**Properties of membrane filter and its application to undrained cyclic triaxial test of unsaturated materials**

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Properties of membrane filter and its application to undrained cyclic triaxial test of unsaturated materials

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Abstract:
The properties of the recently introduced membrane filter as an alternative of the ceramic disk are revealed through diffusion and hydraulic conductive tests. It is shown that diffusion of air through the membrane filter is significantly affected by the suction magnitude and the hydraulic conductivity of the membrane filter may easily affected by the quality of water used in the test. The application of the membrane filter to the soil water characteristic curve tests (SWCC tests) shows that similar SWCCs can be obtained by employing pressure plate apparatuses installed either the ceramic dicks or the membrane filter, and repeatability of the membrane filter pressure plate apparatus is reasonably good. The application of the membrane filter to the undrained cyclic loading test of unsaturated sandy materials shows that the response (the duration to measure the equilibrated pore water pressure of unsaturated materials) of the membrane filter pedestal in a modified triaxial system may be as short as ~2 seconds in certain test conditions, and fairly good pore water and air pressure measurements can be obtained during undrained cyclic loading with the loading frequency of 0.1 Hz.

Keywords: Membrane filter, Unsaturated material, Undrained cyclic triaxial test, SWCC
Introduction

Devices equipped with the high air entry ceramic disks are commonly employed in tests of unsaturated materials such as the soil water characteristic curve test (SWCC test), triaxial test, permeability test, etc. The ceramic disk, however, has suffered from a number of disadvantages in its application, such as the difficulty of saturating the ceramic disk, relatively slow response of measuring suction, time consuming of water drainage, etc. (Ridley and Burland 1993; Gee et al. 2002; Take and Bolton 2003; Oliveira and Fernando 2006). Due to such disadvantages, few works as far as the authors reviewed were reported and well documented suction measurements are rarely available on unsaturated sandy soils during the monotonic and cyclic loadings (Becker and Meißner 2002; Nakayama et al. 2003; Unno et al. 2006, 2008; Milatz and Grabe 2015).

Nishimura et al. (2012) introduced the microporous membrane filter technique applied to the pressure plate apparatus for the SWCC test as an alternative of the ceramic disk. This technique was later introduced to the simple shear and triaxial apparatuses for monotonic or cyclic loading tests (Uchimura et al. 2013; Ishikawa et al. 2014; Wang et al. 2016b), however, the details on the performance of the membrane filter were not comprehensively evaluated.

This paper first illustrates a modified triaxial system developed at the University of Tokyo for the cyclic loading test of the unsaturated soils. Then the diffusion issue and hydraulic conductivity of the membrane filter are described. At last, the performance of the membrane filter is evaluated through results of SWCC tests and undrained cyclic loading tests.

Modified triaxial apparatus

Fig.1 schematically shows the modified triaxial apparatus with the main body of the apparatus in the middle, the vertical loading and cell pressure control systems at the left hand side and detail description of the membrane filter pedestal at the right hand side. For the
pedestal, the membrane filter is fixed by a stainless cover, beneath which a fine porous metal is placed. The membrane filter is saturated separately and installed immediately before the test and the pore water pressure ($u_w$) is measured through a pressure transducer. On the other hand, the pore air pressure ($u_a$) can be measured through the air drainage path from the top cap. Note that a hydrophobic filter is glued on the surface of top cap, which allows free drainage of air, meanwhile, blocks water drainage (the limit water pressure that can be blocked is about 5 kPa).

A double cell system to measure the volume change of the specimen is equipped in the triaxial system, which is of a configuration similar as the traditional double cell system (Ng et al. 2002) except the linkage rod moving simultaneously with the loading shaft above the reference tube (Fig.1). Without the linkage rod, the volume change of the specimen can be obtained by the measurements of differential pressure transducer (DPT) and the vertical displacement transducer (VDT). However, it was recently found that the two transducers (i.e. DPT and VDT) may have slight phase difference of ~0.6s (i.e. unsynchronized responses of two transducers), resulting in significant measurement error during the cyclic loading with frequency of 0.1 Hz (Wang et al. 2016c).

The vertical cyclic loading is controlled by a function generator and applied by a double action cylinder connecting to the loading shaft. Moreover, the cyclic cell pressure can be also applied by a similar system as shown in Fig.1. It was shown by Wang et al. (2016a) that for the undrained cyclic triaxial test of unsaturated soils studying the liquefaction problem, it was necessary to apply a stress condition with the constant total mean principal stress ($p$), and by employing the vertical loading and cell pressure control systems, a reasonably $p$-constant condition was successfully maintained.
Properties of membrane filter

Diffusion issue

It is known that molecules in the air diffuse from one side of a filter with high concentration to the other side with low concentration for either the ceramic disk or the membrane filter (Tindall et al. 1999) and a flushing path is often installed to remove the diffused air in some testing systems. Since the flushing path was not installed in the triaxial system used in this study, the diffusion issue for the membrane filter was studied by employing the device shown in Fig. 2. In the acrylic container filled with de-aired water, the membrane was fixed beneath a very fine steel mesh and certain amount of air pressure was applied from the bottom of the membrane filter, immediately after which an upside acrylic bottle was sealed on the steel plate by the grease. Photos were taken every 30 minutes from the top of the acrylic container until air bubbles in the upside bottle were observed. Three types of membrane filter were tested with various air pressure conditions and the results were summarized in Table 1, in which M450 was also used in other tests in this study. The sustainable duration was the duration from the beginning of applying air pressure until the moment of the first visible air bubble in the upside bottle. It seems that the sustainable duration decreases sharply with increase in the air pressure (i.e. suction), though it increases as the pore size of the membrane filter reduces.

The sustainable duration was further evaluated by observation of \( u_w \) measurements of two similar specimens of Inagi sand with height of 100mm, diameter of 50mm, water content \((w)\) of about 22\% and dry density \((\rho_d)\) of 1.21 g/cm\(^3\) (the \( w \) and \( \rho_d \) was used for comparison with SWCC as shown in later section). \( u_w \) of one specimen was measured by directly mounting it on the membrane filter pedestal of the triaxial system; while a layer of silt slurry with thickness of 2~3mm was first paved on the pedestal before placing the specimen. The properties of Inagi sand and the silt are described in the later section. Both specimens were
only confined by rubber membrane (i.e. zero cell pressure) and the pore air was open to the atmosphere from the top cap.

The measurements of $u_w$ are shown in Fig. 3. For the specimen without the silt pavement, $u_w$ seems to be stabilized near -14kPa~-15kPa, while it lasts for less than half day followed by a sudden jump and a gradual increase to zero, which may be typical signals for air diffusion (Take and Bolton 2003). On the other hand, for the specimen with the silt pavement, $u_w$ seems to be stabilized near -13kPa~-14kPa, and it lasts for nearly two days without any particular changes. The test results suggest that the finer the material directly contacted with the membrane filter (the medium diameter of the silt is 1/5 of that of the Inagi sand), the longer before air diffusion through the membrane filter.

**Hydraulic conductivity**

The hydraulic conductivity ($k$) of the membrane filter (M450) was measured by the falling head method in the triaxial system with the configuration shown in Fig. 4. Water discharge through the membrane filter was measured by a DPT (No. 1) and the water head difference was measured by another DPT (No. 2).

Two tests were conducted by using tap water processed in different ways. The tap water was distilled and de-aired (DD water) for one test, and it was distilled, de-aired and further filtered by a coarser membrane filter (DDF water) for another test. In each test, two cycles of water discharge were conducted, the virgin flow for water in the inner cell falling to a certain level from the original level and the second flow for the similar process after refilling the same fresh water to the original level in the inner cell.

The $k$ was calculated for every two milliliters of water discharge and the water head lost in the water flow path other than the membrane filter was assumed to be nil. Fig. 5 shows the relationship between the hydraulic gradient ($i$) and the hydraulic conductivity ($k$) of the two
tests. It can be seen that \( k \) shows a reducing trend with the decrease in \( i \) (i.e. with the water discharge), while apparently the reduction magnitude is much less for the test with DDF water compared to that with DD water. In both tests, \( k \) in the second flow is generally smaller than that in the virgin flow for the same \( i \), while this difference is much smaller for the test with DDF water. The test results suggest that \( k \) of the tested membrane filter is about \( 1 \times 10^{-5} \) cm/s, and it may be easily affected by the quality of water.

**Testing materials**

Three materials, i.e., Inagi sand and Iron ore fines (IOF) and a non-plastic silt, were mentioned in this study. Inagi sand is a type natural deposit sand which was extensively studied due to the large scale construction plan of Tama New Town from 1960’s in Tokyo (Yoshioka et al. 1973), IOF is a type of bulk cargoes for iron making industry and is being concerned due to its potential to liquefy during maritime transportation (Roberts et al. 2013; Chen et al. 2014; Munro and Mohajerani 2015, 2016), and the non-plastic silt is a commercial product frequently used in laboratory tests. The physical properties and gradation curves are shown in Table 2 and Fig. 6.

**SWCC tests**

Nishimura et al. (2012) compared the drainage durations to achieve equilibrium of water content of similar silt specimens after being subjected to suction of 25 kPa in the pressure plate apparatuses installed either the membrane filter (AEV: 40-100 kPa, thickness: 0.094-0.14mm) or the ceramic disk (AEV: 200 kPa, thickness: 7 mm). They found that the drainage durations conducted in the membrane filters apparatus were all in about 2 minutes, while, it was about 3000 ~4000 minutes for the ceramic disk apparatus. Wang et al. (2014) conducted similar tests on IOF by employing the membrane filter (AEV: 250 kPa, thickness: 0.14mm) and ceramic disk (AEV: 200 kPa, thickness: 4 mm) pressure plate apparatuses, founding that
the equilibrium of the water drainage for each suction step was within 2 hours for the membrane filter apparatus; while it was about one ~ two days for the ceramic disk apparatus. Though the AEV of above filters were different, the thickness difference may be more critical for the efficient performance of the membrane filter compared to the ceramic disk.

Test program

SWCC tests were described in this section to confirm the similarity of SWCCs obtained by the membrane filter and the ceramic disk apparatuses, and to confirm the repeatability of the membrane filter apparatus. Three apparatuses installed the membrane filter (AEV: 250 kPa), a ceramic disk with 2mm thickness (AEV: 200 kPa) and a ceramic disk with 4mm thickness (AEV: 200 kPa), respectively were used to conduct tests of materials, Inagi sand and IOF. The apparatuses are illustrated in Fig. 7 and the testing conditions are summarized in Table 3. Materials for the test were statically compressed to the desired dry densities in a rigid mold for Inagi sand with the initial water content ($w_0$) of 22% and IOF with $w_0$ of 12%, and the pedestals of the apparatuses were pre-saturated before tests. After placing the specimen in the apparatus, the apparatus was immerged in the water tank. The pressure in the water tank was first gradually decreased to -100 kPa, then remained for at least 12 hours for saturation, and at last increased to the atmosphere pressure gradually.

After the saturation process, a burette was connected to the drainage path of the pedestal and the apparatus was hanged to a position slightly higher than the water level in the burette. This condition was remained for another 12 hours for initial stabilization of the specimen. The suction was applied by lifting the specimen at a higher position than the water level in the burette while keeping the pore air of the specimen and the air in the burette open to the atmosphere through considerably small openings. The water content change in the specimens was monitored by a DPT and confirmed by direct reading from the burette. The suction was
applied up to 10 kPa or 20 kPa for the drying process to avoid possible air diffusion. In each step of suction, sufficient time was assigned for water content equilibrium.

Test results

The SWCCs in terms of suction versus degree of saturation (Sr) of Inagi sand specimens, IOF specimens are shown in Figs. 8-10, respectively. For the initial steps with suction less than 0.1 kPa (i.e. H<1 cm in Fig. 7), they were all assigned to 0.1 kPa for convenience. It can be seen that the SWCCs measured by the membrane filter apparatus are generally consistent with the corresponding curves measured by either the 2mm or the 4mm ceramic disk apparatus for both materials in the tested suction ranges. Figs. 8-9 show that the repeatability of SWCCs measured by the membrane filter apparatus is reasonably good. On the other hand, the gap between SWCCs observed in Figs. 8-10 may be induced by two main reasons, firstly, the difficulty of suction control in relatively low suction region, secondly, the micro-structure difference of similar specimen causing difference of SWCCs in relatively high suction region and wetting curves. Nevertheless, it is suggested that the membrane filter may be a good alternative for SWCC tests on sandy materials under relatively low suction range.

Undrained cyclic triaxial test

To study the liquefaction properties of unsaturated sandy materials, Wang et al. (2016b) conducted a series of undrained cyclic triaxial tests on three materials (Toyoura sand, Inagi sand and Iron ore fines) by employing the triaxial system shown in Fig. 1, in which the suction measurements were obtained for some tests. Since the measured suction of three materials were relatively small (less than 5 kPa) and the behavior were quite similar, in this section, the typical suction measurements of Inagi sand specimens are presented (Table 4).
Test preparation

The materials were pre-wetted with the water contents of 22.0% and the specimens were formed by static compaction with the height of 100mm and diameter of 50 mm. Then extra water was carefully added from the top of the specimens to achieve desired water contents and these specimens were cured in the mold for about 10 hours for uniformity of water distribution. The maximum water content difference in the Inagi sand specimens after curing was about 1% based on trial test results (Wang et al. 2016a).

The drainage of the pore water was closed and the pore air was kept open to the atmosphere before applying cyclic loading, and the drainage of the pore air was also closed during cyclic loading. Thus, the consolidation was completed by pore air drainage only and the suction equaled to $-u_w$ before, and $u_a-u_w$ during the cyclic loading.

Suction before cyclic loading

Figs. 11 (a) and (b) show the measurements of $u_w$ of Inagi sand specimens with relatively low ($w=\sim30\%$) and high ($w=\sim34\%$) water contents before cyclic loading, respectively. For specimens with relatively low water content in Fig. 11 (a), equilibrated $u_w$ is close to $-3.8\sim-4.0$ kPa before the consolidation and it slightly reduces to $-4.1\sim-4.2$ kPa during the consolidation. For one of the specimens, $u_w=-3.6$ kPa is measured within 2 seconds after mounting the specimen on the pedestal; while for the other one, it takes longer time to achieve the equilibrium. For the specimens with relatively high water content in Fig. 11 (b), equilibrated $u_w$ is close to $-3.0$ kPa before consolidation, it can be seen that the $u_w$ of $-2.7\sim-3.0$ kPa was measured within one sampling time interval (i.e. 5 seconds) immediately after mounting the specimens. While $u_w$ increases to positive values ($\sim3.0$ kPa) after increase of the cell pressure for consolidation, which may be induced by clogging of the pore air path by the pore water when the water content is relatively high. The observations of the measurements of $u_w$ on Inagi sand specimens and on other materials imply that the response
of $u_w$ measurement system can be as short as ~2 seconds for specimens with relatively low suction, while the response seems to depend on the specimen conditions and materials.

Fig. 12 plots the measurements of suction of Inagi sand before cyclic loading on the SWCC of this material. It seems that the measurements on the triaxial apparatus are close to the wetting curve of the SWCC, which may be induced by the adding water pressure for the specimen in undrained cyclic loading test. Since all the specimens including that for the SWCC test were initially formed with the water content of about 22.0%, the microstructure of the specimens would be similar with each other. The water network, after either water absorption for the SWCC test specimen or adding extra water for the triaxial test specimens, may also be similar, consequently showing the result in Fig. 12.

*Suction during cyclic loading*

Fig. 13 show the typical time histories of deviator stress ($q$), axial stain ($\varepsilon_a$), $u_a$, $u_w$ and suction of a Inagi sand specimen during the undrained cyclic loading. It can be seen that $u_a$ and $u_w$ gradually develop with the cyclic loading values close to the cell pressure at the end of the test. Slightly reducing trend of suction throughout the cyclic loading is observed; while suction significantly variates at the late stages of the tests. It should be noted that the membrane filter pedestal may need time to capture the equilibrated $u_w$, as discussed in Fig. 11, which means the suction in Figs. 13 may not represent the real time value for the tests with loading frequency of 0.1 Hz and data sampling interval of 0.1 second.

**Conclusion**

The following issues and conclusions may be drawn from this study:

1. The duration to resist the air diffusion through the membrane filter may be largely affected by the magnitude of the suction, though it may be also affected by the pore size of the
membrane filter and the contacting materials. Depending on the duration of test and suction level, proper membrane filter may be chosen to avoid diffusion during the test.

2. The hydraulic conductivity ($k$) of the tested membrane filter (M450) is about $1 \times 10^{-5}$ cm/s. It is also found $k$ may be easily affected by the quality of water, which should be paid attention in the permeability test of sandy materials with relatively high $k$.

3. Very similar results of SWCCs obtained from the pressure plate apparatuses installed either the membrane filter or the ceramic dick are obtained, and the repeatability of the membrane filter pressure plate apparatus is also reasonably good, which suggests that the membrane filter technique may be a good alternative to measure the SWCC and suction for sandy materials under relatively low suction range.

4. The membrane filter pedestal in the triaxial system can measure the equilibrated pore water pressure of the specimen within as short as ~2 seconds under certain testing conditions, while the response may become slow depending on the materials, suction values, etc. Reasonable suction measurements are obtained during undrained triaxial cyclic loading with the loading frequency of 0.1 Hz, which show that suction in the specimens may slightly reduce during the cyclic loading.

**Acknowledge**

The first author would like to thank Ms. Y. Okabe for providing valuable data of non-plastic silt in Table 2.

**Reference**


Figure Captions

Fig. 1 Schematic drawing of the modified triaxial system for the undrained cyclic loading test of unsaturated materials

Fig. 2 Schematic drawing of the diffusion measurement device

Fig. 3 Diffusion issue of membrane filter on the triaxial system for Inagi sand specimens

Fig. 4 Schematic drawing of the device for the hydraulic conductivity test

Fig. 5 Relationship between hydraulic gradient and hydraulic conductivity of membrane filter (M450)

Fig. 6 Gradation curves of materials used in this study

Fig. 7 Schematic drawing of the system for the SWCC test

Fig. 8 SWCCs of Inagi sand specimens

Fig. 9 SWCCs of IOF specimens with relatively loose condition

Fig. 10 SWCCs of IOF specimens with relatively dense condition

Fig. 11 Typical $u_w$ measurements of Inagi sand specimens with, (a) $w=30\%$, (b) $w=34\%$

Fig. 12 Comparison between measurement of SWCC and suction measurements on the membrane filter pedestal for Inagi sand specimens

Fig. 13 Typical time histories of $q$, $\theta_a$, $u_w$, $u_a$ and suction for Inagi sand specimen during the undrained cyclic loading
Table 1 Properties of tested membrane filters and test results

<table>
<thead>
<tr>
<th>Membrane type</th>
<th>Pore size (µm)</th>
<th>Thickness (µm)</th>
<th>AEV (kPa)</th>
<th>Air pressure (kPa)</th>
<th>Sustainable duration (hours)</th>
</tr>
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<tbody>
<tr>
<td>M450</td>
<td>0.45</td>
<td>140</td>
<td>250</td>
<td>20</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>M200</td>
<td>0.2</td>
<td>145</td>
<td>350</td>
<td>25</td>
<td>&lt;120 &amp; &gt;70</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>40</td>
<td>2</td>
</tr>
<tr>
<td>M100</td>
<td>0.1</td>
<td>132</td>
<td>--</td>
<td>40</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 2 Properties of tested materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$G_s$</th>
<th>$D_{50}$ (mm)</th>
<th>$F_c$ (%)</th>
<th>$\rho_{d,max}$ (g/cm$^3$)</th>
<th>$w_{opt}$ (%)</th>
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<tr>
<td>Inagi sand</td>
<td>2.656</td>
<td>0.115</td>
<td>29.5</td>
<td>1.66</td>
<td>20.0</td>
</tr>
<tr>
<td>IOF</td>
<td>4.444</td>
<td>0.715</td>
<td>23.6</td>
<td>2.79</td>
<td>12.0</td>
</tr>
<tr>
<td>silt</td>
<td>2.650</td>
<td>0.023</td>
<td>99.1</td>
<td>1.520</td>
<td>22.2</td>
</tr>
</tbody>
</table>

Note: $G_s$, specific gravity; $D_{50}$, median diameter; $F_c$, fines content; $\rho_{d,max}$ and $w_{opt}$, maximum and optimum water content obtained by compaction test.
### Table 3 Conditions of SWCC tests

<table>
<thead>
<tr>
<th>Materials</th>
<th>Dry density $^1$ (g/cm$^3$)</th>
<th>Pedestal type$^2$</th>
<th>Test No.</th>
<th>Specimen dimensions$^3$ (mm)</th>
</tr>
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<tbody>
<tr>
<td>Inagi sand</td>
<td>1.20 (1.18-1.19)</td>
<td>2mm CD</td>
<td>ING-2C</td>
<td>20×25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MF</td>
<td>ING-M</td>
<td>20×25</td>
</tr>
<tr>
<td>IOF</td>
<td>2.00 (1.99-2.02)</td>
<td>4mm CD</td>
<td>IOF-4C-L</td>
<td>20×25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MF</td>
<td>IOF-M-L1</td>
<td>26×25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>IOF-M-L2</td>
<td>26×25</td>
</tr>
<tr>
<td></td>
<td>2.45 (2.44-2.46)</td>
<td>2mm CD</td>
<td>IOF-2C-D</td>
<td>25×25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MF</td>
<td>IOF-M-D1</td>
<td>26×25</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>IOF-M-D2</td>
<td>25×25</td>
</tr>
</tbody>
</table>

Note:  
$^1$Desired densities and (real densities); $^2$CD and MF denote ceramic disk and membrane filter pedestals, respectively, and 2mm and 4mm denote the thickness of the ceramic disks; $^3$Dimension: height × radius.

### Table 4 Conditions of undrained cyclic triaxial test

<table>
<thead>
<tr>
<th>Materials</th>
<th>$\sigma_c$ (kPa)</th>
<th>$\rho_{d0}$ (g/cm$^3$)</th>
<th>$\rho_d$ (g/cm$^3$)</th>
<th>$w$ (%)</th>
<th>$S_{r0}$ (%)</th>
<th>$S_r$ (%)</th>
<th>CSR</th>
<th>Test No.</th>
</tr>
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<tbody>
<tr>
<td>Inagi sand</td>
<td>60</td>
<td>1.09 -1.11</td>
<td>1.26 -1.29</td>
<td>29.8</td>
<td>57</td>
<td>72-74</td>
<td>0.35</td>
<td>ING-L1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.27</td>
<td>ING-L2</td>
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<td>0.25</td>
<td>ING-H1</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>0.17</td>
<td>ING-H1</td>
</tr>
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Note:  
$^1$\(\sigma_c\), cell pressure for consolidation, \(\rho_{d0}\) and \(S_{r0}\), initial dry density and degree of saturation before consolidation, \(\rho_d\) and \(S_r\), dry density and degree of saturation after consolidation, \(w\), water content of the specimen, CSR, cyclic stress ratio (=\(q_{\text{amp}}/2\sigma_0\), where \(q_{\text{amp}}\), amplitude of cyclic loading, and \(\sigma_0\), net stress=\(\sigma_c\)-suction). $^2$"-" except those in the test No. column stands for range of tested specimens.
Fig. 1 Schematic drawing of the modified triaxial system for the undrained cyclic loading test of unsaturated materials
Fig. 2 Schematic drawing of the diffusion measurement device
Fig. 3 Diffusion issue of membrane filter on the triaxial system for Inagi sand specimens
Fig. 4 Schematic drawing of the device for the hydraulic conductivity test
$k = \frac{Q}{A \cdot t \cdot i}$

$Q$: water discharge (=2 ml)

$A$: effective cross-sectional area of membrane filter

$i$: hydraulic gradient (=head/thickness of filter)

$t$: time for 2ml water discharge

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