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THE DYNAMIC RESPONSE OF UNSATURATED CLEAN SAND AT A VERY LOW FREQUENCY

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ABSTRACT

A series of cyclic triaxial tests at very low frequency was carried out on unsaturated clean sand in order to quantitatively investigate the influence of the degree of saturation on dynamic response. The conventional triaxial testing apparatus, which is usually used on saturated soil, was employed to test the unsaturated soil with the additional pore air pressure controller. During the series of tests, four different degrees of saturation level (S_r = 55%, 70%, 85%, 98%) were applied to the soil specimen based on a single value of effective confining pressure (σ'_3). The results revealed that the application of cyclic loading at a very low frequency occurring continuously triggered the decrease of soil resistance. For degree saturation, S_r = 55% revealed that the resistance of soil was stronger in comparison to another level. Furthermore, the experimental results confirmed that applied cyclic loading induced a change in saturation level before and after testing. In addition, at a certain level of saturation, a phenomenon of settlements was likely to occur and the soil specimen then underwent liquefaction.

Keywords: Unsaturated clean sand; Undrained cyclic triaxial testing; Cyclic shear strain

1. INTRODUCTION

Extensive research has been conducted on the topic of soil dynamics in order to obtain comprehensive results on soil characteristics that were resulted from continuous dynamic loading. Research on soil dynamics has garnered many interesting results since the 1930s regarding many aspects of the topic, such as soil dynamic characteristic methods of testing, devices and the variables of soil sample parameters. The dynamic response of soil induced by cyclic loading is important to analyze since it induces granular deformation. It should be controlled within a certain limit in order to prevent the structure from being destroyed or becoming unstable. In geotechnical engineering, the soil medium supports many functions, such as through granules of soil that act as a foundation for engineering structures or engineering material, such as for earth fill for embankment or for roadbeds in earth slope.

The behavior of granular material or clean sand subjected to loading has been observed intensively until now. More recently, laboratory test results of soil dynamic have indicated that granular material interaction changed due to the application of cyclic loading (Kramer, 1996; Vucetic & Dobry, 1991; Atkinson, 2014). Many researchers have stated that shear strain increased continuously even though compressive strength decreased at a minimum value.

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Furthermore, Das (1992) reported that loose sand depicted a contrast result between compressive strength and shear strain during an application of cyclic loading. Wu and Sun (2008) confirmed that the complexity of granular deformation due to cyclic loading could induce a vibrating liquefaction. Nowadays, most studies concerning soil dynamics behavior have been focused on saturated or partially saturated soil caused by earthquake loading (Dobry & Alvarez, 1967; Sitharam et al., 2004; Gupta & Agrawal, 1998; Prakash & Puri, 2010; Karakaş & Coruk, 2007) or on non-saturated soil to reveal the basic concept of soil behavior due to cyclic loading. In fact, many cases of natural hazard were found in unsaturated conditions due to earthquakes, which have a high loading frequency (Orense et al., 2012; Kazama & Uno, 2007; Pastor et al., 2010; Bian & Shahrour, 2009). There has not been much laboratory research on unsaturated dynamic loading at a very low frequency that focuses on dynamic response due to continuous small cyclic loading. Therefore, an exploration of the dynamic response of clean sand at a low frequency needs to be conducted in order to compile comprehensive results. The aim of the present study is to examine cyclic shear strain and the dynamic response of unsaturated clean sand by using a low frequency through laboratory testing. A series of cyclic triaxial tests was conducted on the sample at varying degrees of saturation ($S_r = 98\%$, 85%, 70% and 55%) and under the single condition of effective confining stress (σ'_3). After a presentation of the stress-strain relationship due to cyclic loading, the paper presents a study of degree of saturation that influenced the response of void ratio behavior before and after testing.

2. EXPERIMENTAL SETUP

2.1. Soil Particle Deformation

In the saturated soil sample, all of the void spaces were filled with water and when it was subjected to cyclic loading, it forced particle grains to re-arrange more closely together. On the other hand, they have to expel the water. When the cyclic loading was continued, the water would reach the excessive energy due to the water expulsion. In some cases, it seems like there was an increase in water pressure, which was indicated by the presence of the water release phenomenon at the surface; thus, it could be said the soil was liquefied. In unsaturated soil, void spaces were occupied by water and air that had the smallest compressibility. The application of cyclic loading also triggered an increase in pore water pressure, but it directly replaced the air void in order to dissipate an excessive energy. The phenomenon of increasing pore water pressure in unsaturated and saturated soil is described in detail in Figure 1.

In soil mechanics theory, the presence of a liquid phase (water) and a gas phase (air) influence a soil effective stress parameter. Skempton (1960) stated that for saturated soil, the total stress of the soil is conducted by soil effective stress of soil and pore water pressure and this statement can be represented according to Terzaghi's equation below:

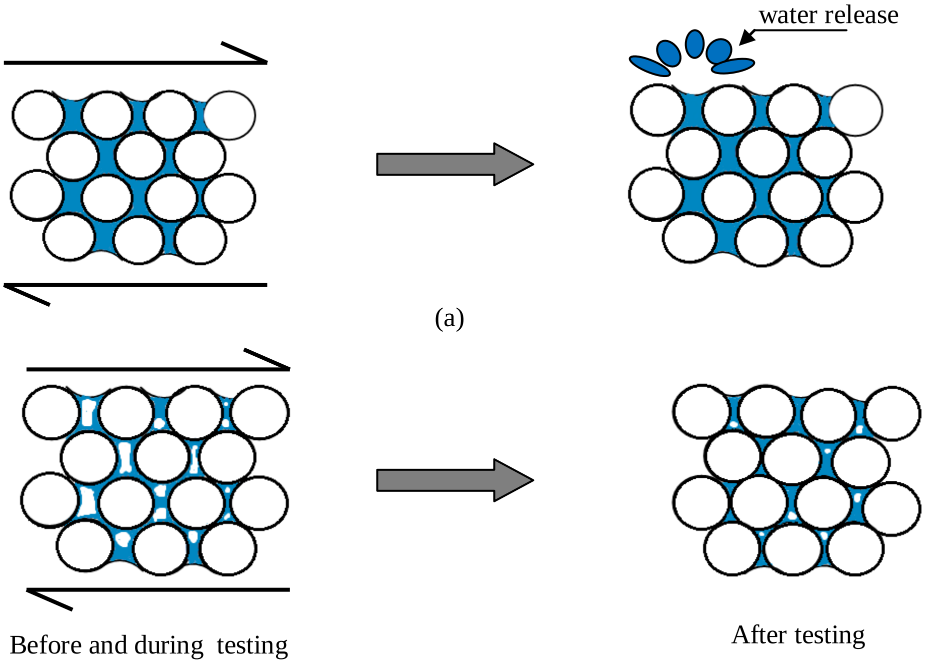
$$\sigma = \sigma' + u_w \tag{1}$$

where σ and σ' are the total stress of soil and soil effective stress, respectively, and u_w is pore water pressure.

Otherwise, in an unsaturated condition, a soil medium consists of a three-phase system; there are liquid (water), gas (air) and soil particles. Air that is trapped in the soil medium influences the behavior of degree saturation. In his research, Bishop (1959) formulated effective soil stress for unsaturated soil as an equation, as shown below:

$$\sigma' = (\sigma - u_a) + \beta\,(u_w - u_a) \tag{2}$$

where u_a and u_w are pore air pressure and pore water pressure, respectively, and β is denoted as a pore pressure coefficient. In the soil geotechnical field, the difference between pore air pressure and pore water pressure is known as matric suction.



(a)

Before and during testing

After testing

(b)

Figure 1 Particle configurations before and after testing

2.2. Materials

The soil samples employed in this research were collected from the University of Muhammadiyah Yogyakarta area in a disturbed condition. In this study, clean sand was used as the testing material in order to explain the general behavior of the unsaturated clean sand dynamic response. Other studies based on unsaturated soil dynamic response were carried out on volcanic sandy soils (Kazama & Uno, 2007; Unno et al., 2006). The results of some soil physical properties and the grain size distribution curve in this study, which have no fine content and a specific gravity of 2.66, are shown in Table 1 and Figure 2. The soil samples were classified as medium clean, well graded sand according to the Unified Classification Soil System (USCS), with fine content (F_c) totaling less than 10%. This sand was composed of angular particles of mean grain size D_{50} = 0.4 mm (Figure 2).

Table 1 Physical properties of the soil sample

No	Variables	Unit	Results
1	Dry density (γ_d)	gr/cm^3	1.67
2	Wet density (γ_b)	gr/cm^3	1.92
3	Maximum void ratio (e_{max})	-	0.81
4	Minimum void ration (e_{min})	-	0.48
5	Atterberg limit	-	Non-plastic

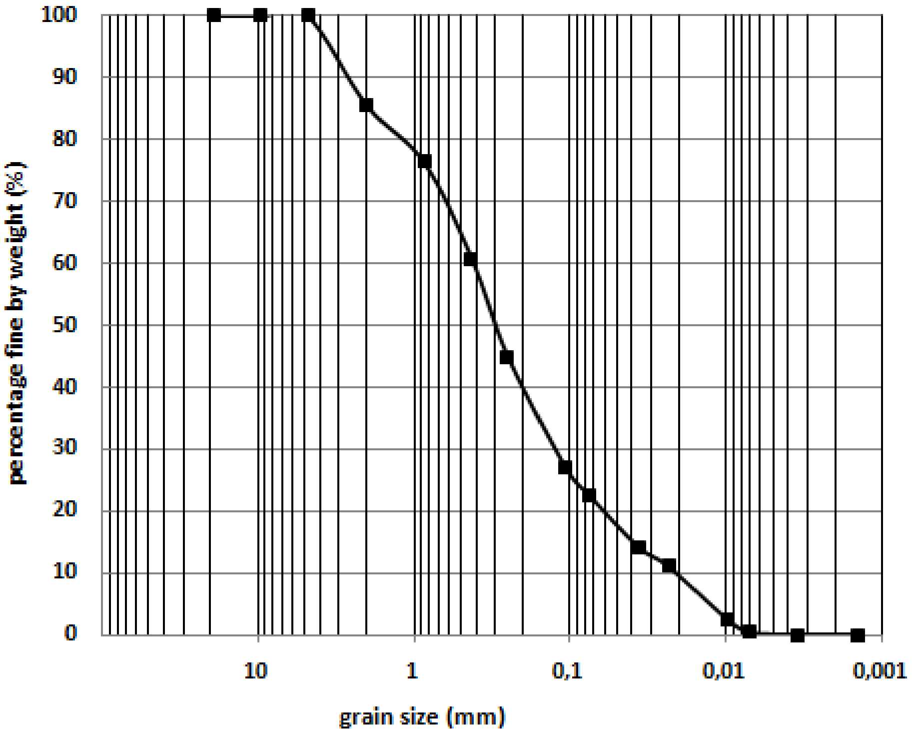


Figure 2 Grain size distribution analysis

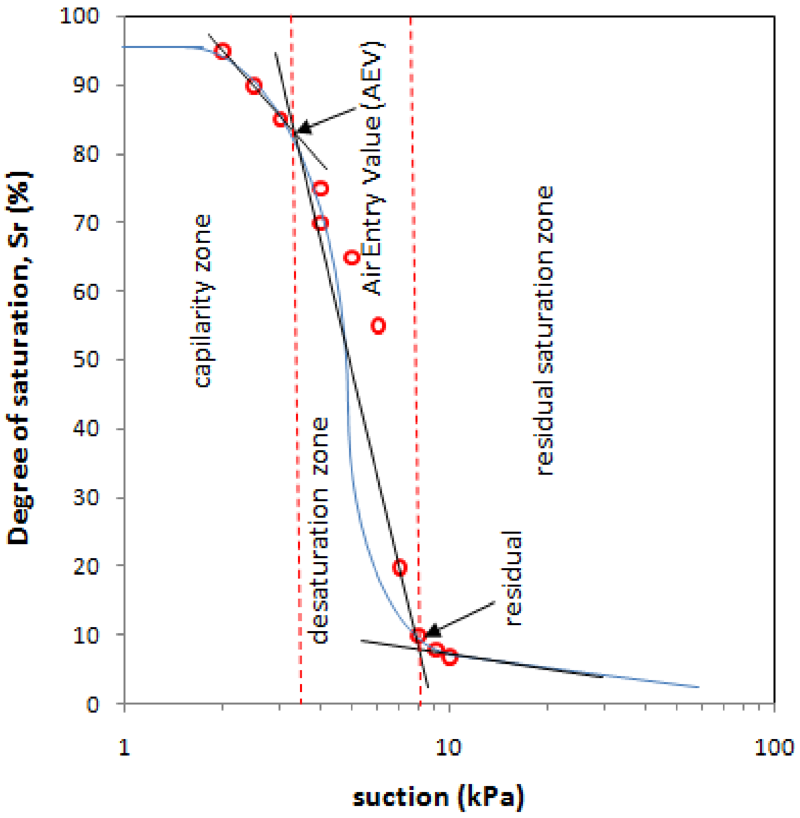


Figure 3 Soil Water Characteristic Curve (SWCC)

From a geotechnical engineering point of view, when a soil element exists under unsaturated conditions, a relationship exists between the suction head and degree of saturation following the drying path of the soil sample. The indication of opening marks of the initial condition of the unsaturated soil sample was illustrated in Figure 3, before cyclic loading was applied. A method of axis translation was conducted in order to obtain the suction value of the soil sample. Figure 3 illustrates a change in suction level from S_r = 98%–55% and likely that the Air Entry Value (AEV) of the soil sample is about 3.5 kPa. The Soil Water Characteristic Curve (SWCC) in Figure 3 denotes that a soil mass element is differentiated into a capillarity zone, a de-saturation zone and a residual zone. Clean sand as a soil sample in this research, based on unsaturated investigation, reached 8% for residual degree of saturation and the maximal suction level was 10 kPa. SWCC in this research illustrated the unsaturated process using a drying process on the specimen, which occurred during the testing. In the beginning of the testing, the soil specimen had to be in a saturated condition and then the increasing air pressure was applied through a porous stone installed on top of the specimen. The curve indicates that the degree of saturation (S_r) decreases slowly at the capillarity zone and rapidly decreases after that in the desaturation zone.

2.3. Sample Preparation and the Cyclic Triaxial Test

A series of cyclic triaxial tests was conducted on four levels of suction that were imposed upon the specimens as S_r = 98%, 85%, 70% and 55%, respectively. All specimens performed on undisturbed field soils or remolded specimen prepared in the laboratory. Several steps were undertaken in order to prepare the unsaturated soil samples by using dry pluviation as a sample preparation method. The first step was to prepare the amount of dry clean sand until there were 330 grams for a specimen with a height of 100 mm and a diameter of 50 mm. Then, the dry soil was dropped into the sample mold and compacted by using a ram corresponding to density relative to the appropriate D_r =25%. The second step was to open the water valve and let water infiltrate through the bottom of the triaxial pedestal to the dry soil. Since the specimen was molded in five layers, this process was repeated four times until the appropriate height for the sample was reached. Then, the specimen in the triaxial cell was isotropically consolidated in the triaxial cell by subjecting it to an effective confining stress 100 kPa. Before unsaturated cyclic triaxial testing began, the specimen had been assured a saturated condition by obtaining a B-value of more than 0.95 after the isotropically consolidated stage.

After all of the above stages were completed, an unsaturated condition was achieved for the specimen in the de-saturation stage by applying suction to the specimen. The axis translation method was carried out on the specimen by applying positive air pressure ($+u_a$) via the top cap, which had a porous stone embedded on its bottom (Fredlund & Rahardjo, 1993). Suction level was injected to the specimen based on the results of suction analysis, which is illustrated in the SWCC curve (Figure 3). A ceramic disc of 300 kPa was installed on the bottom of the pedestal specimen in order to obtain a uniformly unsaturated condition, to reduce the risk of cavitation in the measuring system, and to control the continuity of the pore water and the water in the measurement system easily (Wulfsohn et al., 1998). The application of suction was halted when it was assured that there was not any volume change to the specimen in order to ensure the specimen remained in an unsaturated condition. After obtaining the expected suction, it was maintained on a constant basis during the testing. The cyclic triaxial tests were conducted by applying isotropic stress 50 kPa, while cyclic deviator stress depended on the appropriate amplitude cyclic shear strain. The tests were performed in a conventional triaxial device, which was supported with four controllers and adjusted axial loading, confining pressure, air pressure and backpressure. An undrained condition was strictly applied to all specimens during the testing.

2.4. Drainage Condition

The triaxial dynamic testing was conducted from various initial suction conditions of the specimen. A shear strain controlled cyclic triaxial test was carried out under the undrained condition. It could be said that an act of migration of the pore water and air in the specimen to the outside was not allowed during the testing.

2.5. Loading Condition

After simulating an isotropic initial consolidation, which is described in Section 3.2, a series of cyclic loading was performed in sinusoidal waves that were gradually increased every ten loading cycles (Figure 4). The history of cyclic shear stress applied in this research was constructed under step loading in which each series of axial cyclic shear strain amplitude was 0.015, 0.1, 0.2, 0.4, 0.8 and 1.6. Thus, the testing of unsaturated cyclic triaxial testing consisted of 60 total cycles. The magnitude of loading was multiplied two times in order to obtain the detailed results of soil resistance due to the application of cyclic loading. The frequency of loading was 0.1 Hz due to the limitations of the machine, but this value was adequate for air pore and water pore to provide a good response for clean sand. The variation parameters applied are detailed in Table 2.

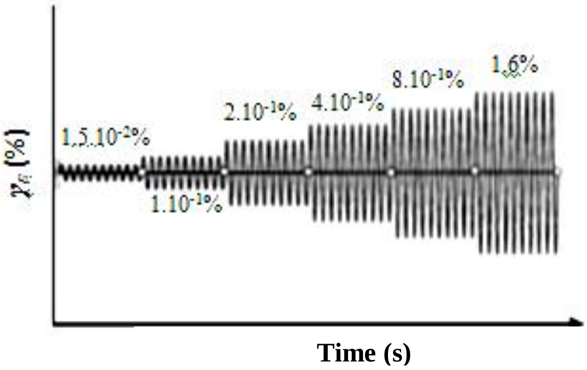


Figure 4 Type of loading applied during the testing

Table 2 Initial condition of the soil sample before the cyclic loading test

Sample ID	Description	D_r (%)	f (Hz)	u_a (kPa)	u_w (kPa)	S_r
US1	Cyclic triaxial strain controlled	25	0,1	0	0	100
US2	Cyclic triaxial strain controlled	25	0,1	2	0	98
US3	Cyclic triaxial strain controlled	25	0,1	3	0	85
US4	Cyclic triaxial strain controlled	25	0,1	4	0	70
US5	Cyclic triaxial strain controlled	25	0,1	5	0	55

3. RESULTS AND DISCUSSION

3.1. Behavior of Unsaturated Clean Sand under Cyclic Loading

The correlation of stress-strain and effective stress path way of unsaturated clean sand at various degrees of saturation (Sr = 55%, 70%, 85%, 98%) is illustrated in Figures 5 and 6, the latter of which depicts the effect of degree saturation on the soil resistance due to cyclic loading. Both figures show the effective stress path and the stress-strain relationship at Sr = 55%, 70% and 98%.

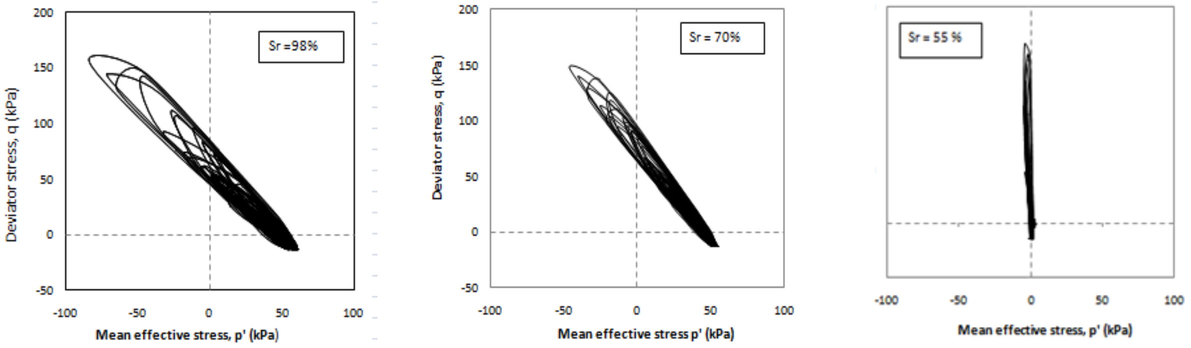


Figure 5 The effective stress path of clean sand

Figure 5 above describes the behavior of the clean sand effective path due to applied cyclic loading. Otherwise, it also revealed that soil was degraded at the higher-degree saturation level because the amplitude of cyclic shear strain was gradually increased. It could be observed from the tilting of the deviatoric stress curve versus mean effective stress. The tilting of the curve toward the axis indicated specimen failure. Samples with high S_r confirmed that the weak response was caused by decreasing the effective mean stress due to suction ($s = u_a – u_w$) and for specimens with low S_r, a contractive result was confirmed.

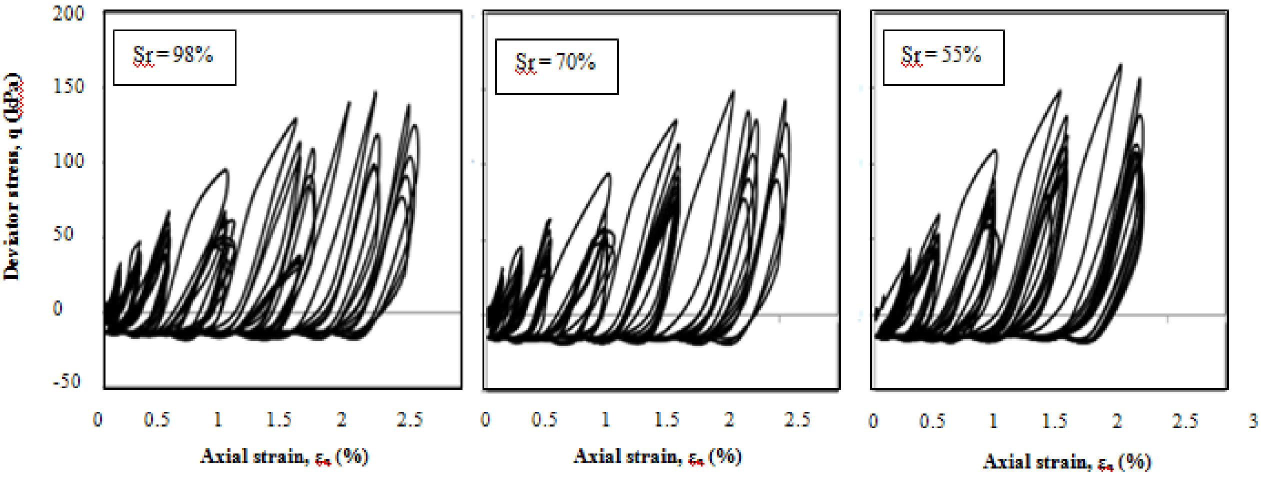


Figure 6 Shear-strain relation due to cyclic loading with different degrees of saturation

The shear-strain behavior for unsaturated clean sand is also illustrated in Figure 6. All of the degrees of saturation that were tested demonstrated that increases in shear strain were accompanied by increases in the level of shear stress applied. The tests indicated that the contact force between soil grains in resisting shear stress underwent changes due to soil grains' movement, which occurred during the testing in a bid to achieve stability. This movement triggered particles to crumble, which was caused by increasing shear strain resistance, which leads a specimen to fail. The slope direction of the stress-strain curve indicated the dilatancy of degraded particles. The slope of the curve increased when the specimen tended to fail. At a low loading frequency, it was confirmed that the amplitude of cyclic shear strain influenced the soil resistance compared to the number of cycles applied. It was confirmed by the area of curve circumstance is constant even the number of cycles applied increased.

3.2. Void Ratio Characteristic

The relationship between the void ratio and degree of saturation of the specimen before and after testing can be seen in Figure 7. It is worthwhile to mention there was a change in the degree of saturation characteristics for each degree of saturation level. Moreover, cyclic loading of unsaturated soil induced settlements of the specimen that signified a decreasing void ratio. From this research, the contrast between the void ratio and degree of saturation prevailed, which can be seen from the curve shown in Figure 7. In the saturated specimen, the decrease in the void ratio and the degree of saturation due to cyclic loading was not significant. On the other hand, the specimen subjected to unsaturated conditions showed significant increases in the degree of saturation present after testing, although the void ratio decrease was very small and could be ignored. This phenomenon highlighted a process of increasing pore water pressure on undrained unsaturated sand due to cyclic loading being more dominant than the void ratio change.

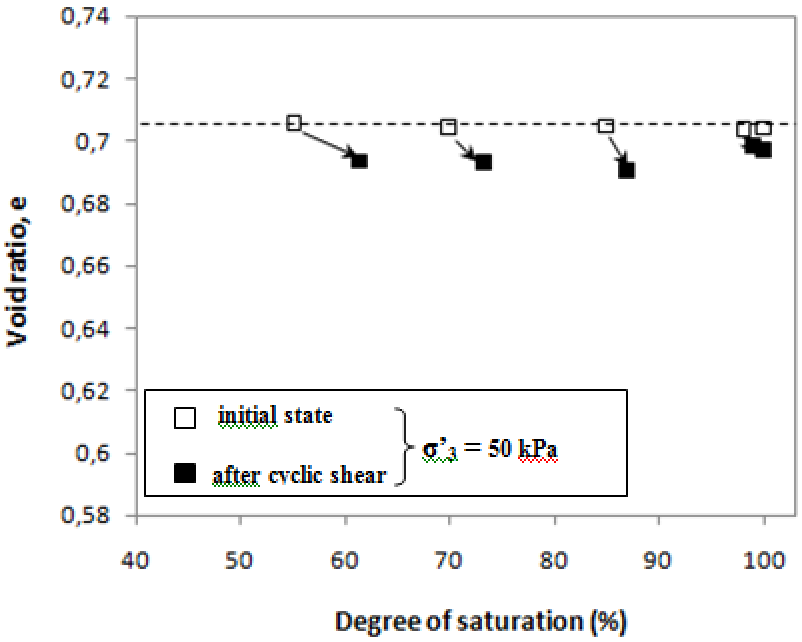


Figure 7 The void ratio and degree of saturation relation on the specimen before and after testing

4. CONCLUSION

The dynamic response of unsaturated clean sand was successfully examined in this research. A series of laboratory tests was conducted by using a cyclic triaxial device in undrained conditions under different degrees of saturation value and amplitude cyclic shear strain. The main findings of the study revealed that the weak response that occurred in the specimen with degree of saturation tended to occur under saturated conditions, which was indicated by decreasing cyclic shear resistance. It could be identified by the tilting of the stress-strain curve toward the axis. A phenomenon of water release occurred in the saturated specimen due to cyclic loading. Otherwise for unsaturated specimens, an application of cyclic loading forced the air void to be expelled and substituted by water and this process induced a degree of saturation change before and after testing. At a certain level of degree saturation, the results confirmed that due to the application of cyclic loading, a soil sample with $S_r > 85\%$ tended to be in a fully saturated condition ($S_r = 100\%$).

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