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Evaluation of the Dynamic P-Y Curves of Soil-Pile System in Liquefiable Ground

액상화 가능성이 있는 지반에 놓인 지반-말뚝 시스템의 동적 p-y 곡선 연구

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요 지

말뚝의 동적 응답 해석을 위한 다양한 방법들이 개발되어 있으며, 이 중에서 비선형 스프링, p-y 곡선을 이용하여 지반-말뚝 상호작용을 고려하는 방법이 널리 사용되고 있다. 그러나, 현재 사용되는 동적 p-y 곡선은 정적 또는 주기 하중에 의한 횡방향 재하 시험에 의해 개발되었다. 또한, p-y 곡선에 scaling factor를 도입하여 액상화에 의한 지반-말뚝 상호작용의 영향을 모사하고자 하는 시도가 이루어져 왔으나, 지금까지 정확한 scaling factor를 산정하지 못하고 있는 실정이다. 이에 본 연구에서는 1g 진동대 실험으로부터 구한 말뚝 주변 지반의 과잉간극수압과 지반-말뚝 시스템의 고유진동수 관계 및 수치해석으로부터 구한 말뚝 주변 지반의 탄성계수의 변화와 지반-말뚝 시스템의 고유진동수 관계로부터, 말뚝 주변 지반의 탄성계수의 변화로 표현되는 p-y 곡선의 scaling factor를 구하였다. 그 결과, scaling factor는 과잉간극수압비에 따른 지수 함수의 형태로 나타났다.

Abstract

Various approaches have been developed for the dynamic response analysis of piles. In one of the approaches, the soil-pile interaction is approximated by using parallel nonlinear springs, namely the p-y curves. Currently available p-y curve recommendations are based on static and cyclic lateral load tests. Other researchers have attempted to extend the p-y curves by incorporating the effects of liquefaction on soil-pile interaction and derived scaling factors of p-y curves to account for the liquefaction. However, opinions on the scaling factors vary. In this study, the scaling factors, which reflect the variation of the elastic moduli of surrounding soils, were established combining the relationship between excess pore pressures and the natural frequencies of a soil-pile system obtained from 1g shaking table tests and the relationship between the elastic moduli of surrounding soils and the natural frequencies of a soil-pile system obtained from numerical analyses. As a result, the scaling factors were presented in an exponential function.

Keywords : Excess pore pressure, Liquefaction, Natural frequency, Pile, Shaking table test

1. Introduction

Predicting the performance of pile foundations in liquefying ground under earthquake loading is a complex problem requiring consideration of the inertial loads from the superstructure and the kinematic loads from the

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surrounding soil. Liquefaction changes these loads because of its influence on free-field soil response and soil-pile-structure interaction. Analyses and design procedures for piles in liquefying ground generally include large uncertainties due to the lack of physical data and the lack of correct understanding of the mechanism involved in the interaction phenomena. These uncertainties must be resolved for earthquake hazard remediation.

Various approaches have been developed for the dynamic response analysis of single piles. In one approach, the soil-pile interaction is approximated by using parallel nonlinear soil-pile (p-y) springs (Matlock, 1978). Currently available p-y curve recommendations (API, 1993) are based on static and cyclic lateral load tests. Other researchers have attempted to extend the recommended p-y curves by incorporating the effects of liquefaction on soil-pile interaction. The Architectural Institute of Japan (AIJ, 1988) and Japan Road Association (JRA, 1980) codes include the scaling factor, that is p-multiplier, of p-y curves to account for liquefaction. Liu and Dobry (1995) also suggested that the scaling factor from centrifuge tests would vary linearly with excess pore pressure ratio and Wilson (1998) found that appropriate p-multipliers were 0.10 ~ 0.20 for liquefying loose soil, and 0.25 ~ 0.35 for liquefying medium dense soil.

However, there is yet a variety of opinions on the scaling factors. To obtain the exact scaling factors, it is necessary to evaluate the stiffness of the liquefying soil as a function the magnitude of excess pore pressure. Therefore, in this study, the variation of the natural frequency of the soil-pile system and the stiffness of the liquefying soil according to the magnitude of excess pore pressure were investigated by 1g shaking table tests and three dimensional FE analyses.

2. Test Program

A series of shaking table model tests were performed to evaluate the dynamic characteristics of a soil-pile system. The dimensions of the soil box were 100 x 44 x 60 cm (length x width x height), and the soil box was made of transparent acrylic plates. Figure 1 shows the test section of the model and the locations of the measurement instruments. The model pile was made of a steel plate and was installed with 7 strain gauges, 2 LVDTs, 6 pore pressure transducers, and 7 accelerometers. The dimensions of the model pile were 60 x 4 x 600 mm (width x thickness x length). And the flexural rigidity (EI) of the model pile was calculated by using the result of one(-) point loading test. Jumoonjin sand was used as the model soil, which is typical clean uniform sand in Korea. The effective grain size, D10, was 0.38 mm and the

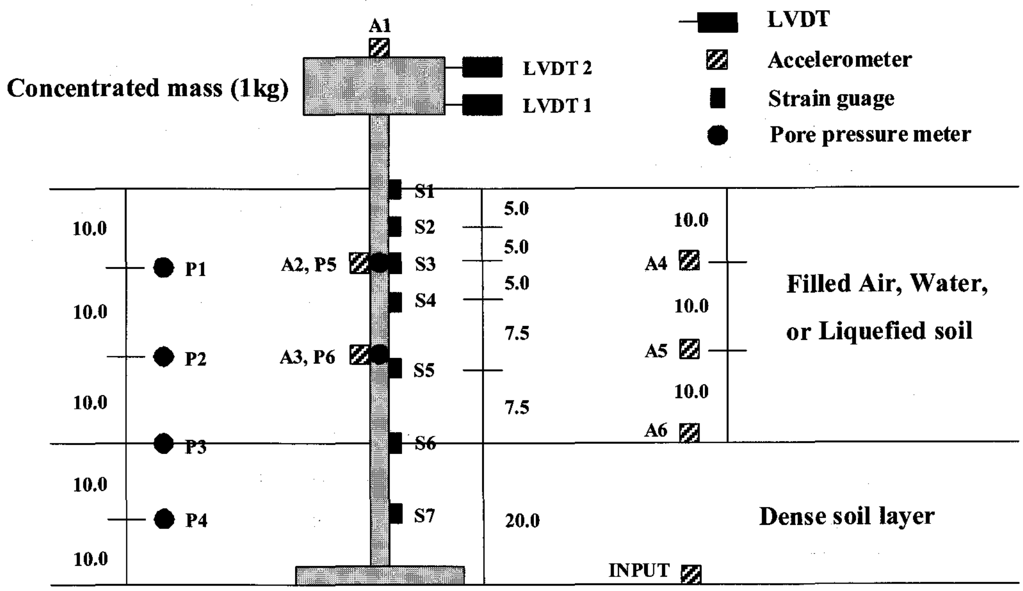


Fig. 1. Test section

coefficient of uniformity was 1.58. The maximum and minimum dry unit weights were 15.99 kN/m^3 and 13.05 kN/m^3, respectively.

Table 1 summarizes the test program used in this study. The shaking table tests were classified into different cases depending on the fill materials in the upper part of the model box. The materials were either air (case 1), water (case 2), or liquefiable soil (case 3). And three different types of tests were performed on the model pile, whose upper part was surrounded by liquefiable soil. In the first test, input acceleration of small amplitude was applied to prevent liquefaction in the soil (case 3a). In the second test, large input acceleration was applied to induce liquefaction in the soil (case 3b). In the third test, a small input acceleration was applied to re-shake the liquefied model system of case 3b (case 3c). The liquefiable layer of 30 cm was prepared by water sedimentation method in every frequencies and the resulting relative density of the soil was about 20% (case 3b). The bottom foundation layer of 20 cm was prepared by pre-shaking the soil. The resulting relative density of the soil was about 80%. Sinusoidal waves of various amplitudes and frequencies were used to produce the input base motions.

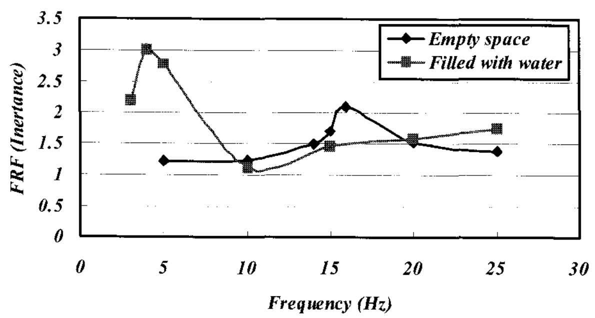
3. Test Results

Hwang (2004) previously performed shaking table tests to determine the natural frequency of a liquefied quay wall system using a random wave as input motion. However, the tests were not successful because the excessive pore pressure did not increase to the liquefaction level under the moderate amplitude of random wave acceleration. Thus, sine waves were used in this study.

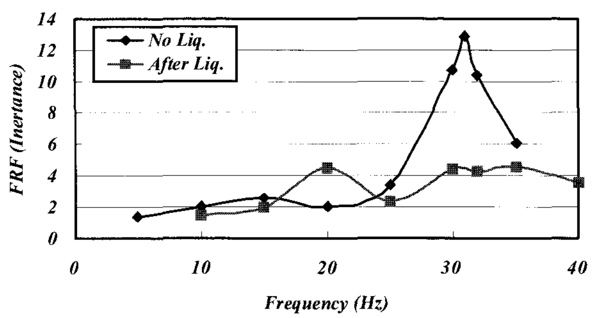
Figure 2 shows the acceleration FRF (Frequency Response Function= Fourier amplitude of upper acceleration / Fourier amplitude of input acceleration) of the soil-pile system for each case of the tests, except case (3b). Acceleration FRF is defined as the pile top acceleration divided by the input base motion for corresponding frequencies, and the 1st natural frequency f_n is taken as the frequency corresponding to the first peak value of FRF. In case (3b), the natural frequency could not be evaluated by FRF because the natural frequency varied with the magnitude of the excess pore pressure in the surrounding soil of the pile. Therefore, the natural frequency in case (3b) was determined differently. Figure 3 shows the excess pore pressure ratio at the center of the liquefiable soil with time and shows the acceleration

Table 1. Test program

Cases	Pile environment (upper layer : 30 cm)	Amplitude of input acc. (g)	Frequency of input acc. (Hz)	Remark
1	Empty space	0.1	5, 10, 14, 15, 16, 17, 20, 25	–
2	Filled with water	0.1	3, 4, 5, 10, 15, 20, 25	–
3a	Filled with liquefiable soil	0.015	5, 10, 15, 20, 25, 30, 31, 32, 35	No liquefaction occurred
3b		0.2	3, 4, 5, 6, 10, 15, 20	Liquefied
3c		0.015	10, 15, 20, 25, 30, 32, 35, 40	Retested after liquefaction

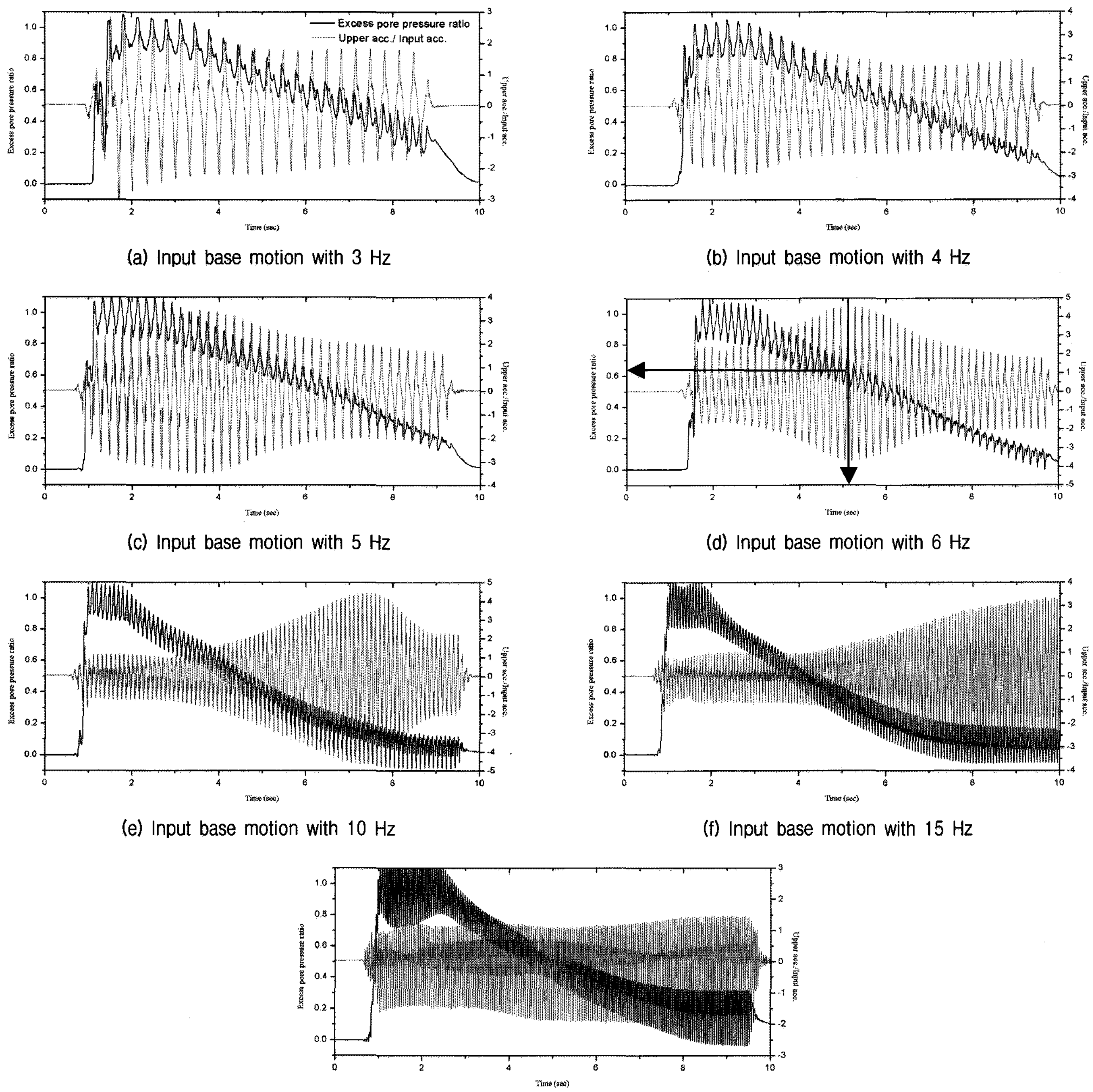


(a) Empty space (Case 1), filled with water (Case 2)



(b) No liquefaction (Case 3a), After liquefaction (Case 3c)

Fig. 2. FRF of soil-pile system



(a) Input base motion with 3 Hz

(b) Input base motion with 4 Hz

(c) Input base motion with 5 Hz

(d) Input base motion with 6 Hz

(e) Input base motion with 10 Hz

(f) Input base motion with 15 Hz

(g) Input base motion with 20 Hz

Fig. 3. Excess pore pressure ratios vs. acceleration amplification ratio (case 3b)

amplification ratio with time, which is the ratio of pile top acceleration to the input base motion. As shown in Figure 3, when the frequencies of the input base motion were 3 and 4 Hz, the pile top acceleration amplified greatly during liquefaction (i.e., when the excess pore pressure ratio was about 1.0). Thus, it can be said that the natural frequencies of the soil-pile system during liquefaction are around 3 to 4 Hz. From Figure 3, the natural frequency of the soil-pile system can be determined for various excess pore pressure ratios by correlating the maximum acceleration ratio with the magnitude of excess pore pressure ratio for each input acceleration frequency. For example, as shown in Figure 3(d), in the case of 6 Hz, when the acceleration amplification ratio is peak, the time is 5.2 sec and the excess pore pressure ratio is 0.65 at this time. Therefore, when the excess pore pressure ratio is 0.65, the natural frequency of the soil-pile system is 6 Hz. Figure 4 shows the variation of the natural frequency of the soil-pile system according to the excess pore pressure ratio, which is the ratio of the excess pore

Table 2. The natural frequency of soil-pile system

Type (Case No.)	Empty space (1)	Filled with Water (2)	No Liq. (3a)	Filled with liquefiable soil Liquefaction (3b)	After Liq. (3c)
N.F. (Hz)	16	4	15	3~4	20

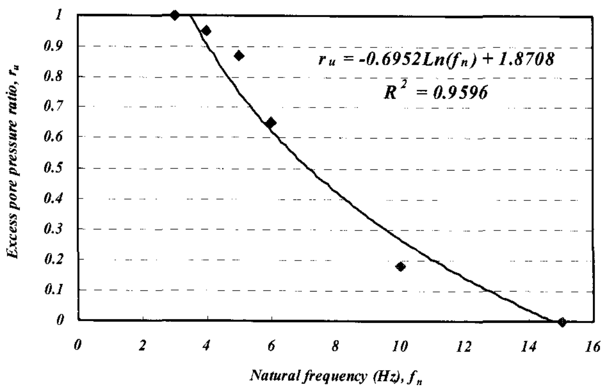


Fig. 4. Natural frequencies of soil-pile system vs. excess pore pressure ratio of surrounding soil (case 3b)

pressure to the vertical effective stress, obtained from Figure 3. It is seen in Figure 4 that the natural frequency of the soil-pile system increases as the excess pore pressure ratio decreases.

The natural frequencies of all cases are summarized in Table 2. The natural frequency of the soil-pile system in case (1) was 16 Hz and in case (2), 4 Hz. In the case of liquefiable soil, the natural frequency was 15 Hz before liquefaction, 3 to 4Hz during liquefaction, and 20 Hz after liquefaction. The natural frequency during liquefaction was similar to that of case (2). This result confirms that the liquefied soil behaves like water. After liquefaction, the natural frequency became larger than that of the no-liquefaction case (3a) probably by the increase of the stiffness due to the densification of the soil during liquefaction.

4. Numerical Analysis

The elastic modulus of the pile surrounding soil of various excess pore pressure ratios, thus, of a pile-soil system with various natural frequencies was calculated by three dimensional FE analyses with a commercial program ABAQUS (1998). In the FE analysis, the model pile and surrounding soil were modeled as an elastic continuum, and the soil-pile system was assumed to be undamped.

Table 3. Input parameters of model pile and surrounding soil for FE analysis

Input parameter	Pile (steel)	Surrounding soil
Elastic modulus	200 GPa	Variation
Poisson's ratio	0.3	0.33
Mass density	7700	1860

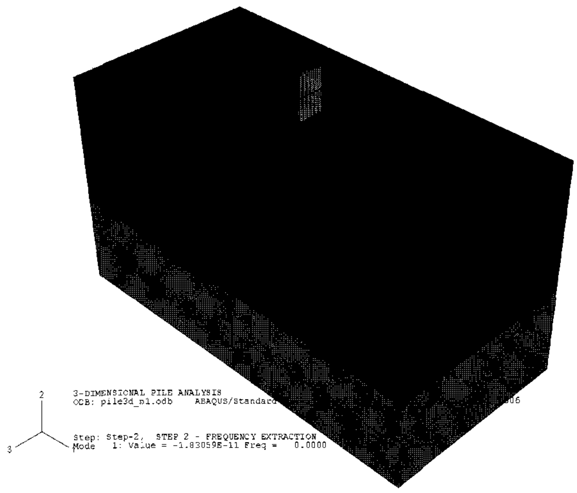


Fig. 5. Mesh for FE analysis of soil-pile system

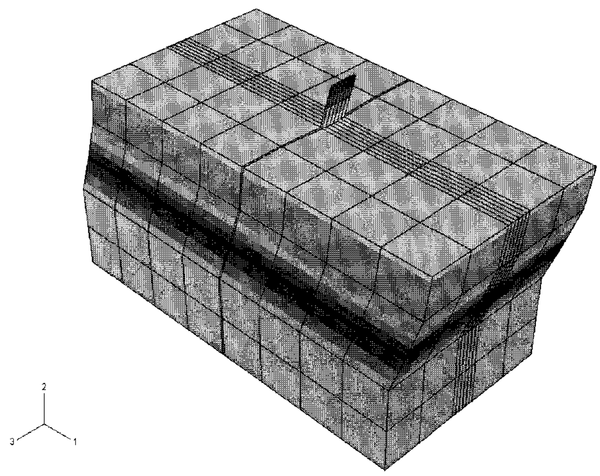


Fig. 6. 1st mode shape of soil-pile system

Important parameters affecting the natural frequency of a soil-pile system are the mass density, elastic modulus and Poisson's ratio of the model pile and the surrounding soil. Input parameters for the numerical analysis are summarized in Table 3. The typical values of the elastic modulus and Poisson's ratio of steel were selected for

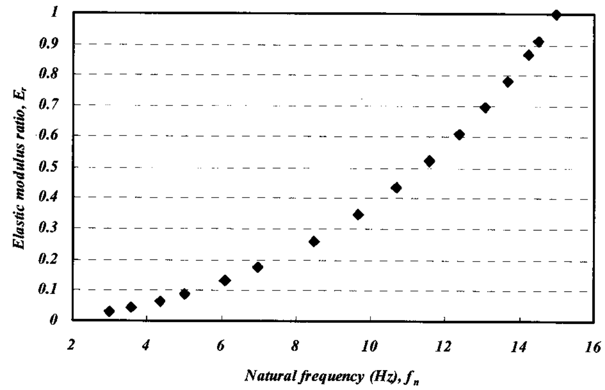
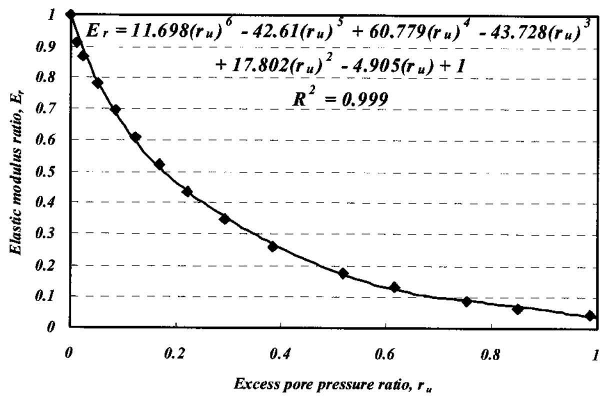
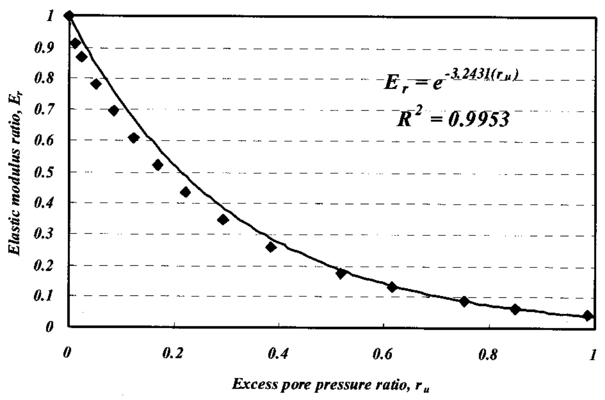


Fig. 7. Elastic modulus ratios of surrounding soil vs. natural frequencies of soil-pile system



(a) Fitting to sixth order polynomial



(b) Fitting to exponential function

Fig. 8. The elastic modulus ratio vs. the excess pore pressure ratio of surrounding soil

the model pile. The mass density of the surrounding soil was the value of saturated Jumoonjin sand. The Poisson's ratio of the surrounding soil was assumed to be 0.33. Figure 5 shows the mesh for the FE analysis. Figure 6 shows the deformed shape of the 1st mode of the soil-pile system.

The natural frequency of the soil-pile system was 15 Hz when the excess pore pressure ratio was zero, and the natural frequencies of the soil-pile system during liquefaction were around 3 to 4 Hz.

From FE analyses, the elastic modulus of the surrounding soil was estimated for the soil-pile system of natural frequencies between 3 and 15 Hz. The results are shown in Figure 7. In this figure, elastic modulus ratios, which are the ratios of respective elastic modulus of surrounding soil of the various states to the soil's elastic modulus of the soil-pile system with the natural frequency of 15 Hz, are plotted against the natural frequencies.

If the natural frequency values in Figure 7 are replaced by the excess pore pressure ratios using the correlation established in Figure 4, an elastic modulus ratio vs. excess pore pressure ratio curve is obtained, as shown in Figure 8. After all, the variation of the elastic moduli of surrounding soils reflects the scaling factor of p-y curve to account for the liquefaction. Two different regression lines are shown in the figures. For easy application in practice, the exponential function correlation (Equation (1)) is recommended.

$$E_r = e^{-3.2431(r_u)} \tag{1}$$

where, E_r : elastic modulus ratio

r_u : excess pore pressure ratio

5. Conclusions

From 1 g shaking table tests, the empirical relations between the excess pore pressures mobilized in a soil ground and the natural frequencies of a soil-pile system were established. From numerical analyses, the relations between the elastic moduli of the soil ground and the natural frequencies of the soil-pile system were also established. Combining these two relations, the relations between the elastic modulus ratios, that is, the scaling factors of p-y curves to account for the liquefaction, and the excess pore pressures of the soil ground were obtained as an exponential function. In pseudo-static analysis, the lateral resistance of liquefied soil is represented as a scalar multiple of its static drained lateral resistance and these scaling factors. Even if the specific results may only apply to the model system tested in this study, they have much potential, because a methodology has been established to find such a correlation, which will be essential for predicting the scaling factors of p-y curves to account for the mobilization of excess pore pressures in soil-structure interaction problems.

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