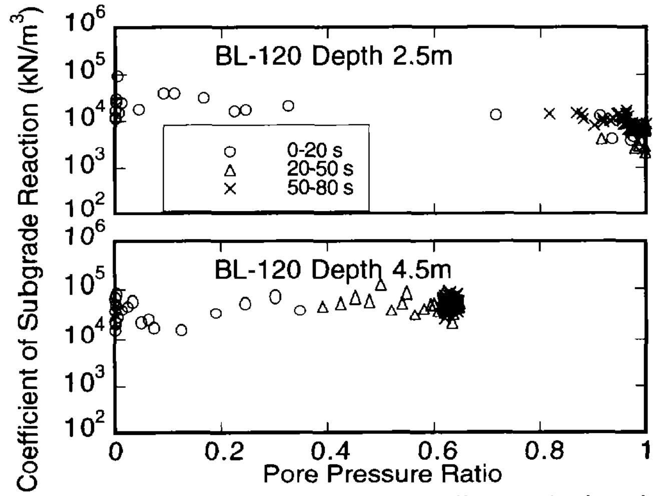

Fig.9. Relationships between coefficient of subgrade reaction and pore pressure ratio in BL-120

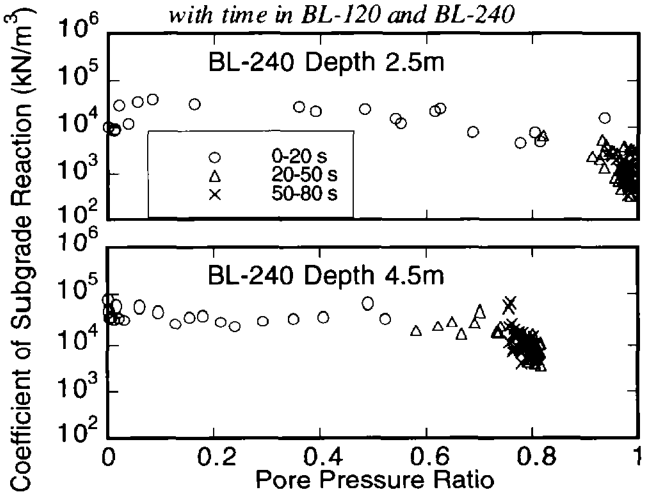

Fig.10. Relationships between coefficient of subgrade reaction and pore pressure ratio in BL-240

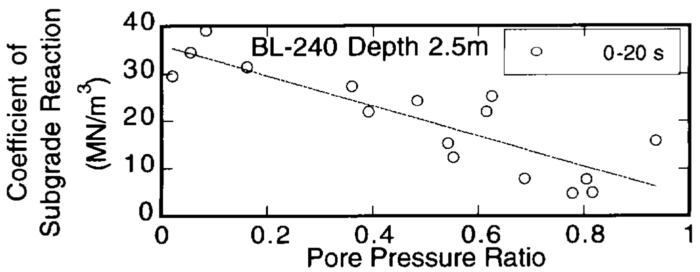

Fig.11. Relationships between coefficient and pore pressure ratio at 2.5m depth in BL-240

BL-240. Because of the larger input acceleration in BL-240, the pore water pressure ratios at a depth of 2.5 m reach to unity in about 10 s and that at a depth of 4.5 m reaches to 0.8 which are much faster and/or higher than those in BL-120.

In each test, the larger the depth, the greater the coefficient of subgrade reaction at any time. This could reflect the effects of confining pressure. Besides, the coefficient of subgrade reaction at any time and at any depth is smaller in BL-240 than in BL-120, possibly because of the higher input motion in BL-240. Figure 8 also suggests that: (1) at 2.5 m depth, the coefficient of subgrade reaction in BL-120 decreases slightly, while that in BL-240 decreases significantly; and (2) at 4.5 m depth, the coefficient of subgrade reaction in BL-120 is almost constant throughout the test, while that in BL-240 decreases considerably in the middle of shaking and then backs again towards the end. The trends indicated herein suggest that the pore pressure ratio and confining pressure as well as relative displacement affect the coefficient of subgrade reaction.

<u>Effects of Pore Pressure Ratio</u>

To examine the effects of pore pressure, the relationships between pore pressure ratio and coefficient of subgrade reaction at depths of 2.5 and 4.5 m in BL-120 and BL-240 are shown in Figures 9 and 10 in semi-log charts. At 2.5 m depth in both tests, the coefficient of subgrade reaction decreases not only with the development of the pore pressure but also after the pore pressure ratio reaches to unity. At 4.5 m depth, the coefficient of subgrade reaction in BL-120 is almost constant irrespective of change in pore pressure ratio less than 0.6, while in BL-240 it decreases after the pore pressure ratio approaches 0.8.

The relation between the pore water pressure ratio and coefficient of subgrade reaction at a depth of 2.5 m in BL-240 before soil liquefaction is presented in linear scale in Figure 11. Although the data are scatter, there is a fairly well defined trend in which the coefficient of subgrade reaction decreases linearly with increasing pore pressure or decreasing effective stress. This is consistent with the previous study by (Liu and Dobry, 1995).

The above findings indicate that the coefficient of subgrade reaction decreases almost linearly with decreasing effective stress until soil liquefaction develops, but it decreases even after the pore pressure ratio reaches to unity.

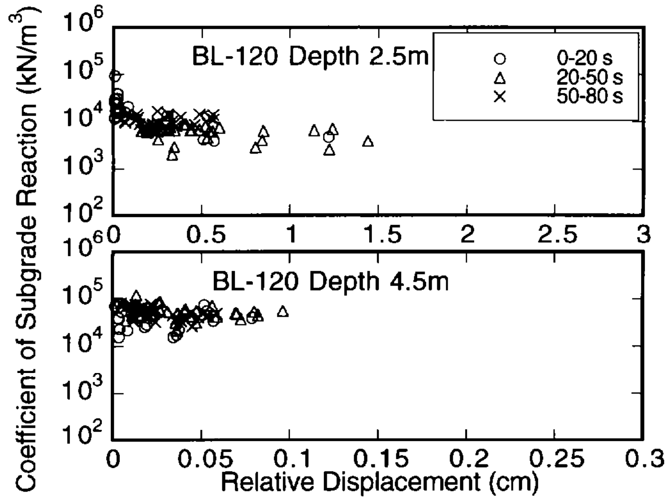

Fig.12. Relationships between coefficient of subgrade reaction and relative displacement in BL-120

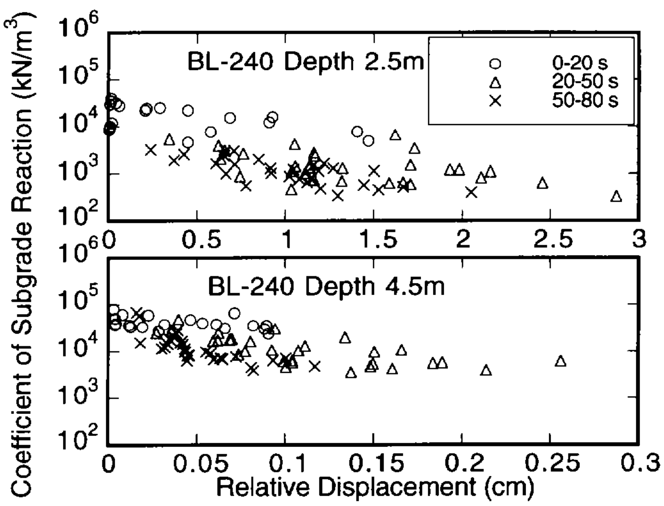

Fig.13. Relationships between coefficient of subgrade reaction and relative displacement in BL-240

<u>Effects of Relative Displacement</u>

The relationships between relative displacement and coefficient of subgrade reactions at depths of 2.5 and 4.5 m in BL-120 and BL-240 are compared in Figures 12 and 13. The coefficient of subgrade reaction depends strongly on the relative displacement in such a way that it decreases with increasing relative displacement. From the data at 4.5 m depth in Series BL, the threshold displacement to induce the degradation of subgrade reaction is about 0.1 cm.

At each depth, the maximum relative displacement is larger in BL-240 than in BL-120, which leads to a smaller coefficient of subgrade reaction in BL-240. The data at the same depth from the two tests, however, follow the same trend until the maximum relative displacement occurs. The data then tend to deviate from and fall below the previous data, even though the relative displacement becomes small towards the end of shaking. Such a trend is particularly noted at 2.5 m depth in BL-240 where a large maximum relative displacement in excess of 2 cm occurs. Such a trend is obscure at 4.5 m depth in BL-120 where the maximum relative displacement is about 0.1 cm.

The relationship between relative displacement and coefficient of subgrade reaction after 20 s at the depth 2.5 m in BL-240 is presented in Figure 14 in a liner scale. The coefficient of subgrade reaction decreases in inversely proportional to the relative displacement. Thus a large relative displacement induced after soil liquefaction is one of the major causes to decrease the coefficient of subgrade reaction after the pore pressure reaches to unity.

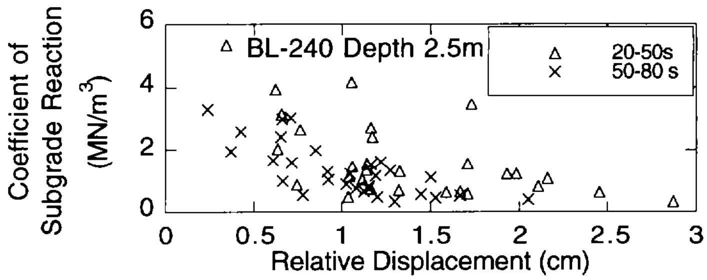

Fig. 14. Relationships between coefficient of subgrade reaction and relative displacement at depth 2.5 m in BL-240

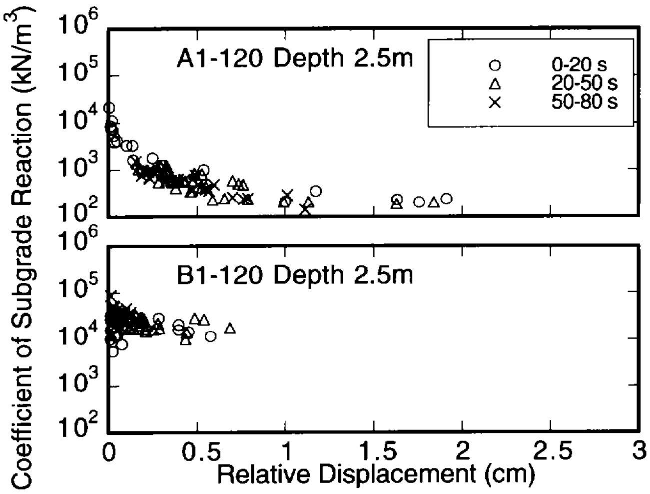

Fig. 15. Relationships between coefficient of subgrade reaction and relative displacement in B1-120 and A1-120

Effect of Density

The relationships between relative displacements and coefficients subgrade reactions at a depth of 2.5 m in A1-120 and B1-120 are presented in Figure 15. In A1-120 with loose sand, the reduction in the coefficient of subgrade reaction is more significant than that in BL-120 with medium dense sand as shown in Fig. 13. In contrast, in B1-120 with dense sand, only a slight reduction in the coefficient of subgrade reaction can be seen.

CONCLUSIONS

Time histories of the p-y behavior during soil liquefaction, defined as the relation between subgrade reaction and relative displacement between pile and soil, were back-calculated based on the shaking table tests using a large-scale laminar box. The results show that, if the pile pushes the soil, the subgrade reaction is correlated with relative displacement between pile and soil. In contrast, if the soil liquefies and pushes the pile, the subgrade reaction becomes correlated with relative velocity between pile and soil. The p-y curve of loose sand shows stress-softening behavior after liquefaction, while the p-y curve of medium dense to dense sand shows stress-hardening behavior. The stress-hardening behavior of tends to diminish if the sand is not sufficiently dense or the input acceleration is high. The coefficient of subgrade reaction is affected by such factors as the pore pressure ratio, relative displacement, and soil density.

ACKNOWLEDGMENTS

The shaking table tests described in this paper were jointly conducted by researchers from NIED, STA, Tokyo Institute of Technology, Kajima Corp., Taisei Corp., Takenaka Corp., Nippon Steel Corp. and Tokyo Soil Research. Their contribution and support for the tests are appreciated.

REFERENCES

Tamura, S., Tsuchiya, T., Suzuki, Y., Fujii, S., Saeki, E. and Tokimatsu, K. [2000]. "Shaking table tests of pile foundation on liquefied soil using large-scale laminar box (Part 1 Outline of test)", Thirty-fifth Japan National Conference on Geotechnical Engineering, Gifu, pp. 1907-1908. (in Japanese)

Liu, L. and Dobry, R. [1995]. "Effect of liquefaction on lateral response of piles by centrifuge model tests", National Center for Earthquake Engineering Research (NCEER) Bulletin, Vol. 9, No. 1, January, pp. 7-11.

Wilson, D. W. [1998]. "Soil-pile-superstructure interaction in liquefying sand and soft clay", Ph. D. Dissertation, University of California, Davis, Report No. UCD/CGM-98/04.