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Reference

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ABSTRACT

It is common to employ a traditional double cell system, of which an open-ended inner cell is installed in an ordinary triaxial apparatus, to measure the volume change of unsaturated specimens. In such a system, the total apparent volumetric strain of the specimen (ε_v) is deduced from the water level change in the inner cell, monitored by a differential pressure transducer (DPT) considering, meanwhile, the top cap intrusion into the inner cell recorded by a vertical displacement transducer (VDT). Severe apparent volumetric strain, caused by the compliance of the double cell system ($\varepsilon_{v,SC}$), was observed during the undrained cyclic loading tests in a previous study. Test results on a steel-spring dummy specimen revealed that $\varepsilon_{v,SC}$ was induced not only by such as the meniscus effect, but unexpectedly also by the asynchronous responses between the DPT and the VDT (i.e., the response of the DPT was delayed compared with that of the VDT). By doing some treatment $\varepsilon_{v,SC}$ could be reduced to some extent, whereas the magnitude of $\varepsilon_{v,SC}$ was still too high to be acceptable when the tested specimen approached the liquefied state. To radically solve these technical difficulties, a modified double cell system, named the linkage double cell system, was developed in this study. In this modified system, a linkage rod moving simultaneously with the loading shaft was introduced, through which the DPT could directly measure ε_v without considering the top cap or loading shaft intrusion. Test results for the steel-spring dummy specimen as well as for saturated and unsaturated soil specimens demonstrated that the linkage double cell system has major advantages in measuring accurately the volume change of the specimen during undrained cyclic triaxial loading tests compared with the traditional double cell system.

Keywords

linkage double cell system, triaxial apparatus, unsaturated soil, volumetric strain, undrained cyclic loading test

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Nomenclature

D_c = degree of compaction ($D_c = \rho_d/\rho_{d\max} \cdot 100$ %)
f = vertical cyclic loading frequency
G_s = specific gravity
S = degree of saturation
V_0 = initial volume of the specimen before applying cyclic loading
ΔV = total apparent volume change of the specimen
ΔV_{DPT} = volume change of all the substances beneath the water level in the inner cell
ΔV_{SC} = apparent volume change induced by the system compliance
ΔV_{sp} = actual volume change of the specimen
ΔV_{VDT} = part of ΔV_{DPT} because of the intrusion of the top cap
ε_a = axial strain of the specimen
ε_v = total apparent volumetric strain of the specimen
$\varepsilon_{v,\mathrm{SC}}$ = apparent volumetric strain of the specimens induced by system compliance
$\varepsilon_{v,\mathrm{sp}}$ = actual volumetric strain of the specimen
ρ_d = dry density of the specimen
$\rho_{d\max}$ = maximum dry density obtained from compaction test

Introduction

In the studies of liquefaction, behavior of the unsaturated soils with degree of saturation (S) up to 99.9 % has been paid attention because of their higher liquefaction resistance than soils under saturated conditions (Sherif et al. 1977; Yoshimi et al. 1989; Ishihara et al. 2001). Recently, liquefaction resistance of unsaturated soils is proposed, according to the undrained cyclic loading test results obtained in the laboratory, to be linked with the volumetric strain of unsaturated soils (Okamura and Soga 2006; Wang et al. 2015). The above example suggests that, like some other geotechnical issues, it is crucial to accurately measure the volume change of unsaturated soils during the undrained cyclic loading.

The techniques of volume change measurement of unsaturated soils are well documented by Ng et al. (2002), Laloui et al. (2006), and Hoyos et al. (2008). Generally, these techniques can be classified in three broad categories: (1) cell liquid measurement, of which the volume change of the specimen is measured indirectly by observing the liquid surrounding the specimen, such as the earlier work by Bishop and Donald (1961), the double-walled cell system (Wheeler 1988), and the double cell system with the open-ended inner cell (Cui and Delage 1996; Toyota et al. 2001; Aversa and Nicotera 2002; Ng et al. 2002); (2) direct air-volume and water-volume measurements, of which the measurement systems are connected to the pore air or pore water network directly and usually used in the drained test (Adams et al. 1996; Laudahn et al. 2005); and (3) direct measurement on the specimen locally by placing the contact or non-contact displacement transducers, such as Hall effect transducers, Wheatstone bridge circuit transducer, proximity transducer, laser transducer, etc. (Clayton et al. 1989; Goto et al. 1991; Hird and Hajj 1995; Messerklinger and Springman 2007), or by employing image-processing technique (Gachet et al. 2003; Fauzi and Koseki 2014).

In the undrained cyclic loading test conducted, the soil specimen may deform largely (i.e., the maximum double amplitude of axial stain may exceed 30 % or more), quickly (i.e., the cyclic loading frequency is normally in the range of 0.1 ~ 1 Hz) and non-uniformly. Concerning such deformation characteristics of the soil specimen, a stress-controlled triaxial apparatus equipped with the double cell system with open-ended inner cell was used to measure the volume change of unsaturated specimens in the undrained cyclic loading test in a previous study (Wang et al. 2016). However, it was found that a significant apparent volume change could be caused by the system compliance of the traditional type of the double cell system.

In this paper, first, the typical technical issues encountered while using the traditional double cell system are described and discussed, and then the innovative linkage double cell system, a modified version of the double cell system developed at the University of Tokyo to overcome those technical issues, is presented. The performance of the two systems is compared through the analysis of typical test results on a steel-spring dummy specimen as well as on saturated and unsaturated sandy soil specimens.

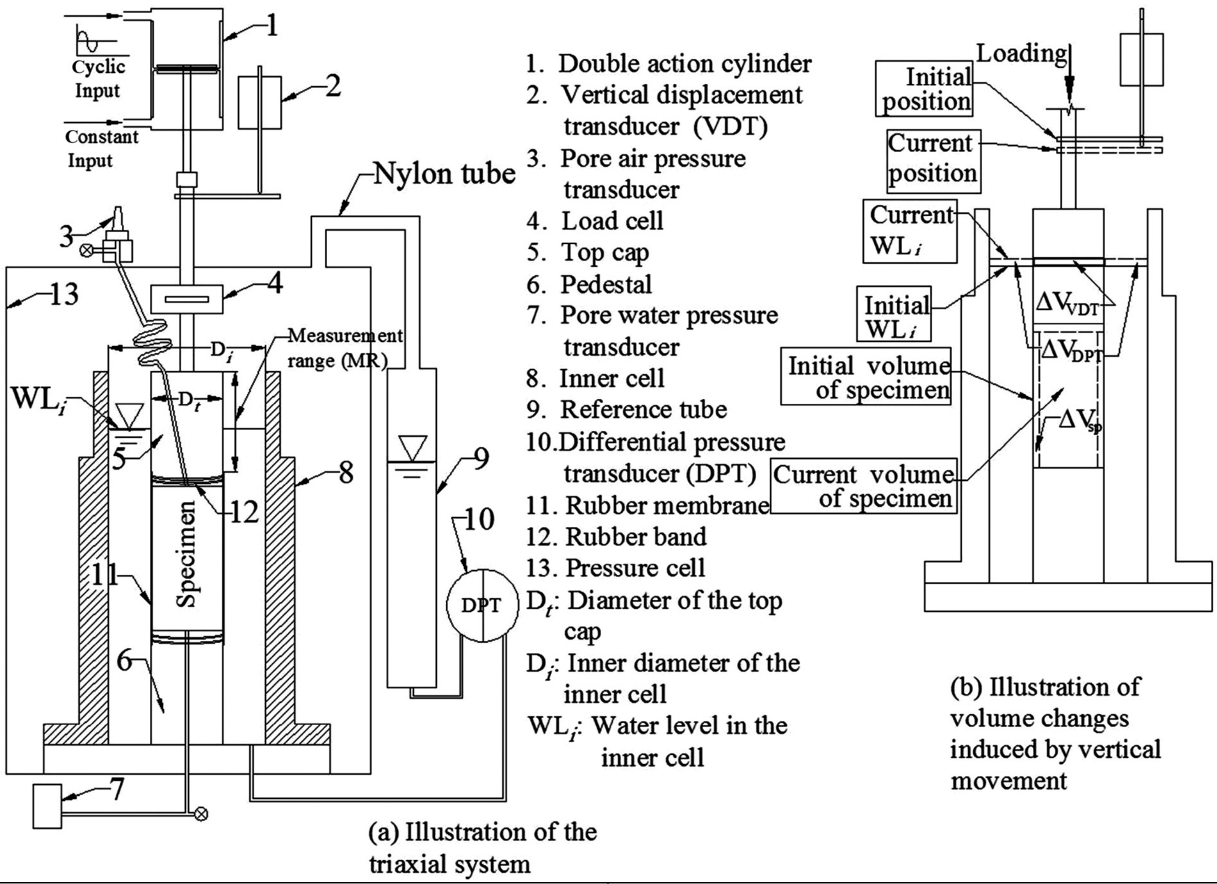
Traditional Double Cell System

CHARACTERISTICS OF THE APPARATUS

Fig. 1(a) schematically illustrates the traditional double cell system mounted in the triaxial apparatus used in this study. The main components of the system include a vertical displacement transducer [VDT, No. 2 in **Fig. 1(a)**], a top cap (No. 5), an inner cell (No. 8), a reference tube (No. 9) and a differential pressure transducer (DPT, No. 10). The top cap having a constant diameter (D_t) is appositely designed longer than the ordinary one to provide a wider measurement range. Note that, the inner diameter (D_i) of the upper part of the inner cell is also constant. The DPT is connected to the reference tube and to the inner cell to measure the change in water level in the inner cell (WL_i). The reference tube is placed outside the pressure cell and connected with the pressure cell by a flexible nylon tube.

Fig. 1(b) schematically illustrates the measurement principal of the volume change of the specimen under undrained conditions. Suppose there is a vertical movement of the top cap, the

FIG. 1 Layout of the traditional inner cell system.



volume change of all the substances beneath WL_i (ΔV_{DPT}) can be deduced by the DPT measurements. Part of ΔV_{DPT} is because of the intrusion of the top cap (ΔV_{VDT}) obtained from the measurement of the VDT. Thus, the total apparent volume change of the specimen (ΔV, set positive for volume reduction of the specimen) is obtained:

$$\Delta V = -(\Delta V_{\mathrm{DPT}} - \Delta V_{\mathrm{VDT}}) \tag{1}$$

ΔV has two components, namely, the actual volume change of the specimen (ΔV_{sp}) and the apparent volume change (ΔV_{SC}) induced by the system compliance (e.g., meniscus effect, etc.). Dividing both sides of Eq 1 by the initial volume of the specimen (V_0, measured immediately before the cyclic loading), the total apparent volumetric strain (ε_v) can be obtained:

$$\varepsilon_{\mathrm{v}} = \varepsilon_{\mathrm{v,sp}} + \varepsilon_{\mathrm{v,SC}} = \frac{\Delta V_{\mathrm{sp}} + \Delta V_{\mathrm{SC}}}{V_0} = -\frac{\Delta V_{\mathrm{DPT}} - \Delta V_{\mathrm{VDT}}}{V_0} \tag{2}$$

where:

$\varepsilon_{v,sp}$ = actual volumetric strain of the specimen, and

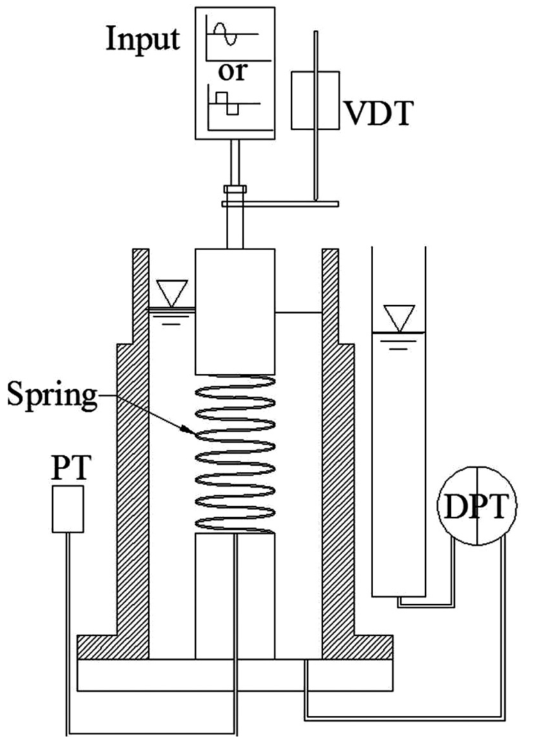
$\varepsilon_{v,SC}$ = apparent volumetric strain induced by system compliance.

TECHNICAL ISSUES IN USING THE TRADITIONAL DOUBLE CELL SYSTEM

It was expected that the meniscus effect was the primary factor inducing $\varepsilon_{v,SC}$ in the double cell system shown in **Fig. 1**. However, as described later, the time response delay in the measurement of the DPT was found to have a significant effect on $\varepsilon_{v,SC}$. To clarify these issues, a series of tests was conducted on a steel-spring dummy specimen, as schematically shown in **Fig. 2**. De-aired water was used to fill the inner cell and the reference tube, and then possible air bubbles trapped within the system as a whole were removed by applying vacuum before the tests. The WL_i was also continuously monitored by a pressure transducer (PT) in this series of tests. In the tests, sinusoidal vertical loading with different amplitudes was applied to the spring specimen and five loading cycles with frequency (f) of 0.1 Hz was applied to each of the loading amplitudes. In addition, for one of the loading amplitudes, five cycles of square-shape loading (f = 0.1 Hz) was also applied to the spring specimen. The sampling time interval of the measured data was set as 0.1 s.

In the stress-controlled undrained cyclic triaxial loading tests, the sinusoidal vertical loading is usually applied to soil specimens. It is often observed in such tests that the actual

FIG. 2 Testing configuration on a steel-spring dummy specimen.

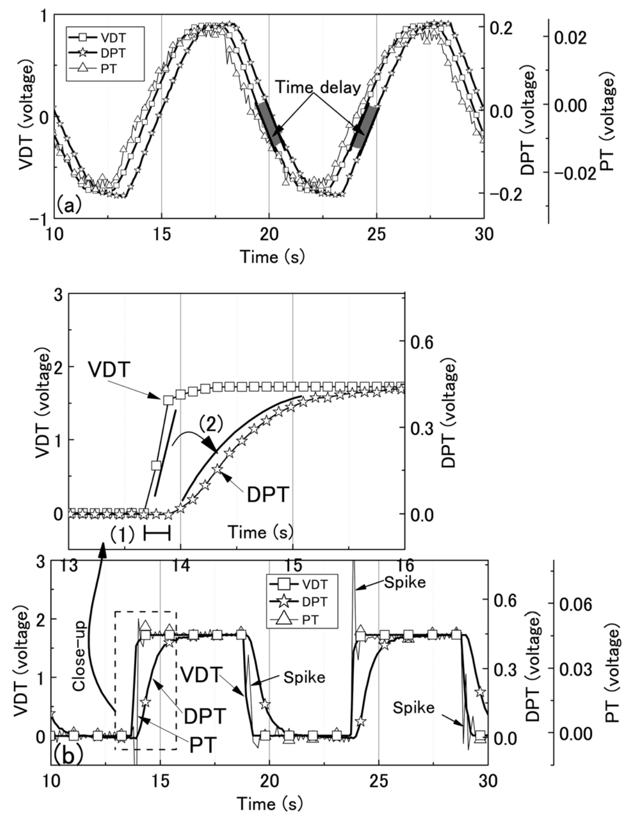


vertical displacement of the specimens is likely to follow the square shape as the specimens approach the fully liquefied state, because of the sharp reduction of the resistance of the specimens against the loading. Thus, it is necessary to examine the performance of the traditional double cell system under both the sinusoidal and square-shape loadings.

Fig. 3(a) shows the typical voltage recordings of the three transducers (VDT, DPT, and PT) under the sinusoidal loading. Note that, for the benefit of comparison, the ranges of the three vertical axes were adjusted to match their amplitudes with each other. It can be seen that there is no significant difference in the time axis between the measurements of the PT and VDT, whereas clearly a delay in time axis is observed for the measurement of the DPT. It is also found that the delay in time axis is generally constant under the sinusoidal loading with different amplitudes (∼0.6 s).

Fig. 3(b) shows the voltage recordings of the three transducers under the square-shape loading. Similar to that shown in **Fig. 3(a)**, the measurements of the PT and VDT are also consistent with each other in the time axis except for some spikes observed in the measurement of the PT. For the measurement of the DPT, two different types of delay in time are observed, as indicated in the close-up in **Fig. 3(b)**: (1) dead time delay (∼0.2 s), a period of time during which the DPT has no response to the input signal; and (2) step signal delay (more than 1 s), a period of time for the DPT to follow the step (or square) shape input.

FIG. 3 Transducer measurements in the traditional double cell system under: (a) sinusoidal loading and (b) square-shape loading.

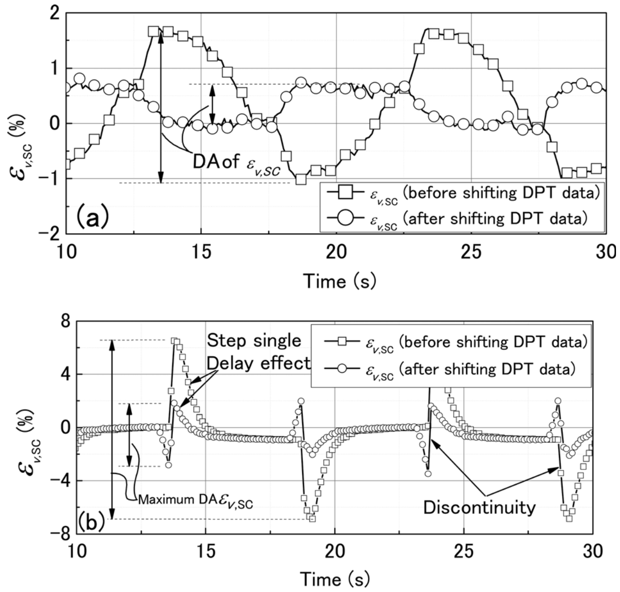


From the results in **Fig. 3**, it is known that the response of the DPT is slower than the other two transducers (VDT and PT), causing $\varepsilon_{v,SC}$ as expressed by Eq 2. The DPT used in this study measured the differential pressure by a micro capacitance silicon sensor. However, it was confirmed that another DPT with a strain gauge type sensor also exhibited a similar issue of delay in time axis.

Because the actual volumetric strain ($\varepsilon_{v,sp}$) of the spring specimen was essentially nil, $\varepsilon_{v,SC}$ of the specimen was then calculated according to Eq 2 by assuming the diameter and the height of the specimen as 50 mm and 100 mm (i.e., same dimensions as an ordinary soil specimen), respectively. In **Fig. 4(a)**, $\varepsilon_{v,SC}$ corresponding to the measurements reported in **Fig. 3(a)** is plotted. It can be seen that the double amplitude (DA) of $\varepsilon_{v,SC}$ indicated by open squares is larger than 2.5 % under the test conditions employed. Because the delay in time under the sinusoidal loading is rather constant, it is reasonable to shift the recorded data of the DPT backward by 0.6 s, which results in the open circles shown in **Fig. 4(a)**. By doing so, DA of $\varepsilon_{v,SC}$ is reduced by approximately two-thirds (i.e., from 2.5 % to ∼0.8 %).

Fig. 4(b) shows $\varepsilon_{v,SC}$ of the spring specimen subjected to the square-shape loading, which corresponds to the recordings

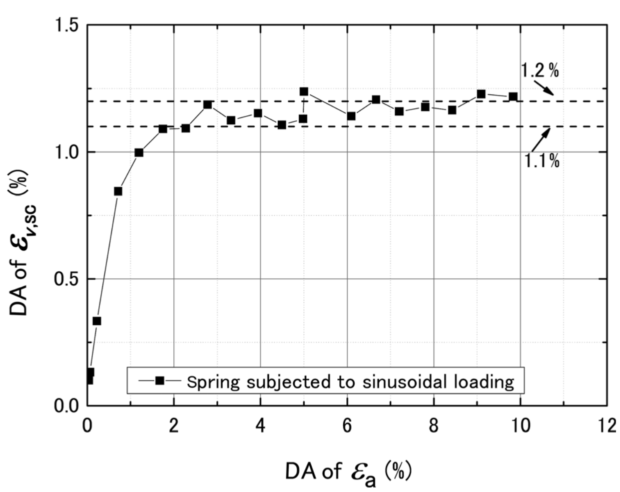
FIG. 4 $\varepsilon_{v,SC}$ measured by the traditional double cell system under: (a) sinusoidal loading and (b) square-shape loading.



shown in **Fig. 3(b)**. It indicates that the maximum DA of $\varepsilon_{v,SC}$ reduced from more than 12 % to about 4 % by shifting the measurement of the DPT in the time axis. However, because of the existence of the step signal delay, discontinuity is still observed even for the shifted data.

Fig. 4 suggests that data treatment by shifting the measured DPT data is quite efficient to reduce the magnitude of $\varepsilon_{v,SC}$. However, it cannot reduce $\varepsilon_{v,SC}$ to an acceptable level when the top cap moves promptly (e.g., under the square-shape loading), under which condition $\varepsilon_{v,SC}$ data are often accompanied by the discontinuity. Nevertheless, the treated DPT data are used to show volume change measured by the traditional system hereafter. **Fig. 5** shows the relationship

FIG. 5 Relationship between DAs of ε_a and $\varepsilon_{v,SC}$ under the sinusoidal loading measured by the traditional double cell system.



between DAs of axial strain (ε_a) and $\varepsilon_{v,SC}$ of the spring specimen subjected to the sinusoidal loading. It can be seen that DA of $\varepsilon_{v,SC}$ increases monotonically with an increase in DA of ε_a until DA of ε_a reaches around 2 %, after which DA of $\varepsilon_{v,SC}$ is relatively constant (1.1 % ~ 1.2 %). $\varepsilon_{v,SC}$ in **Fig. 5** is expected to be mainly induced by the meniscus effect.

For the strain-controlled monotonic triaxial tests of unsaturated soil specimens, $\varepsilon_{v,SC}$ measured by the traditional double cell system may be reduced to a negligible level by careful calibration (Ng et al. 2002). However, it is much more difficult to significantly reduce $\varepsilon_{v,SC}$ for the stress-controlled cyclic loading tests with relatively prompt loading frequency. Moreover, as described later in this paper, $\varepsilon_{v,SC}$ caused by the step signal delay makes the measurement of ε_v of the unsaturated specimen barely able to be used.

New Linkage Double Cell System: Configuration and Performance

The reason why the delay in time of the DPT induces $\varepsilon_{v,SC}$ is that ε_v relates to the vertical displacement of the top cap as indicated in Eq 2. The novelty of the linkage double cell system, as schematically shown in **Fig. 6**, is that a linkage rod moving simultaneously with the loading shaft is introduced to the reference tube, through which ΔV_{VDT} in Eq 2 ideally becomes zero. The main technical differences of the modified version compared with the traditional system are as follows:

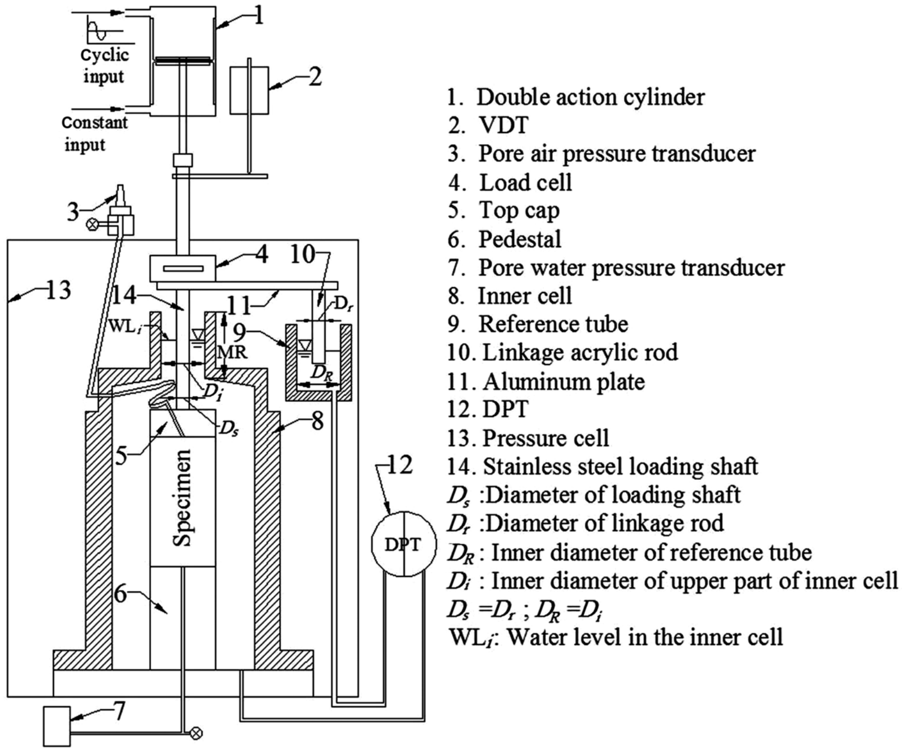
1. The height of the top cap is reduced, and a longer stainless steel loading shaft (No. 14 in **Fig. 6**) is installed between the top cap and the load cell. In addition, the diameter of the upper part of the inner cell is also reduced.
2. The reference tube (No. 9) having an inner diameter (D_R) equals that of the upper part of the inner cell ($D_R = D_i$), is moved into the pressure cell.
3. An aluminum plate (No. 11) is fixed on the loading shaft at one end and connected with an acrylic rod (i.e., the linkage rod, No. 10) at the other end. Note that, the outer diameter of the linkage rod (D_r) is the same as that of the loading shaft (i.e., $D_r = D_s$).

Though the modifications above are not a solution of the time delay issue of the DPT, they, as a whole, make the measurement of ε_v no longer be affected by the vertical movement of the loading shaft. Therefore, ε_v is evaluated as follows:

$$\varepsilon_{\mathrm{v}} = \varepsilon_{\mathrm{v,sp}} + \varepsilon_{\mathrm{v,SC}} = \frac{-\Delta V_{\mathrm{DPT}}}{V_0} \quad (3)$$

In addition, the meniscus effect is expected to be reduced because of the synchronized same direction movement between the linkage rod and the loading shaft. The meniscus effect caused by the use of two different materials (i.e., the stainless steel for the loading shaft and the acrylic for the linkage rod) is

FIG. 6
Layout of the linkage inner cell system.



believed to be negligible. However, when necessary, coating the same film on the surfaces of the shaft and the rod can be a possible solution for such an issue.

The performance of the new linkage double cell system was examined by carrying out an additional series of tests on the steel-spring dummy specimen by using the similar testing configuration shown in **Fig. 2**, but without the use of the PT. De-aired water was circulated into the inner cell and possible air bubbles were removed from the testing system prior to the cyclic loading. Both the sinusoidal and the square-shape loadings with different loading amplitudes were applied to the spring specimen with *f* of 0.1 Hz.

Fig. 7(a) and **7(b)** shows the typical voltage measurements of the VDT and DPT during the application of the sinusoidal and square-shape loadings, respectively. It can be seen that in both cases the output of the DPT has a similar shape with the corresponding input loading and the delay in time is observed as expected. Some spikes in the data of the DPT are observed in **Fig. 7(b)**, which occur just after the change in the loading direction. By recalling the same phenomenon indicated in **Fig. 3(b)** and considering the characteristics of the delay in time of the DPT, it is suggested that the spikes occurred transiently in the inner cell at the moments of alternating loading directions.

In **Fig. 8(a)** and **8(b)**, which correspond to the measurements in **Fig. 7(a)** and **7(b)**, $\varepsilon_{v,SC}$ was calculated according to Eq 3. The measurements (shifted data) in **Fig. 4** obtained by the traditional double cell system were also attached in **Fig. 8**. **Fig. 8** shows that $\varepsilon_{v,SC}$ measured by the new system is mostly within the range of $\pm$0.05 %, which is more than one order less than that measured by the traditional system. The $\varepsilon_{v,SC}$ caused by spikes [**Fig. 8(b)**] introduces some undesired data; however, the magnitude of these data is not significantly high and they can be removed

FIG. 7 Typical voltage measurements using the linkage double cell system under: (a) the sinusoidal loading and (b) the square-shape loading.

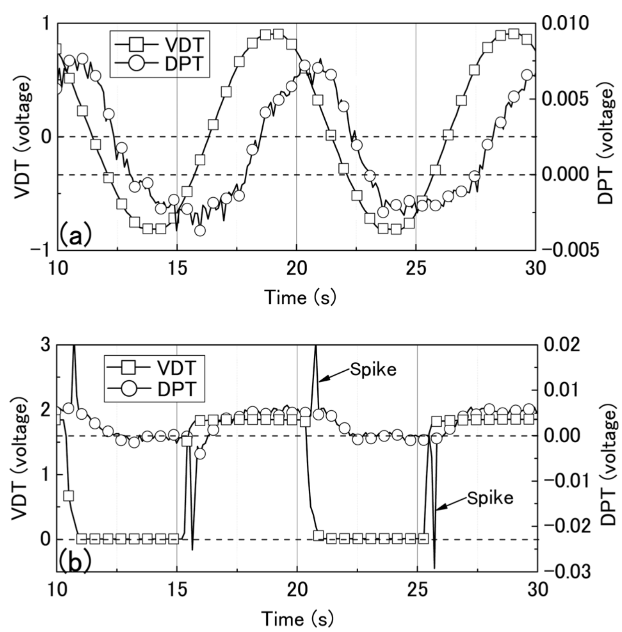
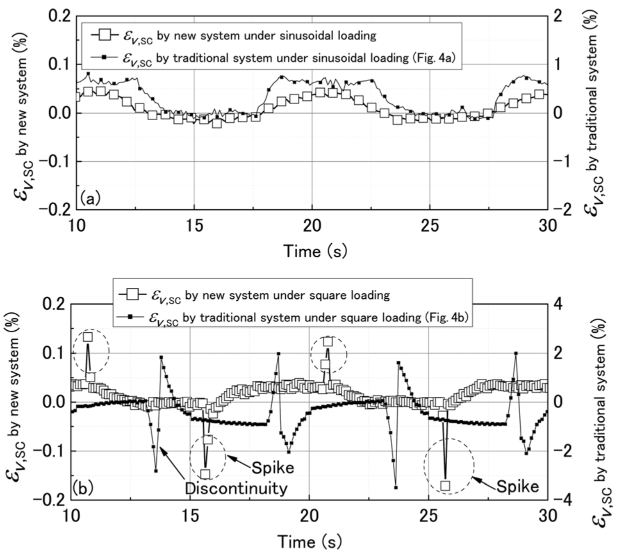


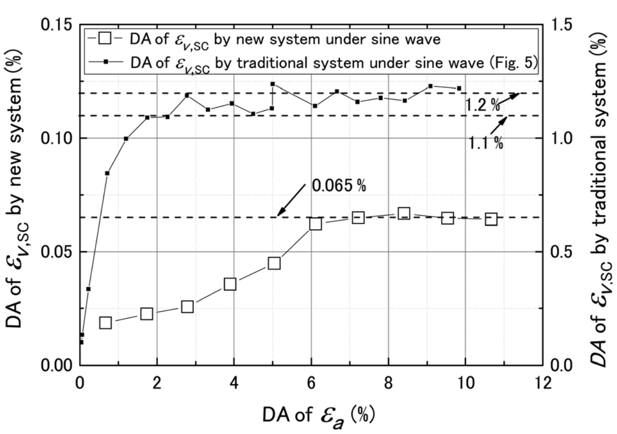
FIG. 8 Typical $\varepsilon_{v,SC}$ measurement using the new linkage double cell system under: (a) the sinusoidal loading and (b) the square-shape loading.



either manually or methodologically by the use of the frequency filter. The latter method is illustrated in later sections. Because the behaviors of water in the inner cell during the alteration of loading direction, which caused the spike, was not analyzed in this study, ways to eliminate the effect of spikes are not available under current state. One should also be aware that in **Fig. 8(b)** the discontinuity was induced by the time delay of the DPT in the traditional system as shown in **Fig. 3**, which is different from the phenomenon of the spike observed in both systems.

Fig. 9 shows the relationship between DAs of ε_a and $\varepsilon_{v,SC}$ of the spring specimen subjected to the sinusoidal loadings measured by the linkage double cell system. Additionally, the data measured by the traditional system (**Fig. 5**) is also plotted in **Fig. 9**. As can be seen, the maximum values of DA of $\varepsilon_{v,SC}$ is reduced more than one order (i.e., from 1.2 % to 0.065 %) by employing the new system; meanwhile, the DA of ε_a, from which the maximum values of DA of $\varepsilon_{v,SC}$ are observed, is about 6 % for the new system, which was much smaller than 2 % observed in the traditional system.

FIG. 9 Relationship between DAs of ε_a and $\varepsilon_{v,SC}$ under the sinusoidal loading.



ε_V of Soil Specimens Measured by the Two Double Cell Systems

To further compare the performance between the traditional and the modified systems, undrained cyclic loading tests were conducted on saturated and unsaturated soil specimens. Inagi sand was selected as the test material. It was a sandy soil with 30 % fines content. Its maximum dry density ($\rho_{d\max}$) and the specific gravity (G_s) were 1.66 g/cm^3 and 2.656, respectively.

A certain amount of pre-wetted Inagi sand with an initial water content of about 22 % was placed in a steel mold with an inner diameter of 50 mm. The soil was compressed from two sides of the mold to form a specimen with a height of 100 mm. A double vacuuming method (Ampadu and Tatsuoka 1993) was applied to saturate the saturated specimens. For the unsaturated specimens, a certain amount of extra water was added from the top of the specimens and curing thereafter for one night in the mold was applied for uniformity of water distribution. It is worth mentioning that pore air drainage was only allowed (i.e., pore water drainage was closed) during consolidation of the unsaturated specimens to maintain the desired degree of saturation (S). The air entry value and magnitude of suction of such unsaturated specimens were about 3 kPa and 4 kPa (Wang et al. 2016), respectively. The S of the specimens was confirmed by the pore pressure coefficient $B \geq 0.95$ for the saturated specimens and by careful measurements of water content after the test for the unsaturated specimens. Sinusoidal vertical loading with f of 0.1 Hz was applied to the specimens after the consolidation process. Two saturated specimens and two unsaturated specimens were prepared with an average degree of compaction (D_c) of 75 %. The detailed specimen conditions and evaluation on the two double cell systems based on the test results are listed in **Table 1**.

Fig. 10 shows the time histories of $\varepsilon_{v,SC}$ and ε_a of the saturated specimens during applying cyclic loading (assuming that $\varepsilon_{v,sp} = 0$ for the saturated specimens) measured by the traditional double cell system. Note that during this test, ε_a approached the limitation because of the restriction of the apparatus, where the water level in the inner cell (WL_i) exceeded the measurement range (see **Fig. 1**). Consequently, as shown in the gray color in **Fig. 10**, part of the $\varepsilon_{v,SC}$ data were overestimated to some extent, and were shifted to the positive side (i.e., $\varepsilon_{v,SC}$ data should have been somehow symmetric about the $\varepsilon_{v,SC} = 0$ line). Nevertheless, it can be seen that $\varepsilon_{v,SC}$ is distributed within the range of ±0.5 % before ε_a reaches approximately 5 %.

TABLE 1 Inagi sand specimen conditions and accordingly evaluation on the traditional and the linkage double cell systems.

	Specimen Conditions		Evaluation on the Two Systems According to Test Results	
Measurement System	S (%)	D_c (%)	In Relatively Small ε_a Level[a]	In Relatively Large ε_a Level[a]
Traditional double cell	100	76 %	$\varepsilon_{v,SC}$ can be within ±0.5 %, measured ε_v can be acceptable	$\varepsilon_{v,SC}$ may far more than ±2.5 %, measured ε_v can barely be used
	69	76 %		
Linkage double cell	100	71 %	$\varepsilon_{v,SC}$ can be reduced to ±0.1 % by passing filter, measured ε_v can be very accurate	
	68	75 %		

[a]The specific magnitude of ε_a is not certain because $\varepsilon_{v,SC}$ is essentially depending on the state of the specimen (i.e., liquid state or not), which can be generally identified from the ε_a level.

Thereafter, the amplitude of $\varepsilon_{v,SC}$ exceeded ±2.5 %. Though $\varepsilon_{v,SC}$ data in gray color are less reliable, it can be seen that the amplitude of $\varepsilon_{v,SC}$ becomes extremely larger than ±2.5 % when the specimen experience large axial strain (liquefied or nearly liquefied state). Meanwhile, the discontinuity of $\varepsilon_{v,SC}$ observed in the close-up in **Fig. 10** indicates that $\varepsilon_{v,SC}$ is mainly induced by the step signal delay of the DPT as explained in **Fig. 4**.

Fig. 11 shows $\varepsilon_{v,SC}$ and ε_a of the saturated specimen measured by the new linkage double cell system. It can be seen that most data of $\varepsilon_{v,SC}$ are distributed within the range of ±0.1 % and a few data (spikes) were within ±0.5 %. However, the spikes could be well removed by using a low pass filter with a cutoff frequency of 0.5 Hz as shown in the close-up figure.

Fig. 12 shows ε_v and ε_a of the unsaturated Inagi sand specimen obtained by the traditional double cell system. It seems that ε_v data are rather smooth at the beginning of the test, whereas discontinuity is once again observed at the later stages (see the close-up in **Fig. 12**). It is known from **Fig. 10** that $\varepsilon_{v,SC}$ induced by the step signal delay effect (indicated by the discontinuity) can be extremely large and, as a result, the measurement of ε_v in the later stage (i.e., at a large ε_a level) of the test can barely be relied on.

Fig. 13 displays ε_v and ε_a measurements of the unsaturated Inagi sand specimen obtained from the linkage double cell system. It is shown that the measured ε_v is very smooth even when the specimen experiences large vertical deformation. The

FIG. 10

$\varepsilon_{v,SC}$ and ε_a time histories for the saturated specimen measured by the traditional double cell system.

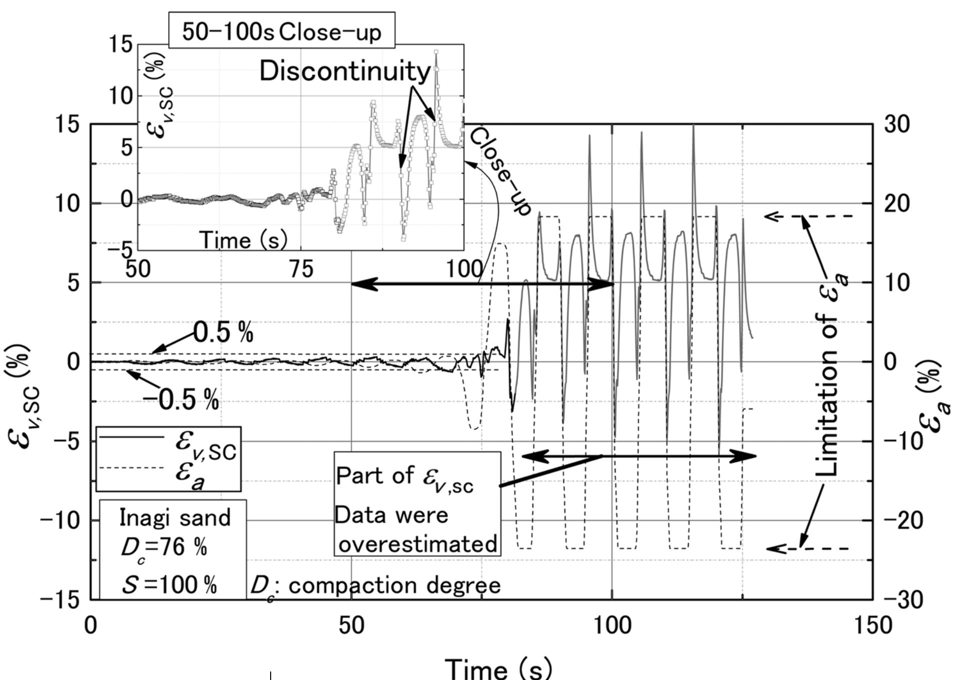
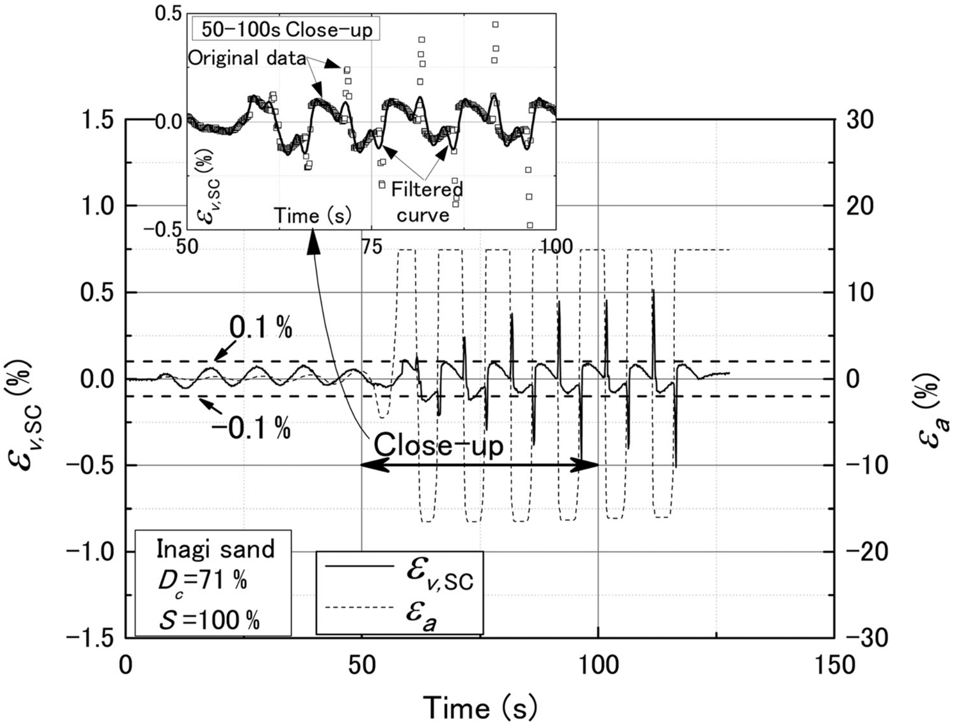


FIG. 11

$\varepsilon_{v,SC}$ and ε_a time histories for the saturated specimens measured by the linkage double cell system.



original and the filtered data are almost completely overlapped, which implies that the spike points did not occur visibly. As can be seen in the close-up in **Fig. 13**, the shape of ε_a is similar to the sinusoidal wave, whereas in **Fig. 11** it is more similar to the square-shape wave, which implies that the vertical deformation of the unsaturated specimen was smoother than that of the saturated specimen, and consequently spikes may not be triggered.

FIG. 12

$\varepsilon_{v,SC}$ and ε_a time histories for the unsaturated specimen measured by the traditional double cell system.

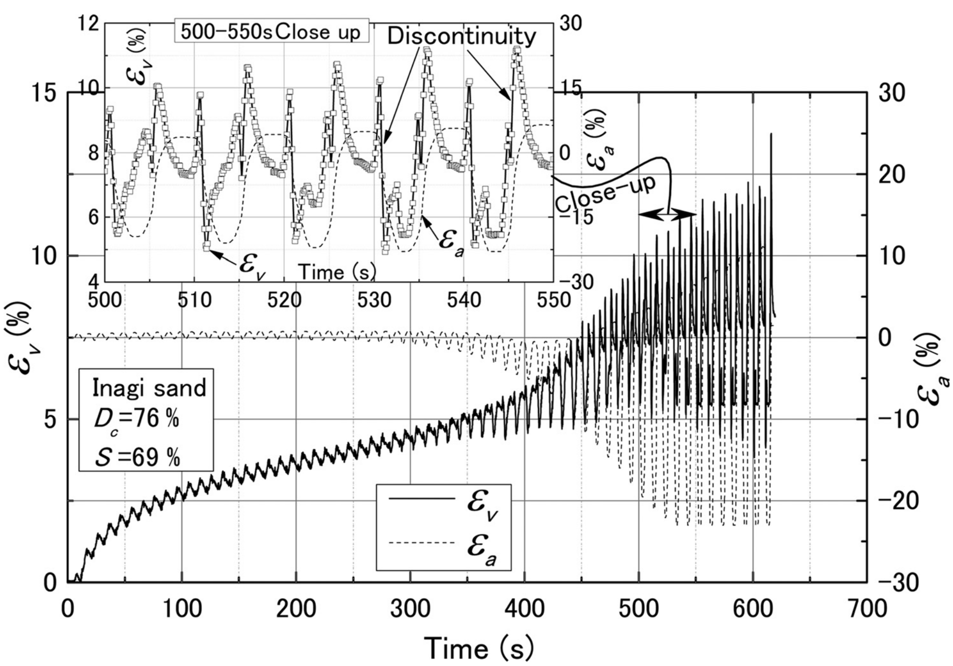
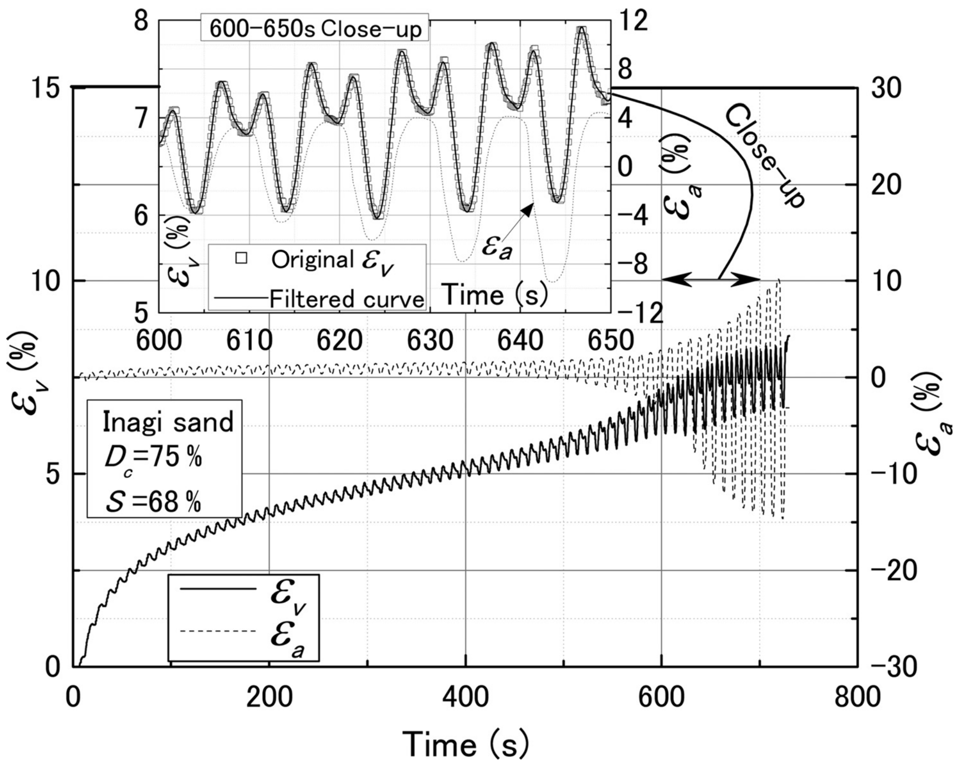


FIG. 13

$\varepsilon_{v,SC}$ and ε_a time histories for the unsaturated specimen measured by the linkage double cell system.



Conclusion

In using the traditional double cell system, a significant apparent volumetric strain induced by system compliance ($\varepsilon_{v,SC}$) was observed. To address this issue, a modified version of such a double cell system, namely, the linkage double cell system is developed. The performance of the traditional and the modified systems are compared in this study and the following main conclusions are drawn:

1. It is found that the traditional double cell system, commonly used to measure the volume change of the unsaturated specimens, may introduce significant amounts of $\varepsilon_{v,SC}$ when it is employed for undrained cyclic loading tests on the stress-controlled triaxial apparatus. The main reason is the time delay issue of the differential pressure transducer (DPT) used to measure the water level change in the inner cell compared with the vertical displacement transducer (VDT). When the vertical deformation of the specimen is relatively small (e.g., at the beginning of the undrained cyclic loading test), the double amplitude (DA) of $\varepsilon_{v,SC}$ can be reduced to less than 1.2 % by simply shifting time axis of the DPT measurement (i.e., subtracting the amount of delay in time). However, the treated $\varepsilon_{v,SC}$ data still become significantly high when the specimen experiences relatively large deformation (e.g., more than 4 % observed from a test on the spring dummy specimen).
2. The new linkage double cell system is then developed to provide a fundamental solution to the issue encountered by using the traditional double cell system. The essential modification in the new system is the installation of a linkage rod, though which the measured ε_v is no longer related to the measurement of the VDT. Tests on the steel-spring dummy specimen demonstrated clearly that the new system can drastically reduce DA of $\varepsilon_{v,SC}$ from 1.2 % to less than 0.065 %.
3. Additional tests on saturated and unsaturated Inagi sand specimens confirmed that $\varepsilon_{v,SC}$ measured by using the new linkage double cell system can be reduced to levels within ±0.1 %, which is at least 5 times smaller than that measured by the traditional double cell system (i.e., $\varepsilon_{v,SC}$ was generally within ±0.5 %). More importantly, the measurement of ε_v by the traditional double cell system is not reliable when the specimen experiences relatively large deformation (i.e., in the liquefied condition) because of the delay in time issue of the DPT. On the contrary, reliable ε_v data can be obtained by using the new linkage double cell system.

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