Comparison of liquefaction behavior for different ground relative densities by centrifuge tests

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ABSTRACT

Liquefaction-induced lateral spreading and geostructure failures are important concerns in geotechnical engineering. Geotechnical researchers have been conducting laboratory tests and in-situ tests to determine liquefaction mechanism and stress-strain response of soil. In the past few decades, experimental simulations and centrifuge tests have been conducted worldwide for studying liquefaction phenomena, which has led to considerable advancement in research, but such tests have been carried out mostly independently. LEAP (Liquefaction Experiments Analysis Project) is an ongoing international collaborative effort to produce high quality experimental data sets to validate existing computational models for simulating the dynamic response in liquefiable saturated granular soils. As a part of the LEAP, centrifuge model tests are performed by applying the same intensity (0.15g) destructive motion on a 5 degree sloping ground with different relative densities (85%, 65%, 50%, 50%) to induce liquefaction. In this paper, the comparisons of pore pressure ratio values, stress-strain curves and displacements of each model for different depths are presented and discussed.

Keywords: Centrifuge model tests, relative density, liquefaction, LEAP, displacement

1 INTRODUCTION

Ground liquefaction is mainly caused by the reduction of shear resistance of the ground when cyclic loading such as during an earthquake is applied to the soft ground under undrained conditions. The reduction of the shear resistance is related to the increase in excess pore water pressure. Also, liquefaction causes ground settlement and horizontal displacements, which affects the stability of the structure. The Nigata earthquake (Japan 1964) and the Alaska earthquake (USA 1964) were two important events where liquefaction damage was largest. After these two earthquakes, the risk of liquefaction has been emphasized and studies on liquefaction are proceeding actively.

In the past few decades, experimental simulations and centrifuge tests have been conducted worldwide for liquefaction, which has led to advancement in research, but such tests have been carried out mostly independently. To address this, LEAP (Liquefaction Experiments Analysis Project) was established, which is an ongoing international collaborative effort to produce high quality experimental data sets for validating existing computational models in simulating dynamic response and liquefaction of saturated granular soils (Manzari et al., 2014). In this study, liquefaction behavior for relative densities of the ground is evaluated as part of LEAP-UCD-2017. The centrifuge model test procedures and results are described.

Relative density is an important parameter that affects liquefaction behavior of saturated cohesionless soils. In this study, 1Hz tapered sine wave of the same intensity (0.15g) was applied to 5 degree sloping grounds with different relative densities (85%, 65%, 50%) for evaluating liquefaction behavior using centrifuge model tests. To clearly observe the phenomena occurring in liquefied ground, a duplication test was also performed on the loose sand model (50%), where the chance of liquefaction occurence is high. Stress-strain curves, effective stress path and pore-pressure ratio values (ru) are provided for liquefaction evaluation at different depths of the model, as well as high-quality displacement data based on recorded video using a high-speed camera during the destructive motions.

2 CENTRIFUGE MODEL TEST

Ottawa F-65 sand was used as the granular soil for liquefaction simulation. The grain size characteristics and property of the soil are as follows: $G_s = 2.665, D_{10} = 0.13mm, D_{30} = 0.17mm, D_{50} = 0.20mm\ and\ D_{60} = 0.21mm$(Kutter et al., 2017). The minimum and maximum densities of soil were determined as $\rho_{dmax} =$ 1752 $\mathrm{kg/m^3}$ and

ρ_{dmin} =1470$\mathrm{kg/m^3}$, respectively.

The target soil densities of the dense, medium dense and loose test conditions in KAIST were specified as 1718$\mathrm{kg/m^3}$, 1648$\mathrm{kg/m^3}$, and 1605$\mathrm{kg/m^3}$ based on the soil properties. The relative density of each model is shown in Table 1, which was the result of ground modeling based on the result of calibration test of slot size and drop height using hand pluviation of sand to achieve the target soil density.

Table 1. Dry soil density by each model

Test description	Dry soil density ($\mathrm{kg/m^3}$)	Relative density (%)
Dense (Dr=85%)	1701.2	81
Medium dense (Dr=65%)	1651.8	62
Loose (Dr=50%)	1634.2	58
Loose dulpication (Dr=50%)	1592.5	45

The model was constructed with a 5° sloping sand ground in a rigid box. The centrifuge tests were performed at 40g centrifugal acceleration to match the prototype dimensions: 22.8 m × 4 m × 9 m (length × depth at midpoint × width), based on the LEAP specifications. In the KAIST centrifuge facility, the 5° inclination along the length of the model was not curved because the shaking plane was perpendicular to the plane of rotation of the centrifuge. The sensors layout is shown in Figure. 1. The responses of the soil model during shaking were monitored using eight accelerometers along the direction of shaking (AH1–AH4 in the soil mass and AH11–AH12 on the rigid container), two vertical accelerometers (AV1 and AV2), and six pore pressure transducers (P1–P6, P9-P10).

Viscous pore fluid was used in all the experiments and the viscosity was scaled according to conventional scaling law $\mu = \mu_{\mathrm{water}}/L^*$. The length scale factor,L^*, is defined as $L^* = L_{model}/L_{prototpye}$. For the centrifugal acceleration of 40 g, the target viscosity was set to 40cSt. The viscous fluid was manufactured with a mixture of water and methylcellulose and the viscosity was measured by an automated viscometer and a falling ball viscometer. Since the viscous fluid is very sensitive to temperature, the achieved viscosity was in the range of 36 to 42 cSt based on the laboratory normal temperature of 18℃ for each model.

Figure.2 shows the schematic of the saturation system used in KAIST. Before saturating, the box was completely sealed from external air. The procedure for the saturation process is as follows: Vacuum pressure (<95 kPa) was applied and low pressure CO_2 (<15 kPa) was flooded in the box repeatedly. This process was performed five times for 40 min each time. The de-aired viscous fluid is an essential requirement when pore pressure needs to be measured, as any dissolved air in the fluid may lead to errors in pore pressure measurements. The reason why the vacuum pressure has to be lower than 95kPa is that the boiling point of the fluid change depending on the vacuum pressure. While maintaining vacuum pressure in the rigid box and the viscous fluid container, the viscous fluid slowly dripped into the ground model. The dripping point was at the downward direction of the slope. In order to minimize the impact of drip on the soil surface, a sponge was put on the ground surface. After the viscous fluid was 5 cm higher than the soil, Okamura's method was used to measure the degree of saturation (Okamura et al., 2012). As a result, the degree of saturation of each ground model was about 99.9%.

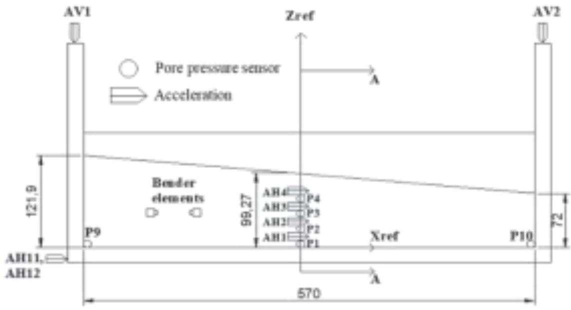

Fig. 1. Schematic of ground model and sensors layout

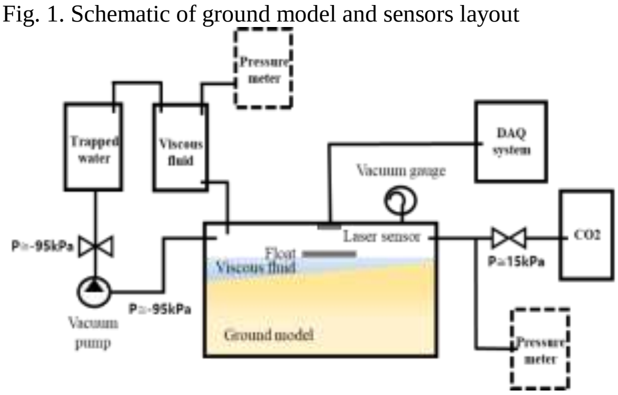

Fig. 2. Schematic of saturation system at KAIST

A high-speed camera was used to capture the instantaneous surface marker's movements while the destructive motion was applied to the ground model. The time of the destructive motion was less than a second, and the high-speed camera was set at 1200 frames per second to track the horizontal displacement. Prior to the centrifuge test, the high-speed camera was focused on the center of the model container for clear marker tracking. Calibration test of the high-speed camera was performed by measuring the distance between the camera and the center of the box at 1g. As a target, red surface markers with a diameter of 26mm which were manufactured by PVC material were installed at 3×6 at regular intervals in Figure 3. The displacements from the acquired video were obtained by a displacement tracking program called TEMA. The horizontal displacements of 18 markers during the destructive motions based on the distance between the reference points (260mm) were calculated on a prototype scale.

Tapered sine waves of prototype frequency 1Hz and various amplitudes were applied to each model. Each destructive motion with a maximum acceleration of 0.15 g was measured by AH11 and AH12 accelerometers attached to the bottom side of the box as shown in Figure 4. The acceleration response spectra for the input motions presented in Figure 5 show that the input motions applied to the models contain some high frequency components. Based on a previous study, the higher frequency components have relatively small effect on the behavior of the model (Kutter et al., 2018). The achieved input motions for each model were close to the target intensity of 0.15g.

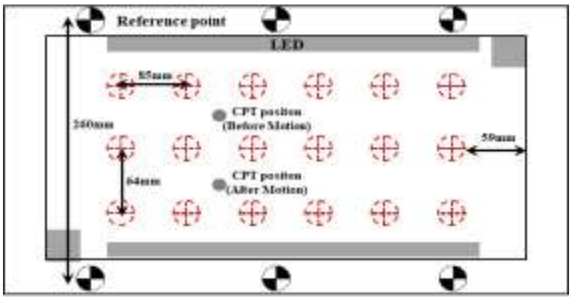

Fig. 3. Top view of the ground model with 18 markers

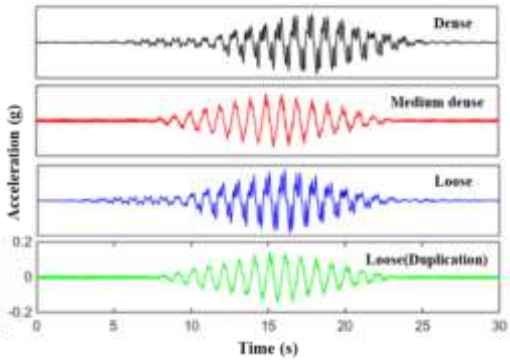

Fig.4. Input destructive motion

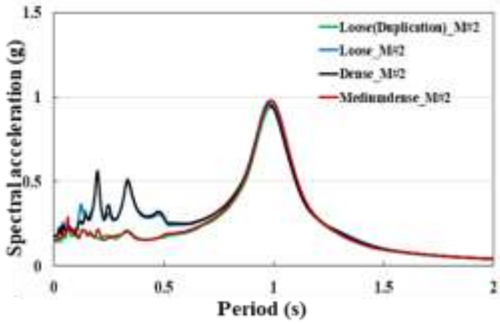

Fig.5. Input response spectra of destructive motions

3 TEST RESULTS

Figure 6 shows the response of pore pressure sensors installed in the central array near the surface (depth = 1 m). However, the pore pressure measurement in medium dense sand was not included due to measurement error of pore pressure transducers. The pore pressure ratio (r_u) is defined as a ratio of the excess pore pressure to the initial vertical effective stress. This is generally used in liquefaction evaluation, and the liquefaction can be assumed to occur when $r_u = 1$. In dense model, the pore pressure ratio did not approach 1 near the surface. On the other hand, the pore pressure ratio approached 1 in the P4 response near the surface of the loose model. As soon as the pore pressure ratio approaches 1, a sharp spike appeared, which is due to the dilatancy behavior of the soil.

Generally, liquefaction is defined as the state of phase transformation from solid to liquid and this means that the effective stress (p') is approximately zero. Zero Effective stress implies that there is no frictional contact force between the soil particles, and hence no shear resistance. Based on the laboratory testing of saturated soils, it is well known that the pore pressure increases and the effective stress decreases as the shear stress increases with the number of loading cycles. However, a large strain cycle instantaneously leads to the reduction of the pore pressure which results in a temporary increase of effective stress due to soil dilatancy characteristic. The negative spikes in the pore water pressure and the spikes in the acceleration time histories, which occurred as a result of soil dilatancy, are defined as de-liquefaction shock waves (Kutter and Wilson et al., 1999).

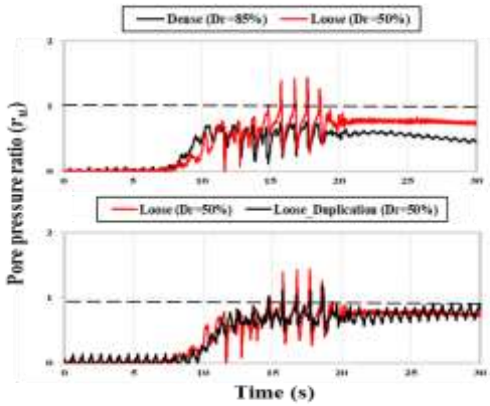

Fig.6. Pore pressure ratio of P4 (1m) installed near the surface

Figure 7 shows the stress-strain curve calculated for each model with different relative density based on accelerometers responses during the same destructive motion (Zeghal et al., 2017). All stress spikes were observed in the downslope direction due to the sloping ground model. Large strain and stress spikes are considered to cause liquefaction. In the liquefied ground, the effective stress is zero, and so the phase transformation from solid to liquid can be confirmed from the effective stress path. In the case of the medium dense model, it is impossible to measure the excess pore water pressure due to the defect in the pore pressure transducers. Thus, the effective stress path of the medium dense model cannot be shown in Figure 7. At the depth of 1 m in the loose model, the effective stress approached 0, which shows that the phase transformation and hence liquefaction has occurred.

Figure 8 shows the stress-strain curve for a duplication test of a loose model in which it is easy to induce liquefaction. The stress-strain response patterns of the both models show an overall similar trend. All spikes occurred in downslope due to the sloping ground model. Also, the momentary spikes due to dilatancy have appeared in the accelerometer response. It is also observed that phase transformation has occurred based on the effective stress path of both models.

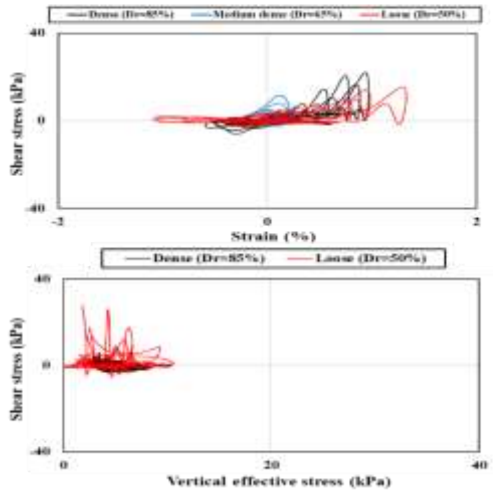

Fig.7. Shear stress-strain histories for destructive motion based on the acceleration response near the surface (1m)

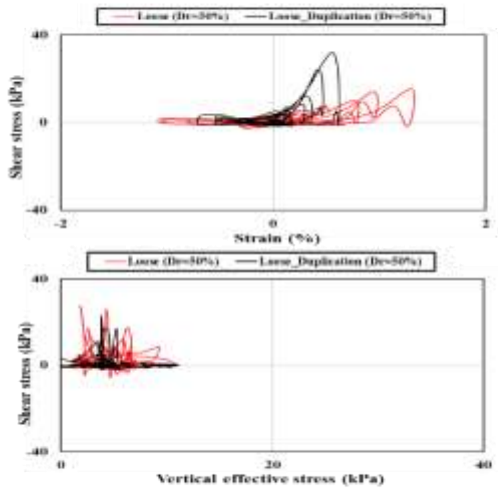

Fig.8. Effective stress path for destructive motion based on the acceleration response near the surface (1m)

The changes in horizontal displacement before and after destructive motion for the dense, medium dense, and loose models are shown in Figure 9 through contour lines. Larger horizontal displacements occurred for loose models while the horizontal displacements hardly occurred in the dense model. In the medium dense and loose models, the markers moved on average in the downslope direction by 20 mm and 92 mm (prototype) after the destructive motion, respectively. On average, the markers moved 134 mm in the downslope direction in the duplication test of the loose model. This means that large displacements occurs in loose saturated ground following soil liquefaction.

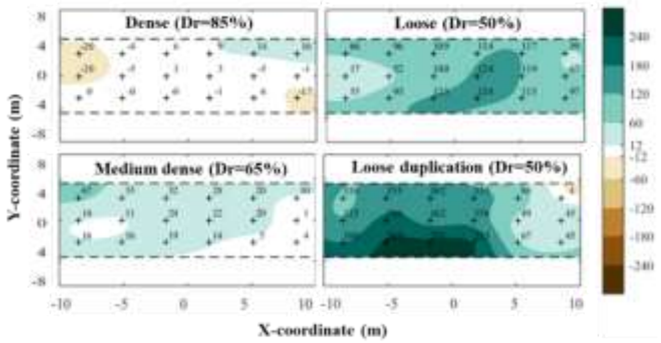

Fig.9. Contour line is presented using calculation of the horizontal displacement for each marker by using TEMA software

4 Summary

Four types of centrifuge tests were performed for evaluating liquefaction behavior with different relative densities. All tests were conducted on a 5 degree sloping ground model at 40g centrifugal acceleration using1Hz tapered sine wave of 0.15g The comparison of r_u values, stress-strain curves, and displacements for each model is described in context of liquefaction susceptibility in grounds of different relative densities.

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