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CONTRIBUTION OF VISCOUS FORCE TO HORIZONTAL SUBGRADE REACTION DURING SOIL LIQUEFACTION BASED ON PILE TOP VIBRATION TESTS

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SUMMARY

Horizontal subgrade reaction of a pile during soil liquefaction is investigated based on pile top vibration tests using a large-scale shear box. The subgrade reaction is resolved into an elastic force component and a viscous force component by back analysis using the Voigt model. It is shown that (1) the elastic force and the viscous force are independent of frequency under the conditions of constant displacement amplitude and excess pore water pressure; (2) as the excess pore water pressure increases, the modulus of elasticity decreases much more sharply than the coefficient of viscosity; (3) the contribution of the viscous force to the horizontal subgrade reaction increases with an increase in the excess pore water pressure.

INTRODUCTION

The performance of pile foundations in soil deposits that liquefy during earthquake is a major issue for many structures. To design pile foundations, the horizontal subgrade reaction of a pile is important factor. Therefore, the horizontal subgrade reaction of piles during soil liquefaction has been studied by investigations of damaged piles(e.g. Fujii et al.[1], Tokimatsu et al.[2]), centrifuge tests(e.g. Miyamoto et al.[3], Sato et al.[4], Wilson et al.[5]), shaking table tests(e.g. Kagawa et al.[6], Tokimatsu et al.[7]), horizontal loading tests (e.g. Susuki et al.[8])and pile top vibration tests(e.g. Hirade et al.[9]). Dynamic horizontal subgrade reaction consists of an elastic force component depending on displacement and a viscous force component depending on velocity. The elastic force is generally dominant; therefore, many researchers concentrate on studying p-y curves, where p is soil resistance and y is pile deflection. It has been pointed out that the subgrade reaction depends on the relative velocity in liquefied soil(Hamada et al.[10]). This suggests that the viscous force is dominant during soil liquefaction, although little attention has been given to the viscous force component of the subgrade reaction. Therefore, basic knowledge of the viscous force remains limited. This paper investigates the viscous force during soil liquefaction based on pile top vibration tests using a large-scale shear box.

This study aims 1) to examine the contribution of viscous force to horizontal subgrade reaction of a pile, and 2) to study the effects of excess pore water pressure and frequency on the viscous force.

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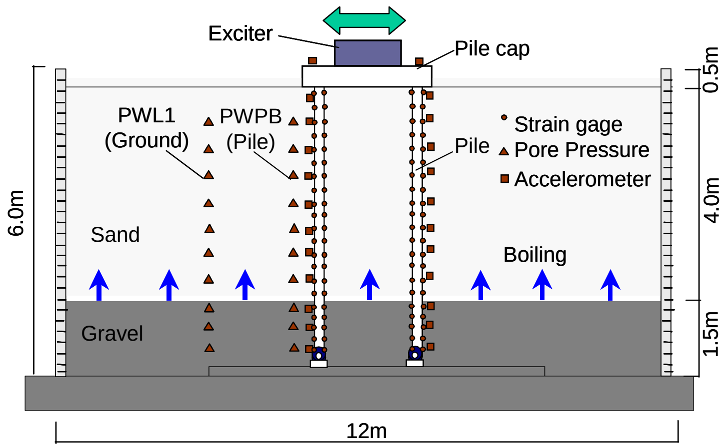

Figure 1. Model setup

Table 1. Test cases

	Pile top vibration test
Ex0	Before boiling
Ex1	1 minute after boiling
Ex2	2.5 minutes after boiling
Ex3	4 minutes after boiling

PILE TOP VIBRATION TESTS

Pile top vibration tests were performed at NIED (National Research Institute for Earth Science and Disaster Prevention) in Tsukuba, Japan. The large-scale laminar shear box (6m high, 12m long, and 3.5m wide) including a soil-pile-structure system is diagrammed in Fig. 1. An exciter was mounted on the footing which was supported by 2x2 steel piles. The pile heads were rigidly linked to the footing, while their tips were connected to the shear box by hinges. A pile with a diameter of 165mm , a length of 5.3m, a thickness of 3.7mm and EI=1259 kNm^2 was installed in a two-layer soil profile with a thickness of 5.5m. This profile includes a 4m layer of Kasumigaura sand (Vs=75m/s), placed on the top of a 1.5m layer of gravel (Vs=230m/s). Accelerometers, excess pore water pressure gauges and strain gauges were set on the piles, and excess pore water pressure gauges were set within the soil profile. Pile displacement was calculated by double integrating accelerations and bending moment was calculated from the bending strain. Subgrade reaction was calculated by the double differentiation of the bending moment. In this paper, the pile displacement corresponds to relative displacement between the soil and the pile and the pile velocity corresponds to relative velocity. This is because that the soil was not made to vibrate.

A boiling was performed at GL-4m, the top of the gravel layer. Four cases of pile top vibration tests were carried out before and after the boiling (Table 1). The eccentric moment of the exciter was 98kNm at frequency in the 4- to 10-Hz range.

TEST RESULTS

Figure 2 shows the vertical distribution of excess pore water pressure measured on the pile and within the soil. Figure 3 shows the vertical distribution of the pile displacement. In Test Ex0, excess pore water pressure occurred near the upper part of the pile, while it did not occur within the soil. This indicates that excess pore water pressure near the pile was excited by the pile vibration. The pile deformation was limited to the upper part of the pile. In Test Ex1, the distribution of the excess pore water pressure measured on the pile was almost same as that of the soil. The excess pore water pressure of the upper part of the soil reached the line of initial effective stress, indicating that the soil was liquefied completely. The pile deformation was large from the middle part of the pile to the pile head. In Ex2 and Ex3, the excess pore water pressure gradually dissipated from the bottom to the upper layer. The pile displacement distribution of Ex3 was similar to that of Ex0.

To design pile foundations, examinations of the mechanism of horizontal subgrade reaction in somewhat deep soil are desirable. The lower part of the soil, however, did not liquefy in Test Ex1 and the pile displacement was extremely small at the lower part of the pile, as stated above. The present focuses on the test results at a height of 4m (1.5m deep).

The relation between the subgrade reaction and the pile displacement, and that between the subgrade reaction and the pile velocity at a height of 4m are shown in Fig. 4. In Ex0, the relation between the pile

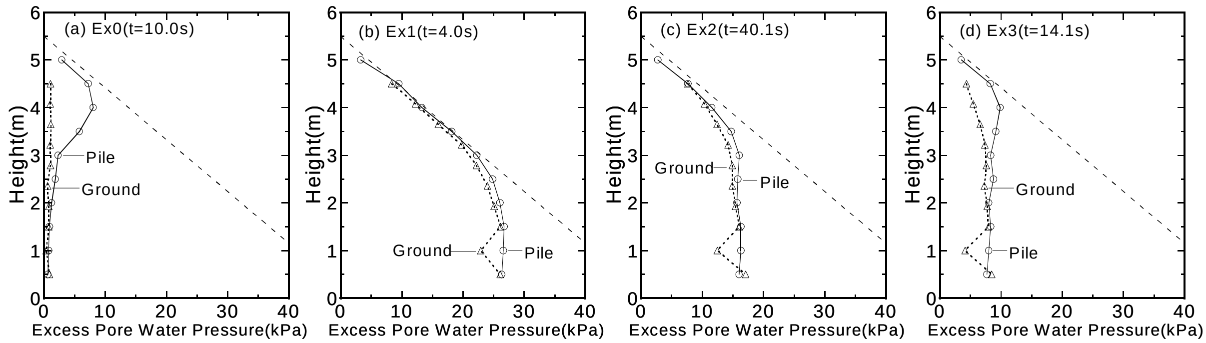

Figure 2. Distribution of excess pore water pressure

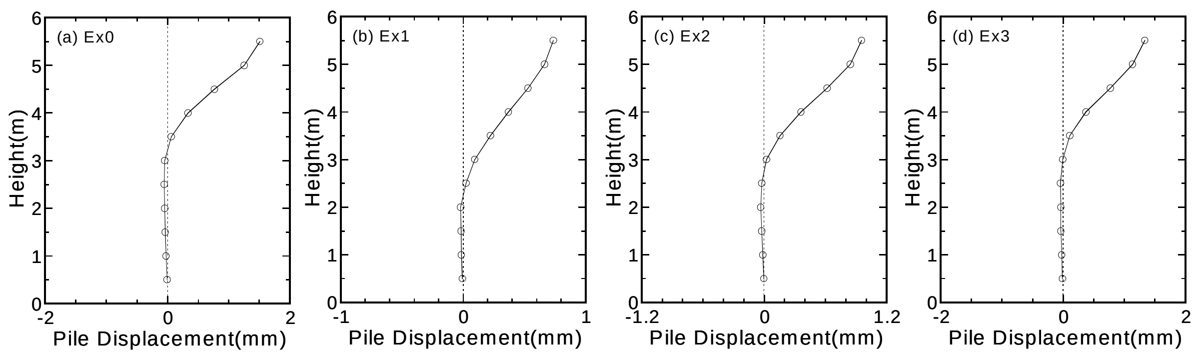

Figure 3. Distribution of pile displacement

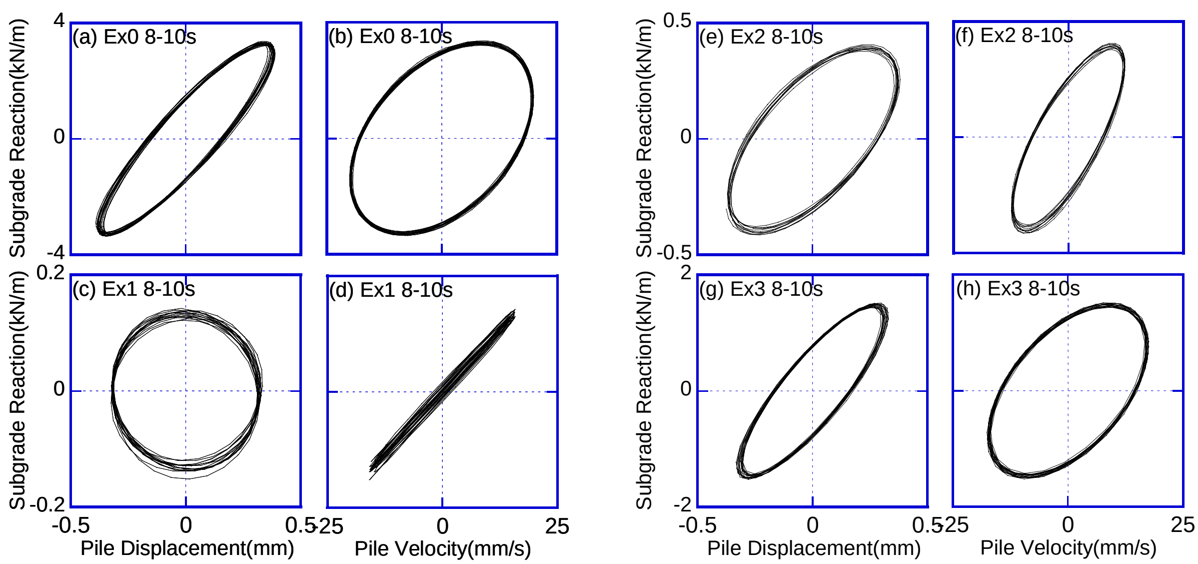

Figure 4. Subgrade reaction with pile displacement and pile velocity at height of 4m

displacement and the subgrade reaction is an oblate ellipse, while the relation between the pile velocity and the subgrade reaction is an ellipse that approaches a circle. This indicates the subgrade reaction depends on the pile displacement in non-liquefied soil. In Ex1, the subgrade reaction is proportional to the pile velocity, indicating that the subgrade reaction depends strongly on the pile velocity. The subgrade reaction of Ex2 also tends to depend on pile velocity, while that of Ex3 tends to depend on the pile displacement. Judging from the above, the dependence of the subgrade reaction on displacement and velocity is clearly affected by the excess pore water pressure ratio.

ELASTIC FORCE AND VISCOUS FORCE

Modeling of Horizontal Subgrade Reaction

The relation between the pile displacement and the subgrade reaction can be drawn as an inclined elliptical orbit (Fig. 5). The inclined ellipse consists of an inclined line component and a non-inclined ellipse component. The inclined line corresponds to the elastic force (P_d) and the non-inclined ellipse corresponds to the viscous force (P_v). The horizontal subgrade reaction can be expressed by the following equation, according to the Voigt model (Fig. 6),

$$P = \mu \cdot D + \mu' \cdot \frac{dD}{dt} \tag{1}$$

where D is the pile displacement, μ is the modulus of elasticity and μ' is the coefficient of viscosity. The first term in the right-hand side corresponds to the elastic force and the second term corresponds to the viscous force. μ and μ' can be estimated from the following formula.

$$\mu = \frac{P_1}{D_a} \tag{2}$$

$$\mu' = \frac{P_2}{\omega \cdot D_a} \tag{3}$$

where ω is circular frequency, D_a is the amplitude of the pile displacement, P_1 is the subgrade reaction with $D = D_a$, and P_2 is the subgrade reaction with D = zero (Fig. 5). The modulus of elasticity and the coefficient of viscosity were evaluated at every half cycle of the pile displacement.

To examine the proposed method, the horizontal subgrade reaction was calculated by equations (1) through (3). Figure 7 shows the time histories of the horizontal subgrade reaction of the estimated value and the experimental value for Ex0 and Ex1. The estimated values agree well with the experimental results, indicating that the proposed method

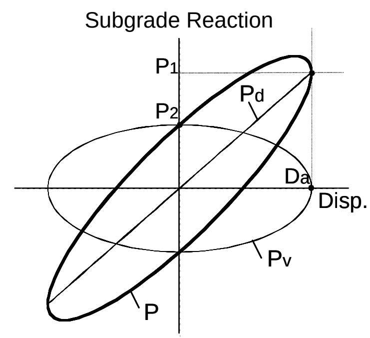

Figure 5. Schematic of relation between subgrade reaction and displacement

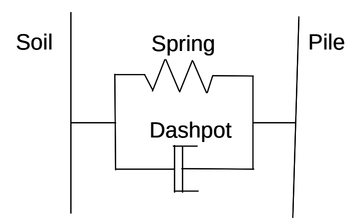

Figure 6. Voigt model

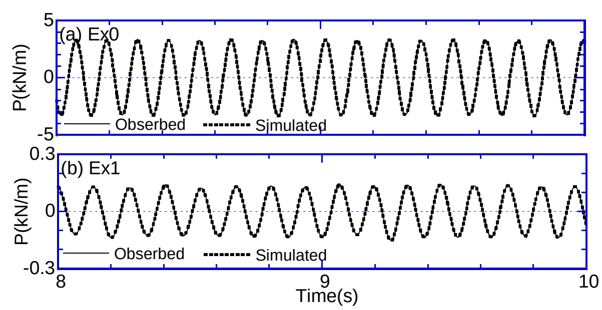

Figure 7. Observed and simulated subgrade reaction

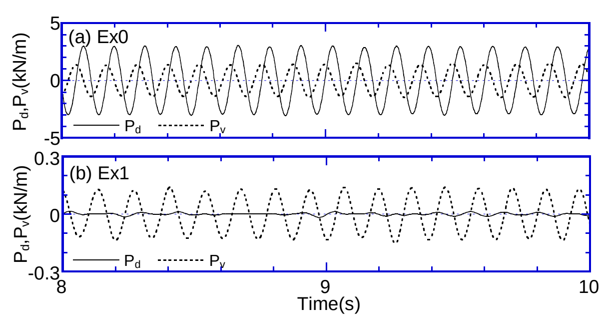

Figure 8. Elastic force and viscous force

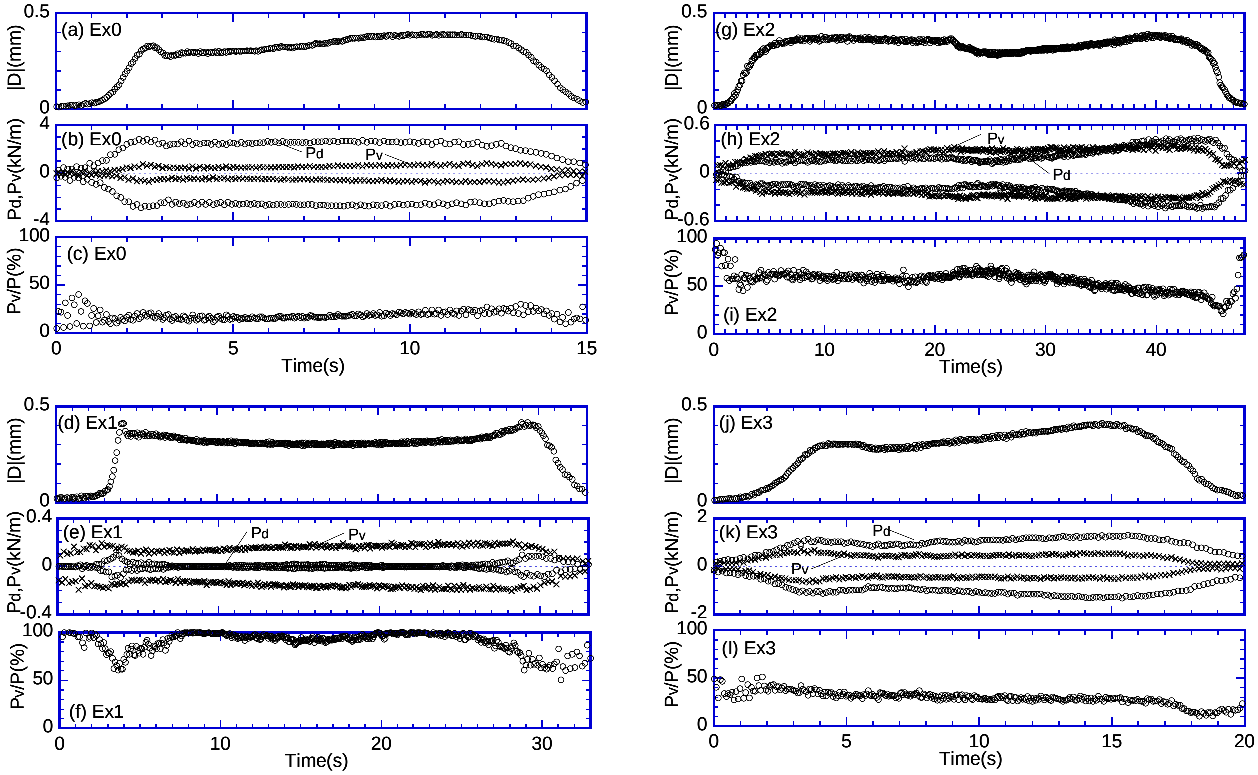

Figure 9. Pile displacement, elastic force, viscous force and contribution of viscous force to subgrade reaction

can simulate the experimental subgrade reaction.

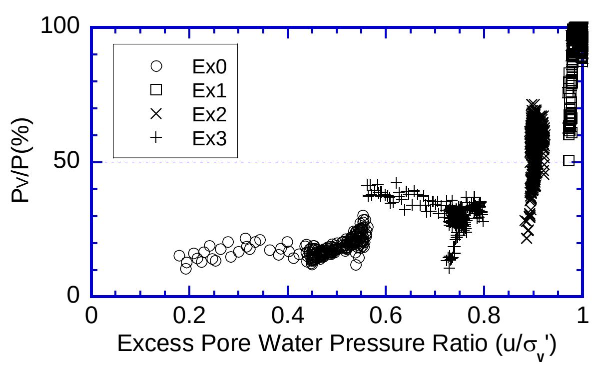

Figure 10. Contribution of viscous force to subgrade reaction

The estimated elastic force and the estimated viscous force are shown in Fig. 8. In Test Ex0, the amplitude of the elastic force is larger than that of the viscous force. On the other hand, the amplitude of the elastic force is far smaller than that of viscous force in Test Ex1.

Contribution of Viscous Force to Subgrade Reaction

Figure 9 shows time histories of the pile displacement amplitude, the elastic force, the viscous force and the contribution of the viscous force to the subgrade reaction (P_v/P). The value of the elastic force and the viscous force were evaluated at a peak of every half cycle of the subgrade reaction. In Test Ex0, the viscous force is smaller than the elastic force all the time and P_v/P is less than 20%. In Test Ex1, P_v/P is more than 90%, indicating that the viscous force is dominant during the soil liquefaction. In Test Ex2, P_v/P tends to decrease with the dissipation of the excess pore water. The viscous force becomes smaller than the elastic force at 34 seconds. In Test Ex3, the viscous force is smaller than the elastic force all the time and P_v/P is 30%-40%.

Figure 10 shows the relation between the excess pore water pressure ratio (u/σ_v') and P_v/P. P_v/P is between 0.1 and 0.2 when the excess pore water pressure ratio is less than 0.5. P_v/P increases with an increase in the excess pore water pressure. When the excess pore water pressure ratio is greater than 0.9, the contribution

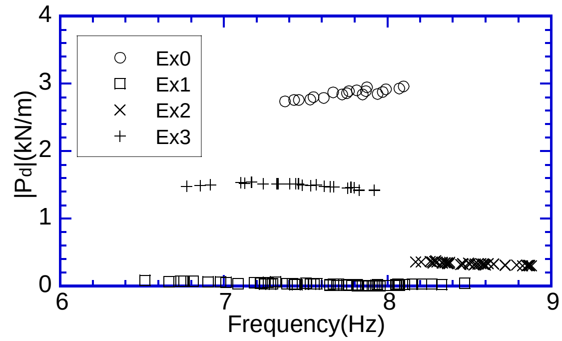

Figure 11. Relation between elastic force amplitude and frequency

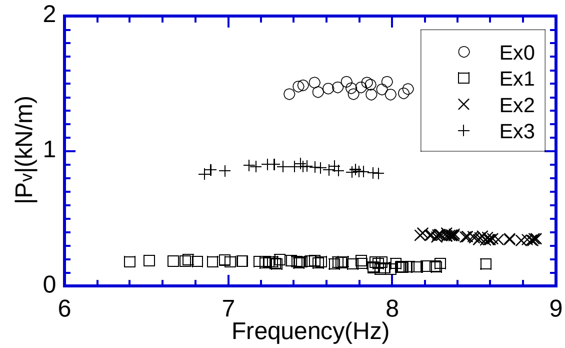

Figure 13. Relation between viscous force amplitude and frequency

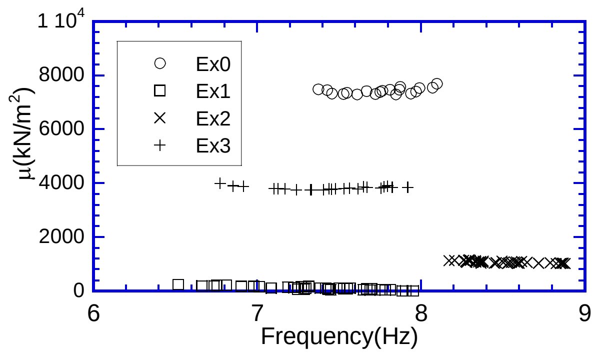

Figure 12. Relation between modulus of elasticity and frequency

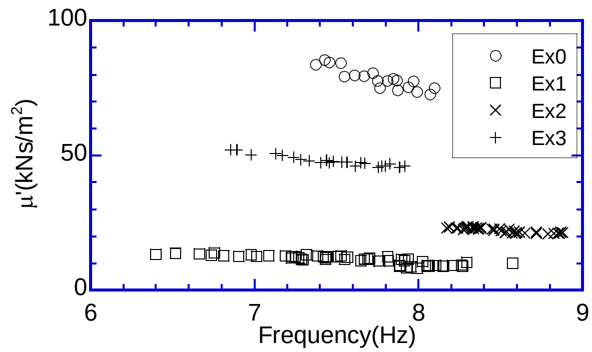

Figure 14. Relation between coefficient of viscosity and frequency

of the viscous force is greater than 50%.

Relation between Frequency and Elastic Force and that between Frequency and Viscous Force

Figure 11 shows the relation between the pile displacement frequency and the elastic force amplitude. Considering that the changes of the pile displacement amplitude and the excess pore water pressure affect the elastic force, the data in the figure were adopted under the condition that the pile displacement amplitude and the excess pore water pressure ratio were constant within a precision of ±0.02mm and ±0.01, respectively. The amplitude of the elastic force does not depend on the frequency. The modulus of elasticity (μ) is also independent of the frequency (Fig. 12).

Figure 13 shows the relation between the pile displacement frequency and the viscous force amplitude. Only those data that satisfy the conditions of constant pile displacement and excess pore water pressure ratio were adopted. The amplitude of the viscous force does not depend on the frequency. Figure 14 shows the relation between the frequency and the coefficient of viscosity. As the pile frequency increases, the coefficient of viscosity decreases. For this reason, the amplitude of the viscous force does not depend on the pile frequency.

Effects of Excess Pore Water Pressure on Modulus of Elasticity and Coefficient of Viscosity

Figure 15 shows the relation between the excess pore water pressure ratio and the modulus of elasticity at the pile displacement range of 0.28–0.32mm considering that the changes of pile displacement affect the elastic force. The increase in the excess pore water pressure decreases the modulus of elasticity. The solid and broken lines in the figure are calculated by the following equations, respectively.

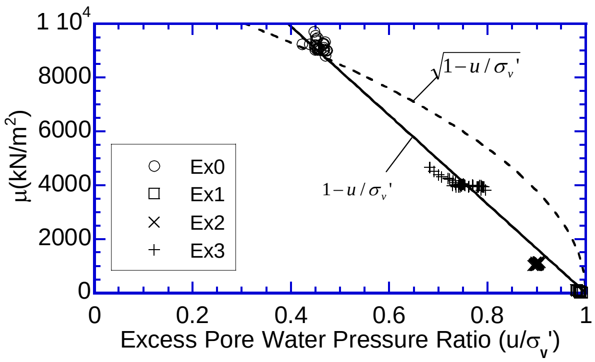

Figure 15. Relation between modulus of elasticity and pore water pressure

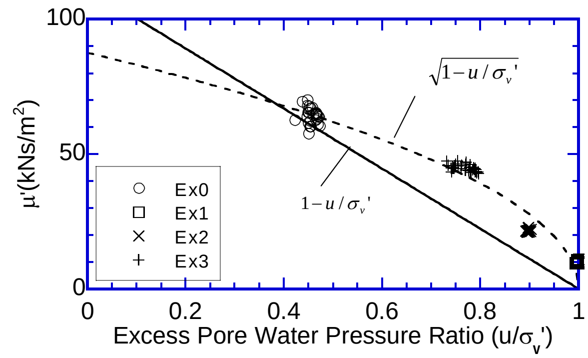

Figure 16. Relation between coefficient of viscosity and pore water pressure

$$r_d = 1 - u / \sigma_v{}' \tag{4}$$

$$r_d = \sqrt{1 - u / \sigma_v{}'} \tag{5}$$

The experimental data correspond to the solid line calculated by equation (4), indicating that the modulus of elasticity decreases in proportion to the effective stress ratio ($1\text{-}u/\sigma_v'$).

Figure 16 shows the relation between the excess pore water pressure ratio and the coefficient of viscosity, in the pile displacement range of 0.28mm–0.32mm and the pile frequency range of 8.5Hz–9.5Hz. The increase in excess pore water pressure decreases the coefficient of viscosity. The experimental data correspond to the broken line calculated by equation (5) and the coefficient of viscosity decreases in proportion to the square root of the effective stress ratio, $(1\text{-}u/\sigma_v')^{0.5}$. These results clearly show that the contribution of the viscous force to the horizontal subgrade reaction increases with an increase in the excess pore water pressure, because the modulus of elasticity decreases much more sharply than the coefficient of viscosity.

CONCLUSIONS

The horizontal subgrade reaction of a pile during soil liquefaction was back-calculated based on pile top vibration tests using a large-scale shear box. The subgrade reaction was resolved into an elastic force component and a viscous force component by back analysis using the Voigt model. The following conclusions are drawn:

(1) The elastic force and the modulus of elasticity are independent of the frequency under constant displacement amplitude and excess pore water pressure. The coefficient of viscosity decreases with an increase in the frequency, and the viscous force is independent of the frequency.

(2) As the excess pore water pressure increases, the modulus of elasticity decreases much more sharply than the coefficient of viscosity. Therefore, the contribution of the viscous force to the horizontal subgrade reaction increases with an increase in the excess pore water pressure. When the excess pore water pressure ratio is greater than about 0.9, the contribution of the viscous force is greater than 50%.

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