6th International Conference on Earthquake Geotechnical Engineering
1-4 November 2015
Christchurch, New Zealand

Study on Horizontal Subgrade Reaction of Piles in Volcanic Ash Ground during Liquefaction

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ABSTRACT

Byproducts of volcanic activity are present widely across Japan. While pile foundations in volcanic ash ground are designed based on the specifications of sandy soil, particularly volcanic coarse-grained soil has peculiar mechanical characteristics due to particle breakage. Accordingly, the ground-pile interaction at the time of earthquake is expected to differ between volcanic coarse-grained soil and sandy soil. For the purpose of clarifying the relationship between horizontal subgrade reaction and displacement of piles during liquefaction of volcanic ash ground, a centrifuge model test was carried out by parameterizing liquefaction strength ratio of ground. Test results revealed that the coefficient of horizontal subgrade reaction of piles during liquefaction reduced less markedly in volcanic ash ground in comparison with sandy ground as the former had the smaller coefficient of static horizontal subgrade reaction than the latter before shaking where the both were made to have equal liquefaction strength ratio.

Introduction

Due to continuous volcanic activities since the Quaternary period, various kinds and properties of volcanic byproducts are present widely across Japan, where designs of pile foundation constructed in volcanic ash ground are based on those for sandy soil and cohesive soil. Likewise, seismic factors such as a coefficient of horizontal subgrade reaction of piles against earthquake are determined in accordance with normal (static) design values. However, it has come to light that volcanic ash soil possesses peculiar mechanical characteristics.

Particularly in volcanic coarse-grained soil, particle breakage attributed to its fragile porous particle structure and welding consolidation formed in the process of sedimentation occur, presenting different physical and mechanical characteristics from sandy soil (see, Miura et al. 2003). In past studies on pile foundation in volcanic coarse-grained ground, it was confirmed that observed values of skin friction of piles were smaller than the design value for sandy soil and that horizontal resistances of piles were different from those in sandy ground (Tomisawa et al. 2011). From those findings, the ground-pile interaction in volcanic ash soil during earthquake is expected to be different from that in sandy soil.

In examining the ground-pile interaction during earthquake, it's important to clarify the relationship between horizontal subgrade reaction and displacement of piles during liquefaction. In these contexts, the authors carried out a centrifuge model test to trace the relationship between horizontal subgrade reaction and displacement of piles during liquefaction of volcanic ash ground (Egawa et al. 2014).

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The experiment was conducted by parameterizing a liquefaction strength ratio of ground against external seismic force. In this report, we will discuss the downward trend of the coefficient of horizontal subgrade reaction of piles during liquefaction of volcanic ash ground depending on the difference in liquefaction strength ratio.

Outline of the experiment

In the centrifuge model test, a one-fiftieth scale model shown in Figure 1 was allowed to make 50G centrifugal acceleration, and a dynamic shaking test following a static horizontal load test was carried out under the conditions listed in Table 1: input seismic motion with 20 sine waves, 1.5Hz frequency in real scale and 400cm/s^2 peak acceleration.

A model pile was steel-made (SS400) with an outside diameter of D=10.0mm, a thickness of t=0.2mm and a length of L=400mm (D=500mm, t=10mm and L=20m in real scale). As Figure 1 illustrates, two piles were arranged in two lines with a pile center distance of 3D. A pile end was fixed whereas a pile head was made a weighted free end. Two strain gauges were attached to each of six different depths on one out of four piles.

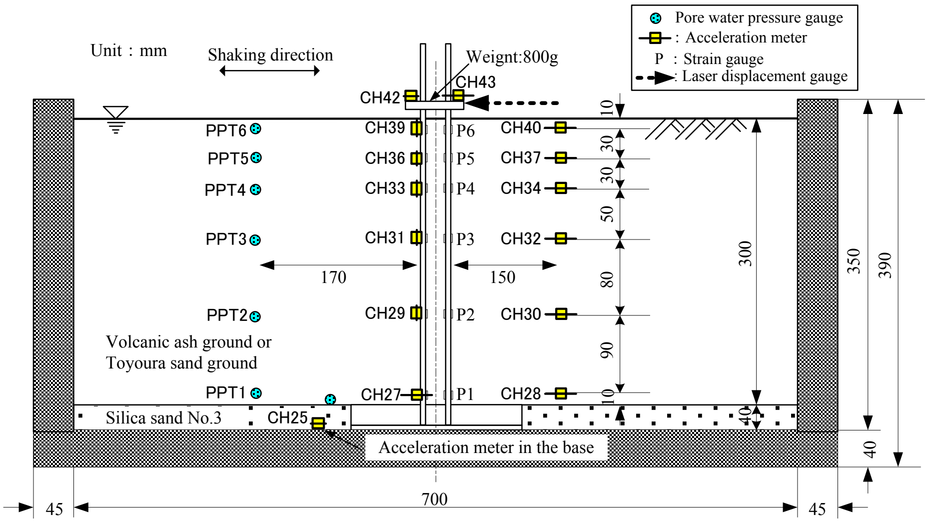


Figure 1. Outline of the test model

Table 1. Test cases

Case	Model ground	Input seismic motion
1	Volcanic ash soil D_r=85%, ρ_d=1.097g/cm^3, R_{L20}=0.183	20 sine waves Frequency 1.5 Hz Max. Acc. 400 cm/s^2 in Prototype scale *Where, 1cm/s^2 = 0.01m/s^2
2	Volcanic ash soil D_r=81%, ρ_d=1.082g/cm^3, R_{L20}=0.149	
3	Toyoura sand D_r=55%, ρ_d=1.493g/cm^3, R_{L20}=0.183	
4	Toyoura sand D_r=40%, ρ_d=1.449g/cm^3, R_{L20}=0.149	

As for volcanic ash ground, Shikotsu pumice-flow deposit (Spfl) passed through a 0.85mm sieve was used as Japan's typical volcanic coarse-grained soil, and Toyoura sand which is standard test sand used mostly in Japan was employed to make sandy ground. Physical properties of materials for each model ground are shown in Table 2. The fine fraction content

(F_C) of the volcanic ash soil was larger than that of Toyoura sand, but all the materials for each model ground would be classified as a sandy soil layer which needs liquefaction assessment according to Japanese standards ($F_C \leq 35\%$, $D_{50} \leq 10$mm and $D_{10} \leq 1$mm).

Different types of model ground were prepared as Table 1 demonstrates. Two pairs of volcanic ash ground and sandy ground, namely Cases 1 and 3 and Cases 2 and 4, were given the same liquefaction strength ratio (R_{L20}) each, based on which respective relative densities (D_r) were determined beforehand. Here, the liquefaction strength ratio (R_{L20}) is the cyclic stress amplitude ratio, $\sigma_d/2\sigma'_0$ (σ_d :cyclic deviator stress, σ'_0 :effective confining pressure), responding to the double amplitude of linear strain DA=5% and the number of cycles N_c=20 in a cyclic undrained triaxial test of soil (JGS0541-2009). Liquefaction strength curves obtained from a cyclic undrained triaxial test for each model ground are illustrated in Figure 2. Under the condition of equivalent liquefaction strength ratio, the level of relative density turned out to be different between the paired two. Accelerometers and piezometers were placed in the model ground as is shown in Figure 1. Regarding pore fluid, silicon oil of dynamic viscosity 50 times greater than water was used for each model ground and saturated in a deaerating tank.

Table 2. Physical properties of model ground materials

	Volcanic ash soil	Toyoura sand
Sand fraction (%)	67.1	99.8
Silt fraction (%)	24.2	0.1
Clay fraction (%)	8.7	0.1
Fine fraction content F_C (%)	32.9	0.1
Maximum grain size Dmax (mm)	0.85	0.43
50% grain size D_{50} (mm)	0.143	0.164
10% grain size D_{10} (mm)	0.007	0.115
Coefficient of uniformity U_c	29.90	1.60
Coefficient of curvature U_c'	2.60	0.91
Soil particle density ρ_s (g/cm^3)	2.434	2.643

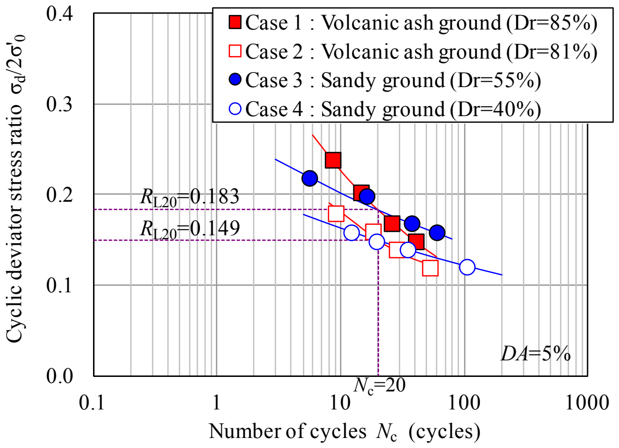


Figure 2. Liquefaction strength curves of model ground

Test results and review

Data obtained from the centrifuge model test under the above mentioned conditions was collated and reviewed. The numerical data hereafter are values converted to prototype scale.

Evaluation of the coefficient of horizontal subgrade reaction of piles

Changes of the coefficient of horizontal subgrade reaction in response to pile displacement, which take place in various tests, are evaluated through the method proposed by Tokimatsu (Tokimatsu et al. 2002). In this method, the bending moment is obtained from bending strain of piles measured at each depth in the test, to which second-order differential or integral calculus is applied in the direction of depth. Then, the resultant horizontal subgrade reaction and horizontal displacement of piles are evaluated.

Figure 3 demonstrates the method to calculate the coefficient of horizontal subgrade reaction in a static horizontal loading test as well as during shaking. The depth distribution of bending moment of piles was arranged by interpolating each measurement point based on the cubic spline interpolation method.

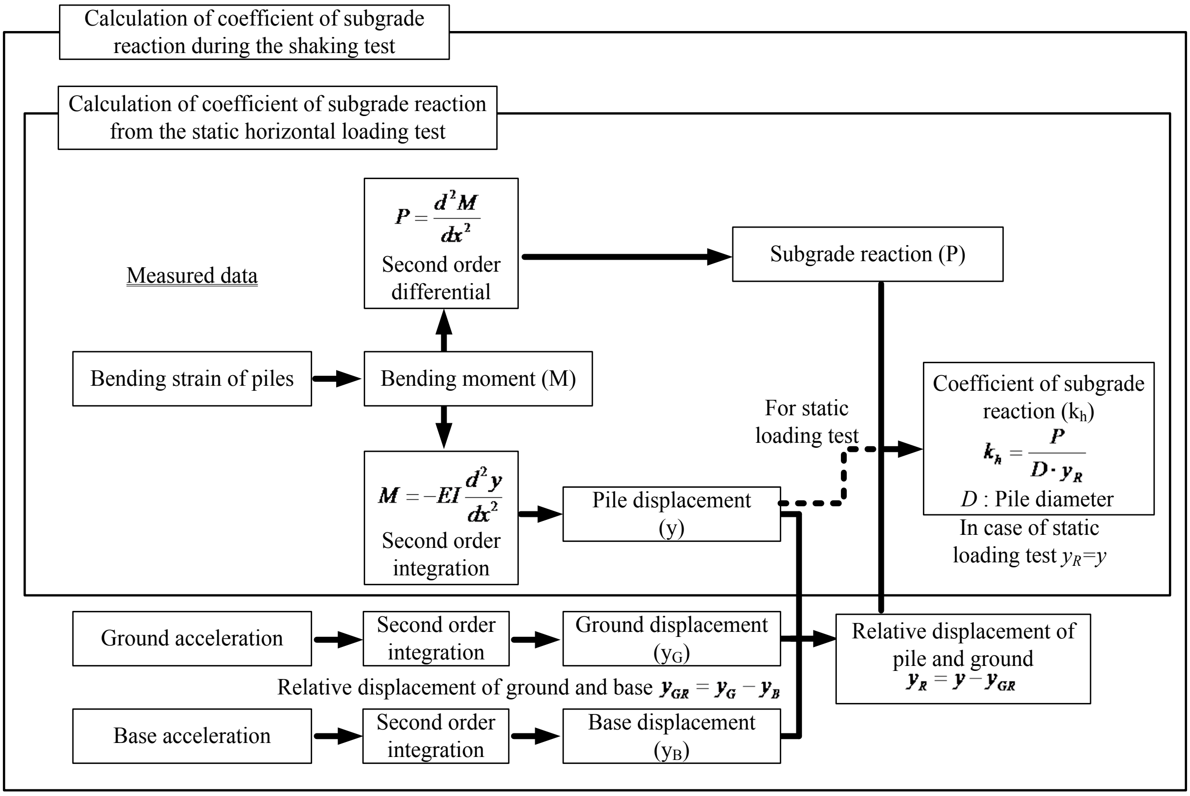


Figure 3. Calculation of the coefficient of horizontal subgrade reaction in a static horizontal loading test and during shaking

Coefficient of horizontal subgrade reaction during shaking

Figures 4 illustrates the time history of relevant data calculated from measurements during shaking at P4 (G.L.-3.5m) located within the range of characteristic length $1/\beta$ of the pile for each case. Due to space limitation, time histories data of P5 (G.L.-2.0m) were not shown, however their tendency were the same with P4 as shown in Figure 4. Here, $1/\beta$ is the depth of ground which related to the lateral resistance of pile. β is defined as below.

$$\beta = \sqrt[4]{(k_H D)/4EI} \qquad (1)$$

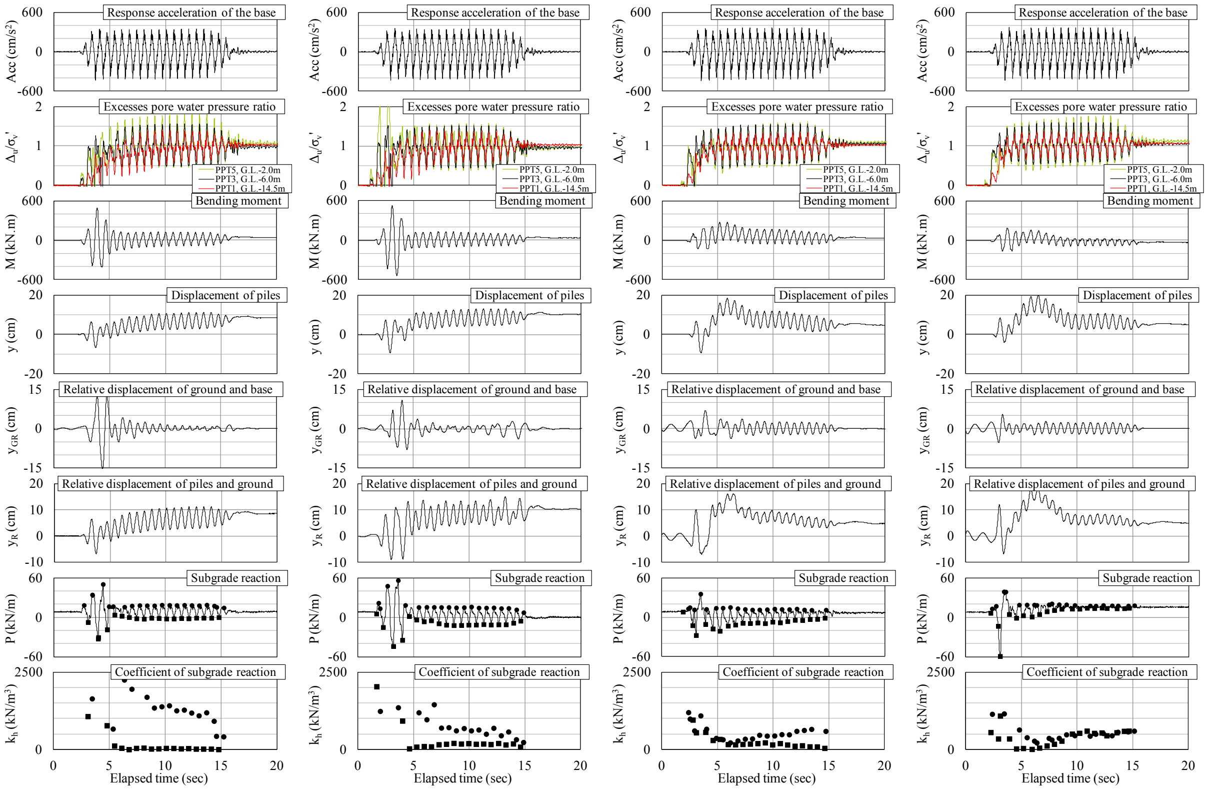
Where,

β : Characteristic value of pile (m^{-1})
k_H : Coefficient of horizontal subgrade reaction of pile (kN/m^3)
D : Diameter of pile (m)
EI : Bending rigidity of pile ($kN.m^2$)

In Figure 4, the excess pore pressure ratios, Δ_u/σ_v', at depths of 2.0m, 6.0m, and 14.5m are included so that the behavior of the piles along with the rise in excess pore pressure can be confirmed. Down to a deep level of ground in all the cases, Δ_u/σ_v' reached 1.0, suggesting that liquefaction took place in the whole ground.

The bending moment of piles presented a high amplitude during an early stage of shaking, the degree was varying between cases though, and the amplitude decreased along with the rise in excess pore pressure by shaking, that is the development of liquefaction. Reduction in amplitude was conspicuous in volcanic ash ground with large relative density regardless of liquefaction strength ratio. In the case of sandy ground with a relative density of D_r=85%, similar results were obtained in past (Egawa et al. 2014).

As for the relative displacement between ground and foundation which was obtained from ground and response acceleration of foundation, they produced a large amplitude during an early stage of shaking, which decreased or fluctuated with the development of liquefaction. This trend was conspicuous in volcanic ash ground with large relative density regardless of liquefaction strength ratio.



(a) Case1 : Volcanic ash ground
D_r=85%, R_{L20}=0.183

(b) Case2 : Volcanic ash ground
D_r=81%, R_{L20}=0.149

(c) Case3 : Sandy ground
D_r=55%, R_{L20}=0.183

(d) Case4 : Sandy ground
D_r=40%, R_{L20}=0.149

Figure 4. Time history of relevant data calculated from measurements at P4 (G.L.-3.5m)

This is possibly attributed to the facts that ground with larger initial shear rigidity exhibits greater acceleration response and reacts markedly during an early stage of shaking but that the ground reduces its initial shear rigidity and softens with the development of liquefaction. It is noticed that the relative displacement between piles and ground starts to lean toward the positive side from the point where the amplitude of relative displacement between ground and foundation decreases or fluctuates. The horizontal subgrade reaction as well produced a large amplitude during an early stage of shaking, which decreased or fluctuated with the development of liquefaction.

It can be asserted that the coefficient of horizontal subgrade reaction obtained on the basis of these relationships decreased along with the development of liquefaction. As for volcanic ash ground, the coefficient of horizontal subgrade reaction reduced less in Case 2, which had a low liquefaction strength ratio compared with Case 1. In the case of sandy ground, no big difference was seen in the coefficient of horizontal subgrade reaction between the two of different liquefaction strength ratios, where the recovering trend was noticed in the later shaking stage. As a reason for it, it is suspected that the ground density increases due to soil compression when the relative density of the ground is low.

From these outcomes, the following can be considered regarding the ground-pile interaction during the process of ground liquefaction. The greater amplitude of pile was occurred in accordance with the increase of amplitude of ground motion at the beginning stage of earthquake motion. However, horizontal subgrade reaction and coefficient of horizontal subgrade reaction decrease with development of ground liquefaction. This is considered to be caused by the initial shear rigidity of ground decrease during liquefaction. In other words, the ground would lose its function as a reactive body to piles, and eventually the amplitude on the pile side decreases or fluctuate. Tobita et al. have reported in their relevant studies that the amplitudes of bending moment and pile displacement remained with no reduction in dry sand, but that a large amplitude was confirmed in the early shaking stage and started declining with the development of liquefaction in saturated sand in the same manner as this study. Reasons for these would be attributable to the movement of piles together with ground and the decrease in the coefficient of subgrade reaction during shaking due to nonlinearity of ground caused by vibration (Tobita et al. 2003).

Downward trend in the coefficient of horizontal subgrade reaction of piles with different liquefaction strength ratio of ground

Figure 5 illustrates the relationship between the coefficient of horizontal subgrade reaction of piles and the pile-ground relative displacement at P4 (G.L.-3.5m) and P5 (G.L.-2.0m) for all the cases before and during shaking (liquefaction) according to liquefaction strength ratio. In each case, the coefficient of horizontal subgrade reaction during liquefaction decreased from that of static horizontal subgrade reaction before shaking. Except for P4 in Case 4, their reduction rate was small in volcanic ash ground, which possessed a lower coefficient of static horizontal subgrade reaction before shaking in comparison with sandy ground.

To clarify a downward trend in the coefficient of horizontal subgrade reaction during liquefaction, Figure 6 shows data during shaking (liquefaction) which were extracted from Figure 5 and plotted over the graphs with a rescaled y-axis. The coefficient of horizontal subgrade reaction during liquefaction reduced to a similar level in all cases regardless of ground type or liquefaction strength ratio. From these outcomes, it can be assumed that the reduction rate in the coefficient of horizontal subgrade reaction during ground liquefaction is

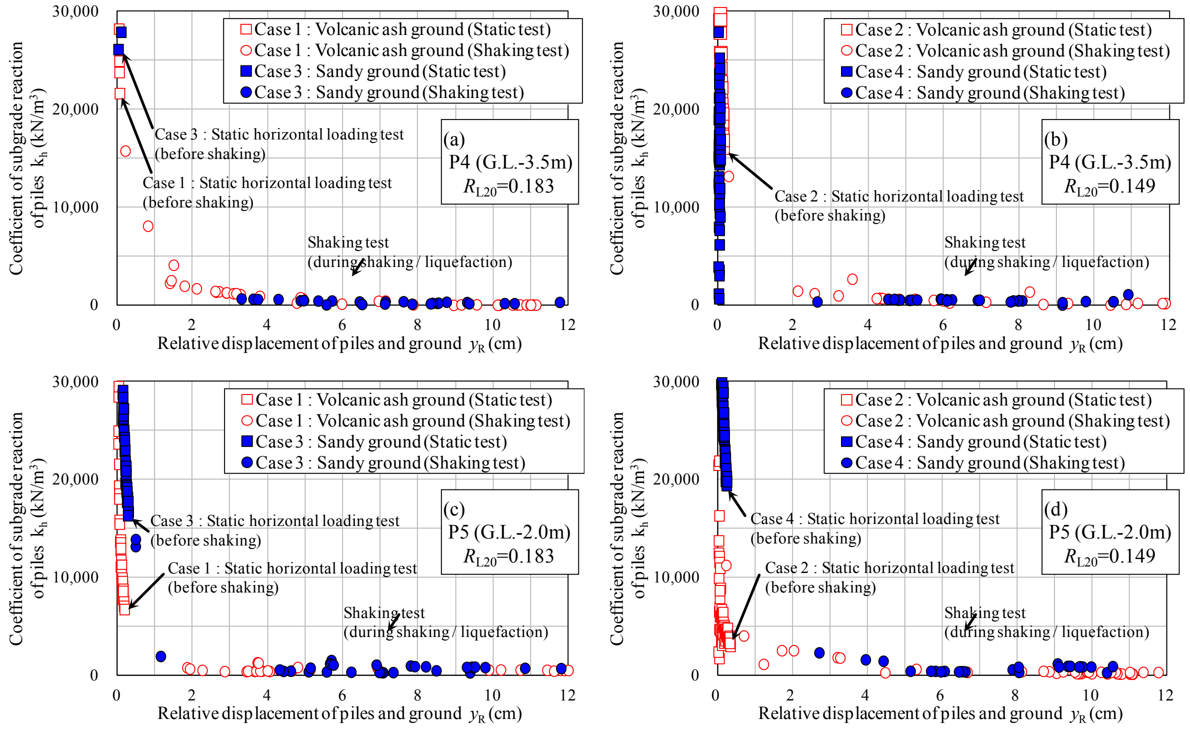


Figure 5. The relationship between the coefficient of horizontal subgrade reaction and the pile-ground relative displacement before and during shaking (liquefaction) at P4 (G.L.-3.5m) and P5 (G.L.-2.0m) according to liquefaction strength ratio

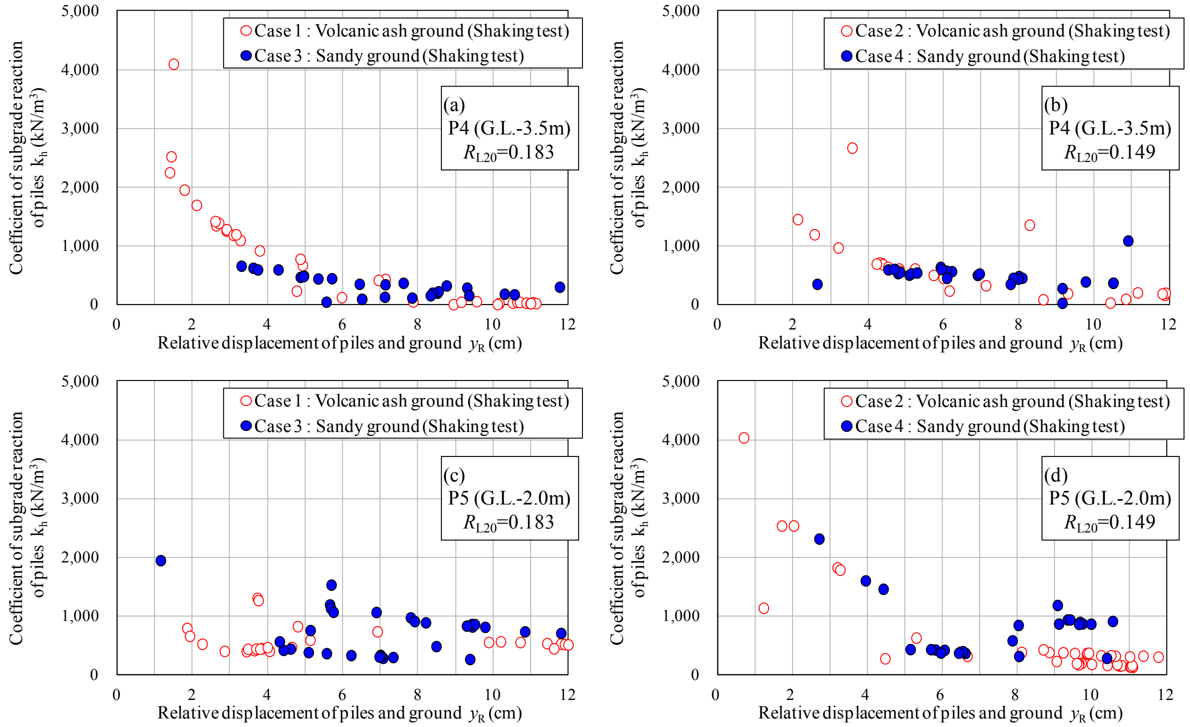


Figure 6. The relationship between the coefficient of horizontal subgrade reaction and the pile-ground relative displacement during shaking (liquefaction) at P4 (G.L.-3.5m) and P5 (G.L.-2.0m) according to liquefaction strength ratio

large in sandy ground because its coefficient of static horizontal subgrade reaction before shaking is high, whereas the reduction rate is smaller in volcanic ash ground because its coefficient of static horizontal subgrade reaction before shaking is low compared with sandy ground.

The reduction rate in the coefficient of horizontal subgrade reaction of sandy ground with different liquefaction strength ratio was evaluated to be nearly equivalent under the conditions of this study. In the meantime, the reduction rate in volcanic ash ground differed between the two cases since the coefficient of static horizontal subgrade reaction before shaking was smaller in Case 2 with lower liquefaction strength ratio than Case 1. From these outcomes, the difference in liquefaction strength ratio of volcanic ash ground is considered to be greatly associated with the reduction rate in the coefficient of horizontal subgrade reaction. Thus, an appropriate reduction rate responding to liquefaction strength ratio needs to be sought for.

Conclusions

The coefficient of horizontal subgrade reaction of piles during liquefaction reduced to a similar level regardless of ground type or liquefaction strength ratio. The reduction rate in sandy ground was large because its coefficient of static horizontal subgrade reaction before shaking was high, whereas the reduction rate in volcanic ash ground was smaller because its coefficient of static horizontal subgrade reaction before shaking was low compared with sandy ground.

The reduction rate in the coefficient of horizontal subgrade reaction of sandy ground with different liquefaction strength ratio was evaluated to be nearly equivalent under the conditions of this study. In volcanic ash ground, however, the reduction rate differed between two cases since the coefficient of static horizontal subgrade reaction before shaking was smaller in the case with lower liquefaction strength ratio. For volcanic ash ground, the difference in liquefaction strength ratio is considered to be greatly associated with the reduction rate in the coefficient of horizontal subgrade reaction. Thus, an appropriate reduction rate responding to liquefaction strength ratio needs to be sought.

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