Dependencies of Shear Wave Velocity and Shear Modulus of Soil on Saturation

Yi Dong, A.M.ASCE1; and Ning Lu, F.ASCE2

Abstract: Shear wave propagation in soil is a physical phenomenon and has been used widely for monitoring and seismic property assessment in geotechnical engineering. Shear wave velocity \( V_s \) and small-strain shear modulus \( G_0 \) are the key parameters in defining material response to various dynamic loadings. To date, the dependencies of \( V_s \) and \( G_0 \) on saturation, especially in high suction range, are still not well understood because of the limited testing methodology and experimental evidence. In this study, the authors present a new laboratory instrumentation of measuring shear wave propagation in different types of unsaturated soils. Low relative humidity and water mist injection environment are used for measuring shear wave velocity under both drying and wetting conditions. Bender element technique was used to measure the shear wave responses. Step function was used as excitation, and determination of a first arrival time was identified and consistently used for all shear wave measurements. Shear wave evolution and the calculated \( V_s \) and \( G_0 \) with varying volumetric water content under zero total stress condition along drying and wetting are presented. The effects of different soil–water regimes on the evolution of \( G_0 \) are examined. It is found that \( V_s \) or \( G_0 \) depends highly on soil types, saturation, and drying/wetting state. Parameter \( V_s \) or \( G_0 \) is the lowest when a soil is saturated and the highest when it is dry—varying from tens of meters per second for \( V_s \) or a few megapascals for \( G_0 \) at full saturation for all soils to up to 1,800 m/s of \( V_s \) or 2 GPa of \( G_0 \) in clayey soil at dry state. The variability of \( V_s \) or \( G_0 \) on soil type becomes more pronounced as soil has more clayey materials. It is also identified that hydraulic hysteresis of \( V_s \) or \( G_0 \) is prominent only in the capillary water retention regime for all types of soil. DOI: 10.1061/(ASCE)EM.1943-7889.0001147. © 2016 American Society of Civil Engineers.

Author keywords: Shear wave velocity; Small-strain shear modulus; Unsaturated soils; Bender element; Water content.

Introduction

Small-strain shear modulus \( G_0 \) provides valuable information on soil skeleton stiffness, which is a fundamental physical property relevant to liquefaction assessment, dynamic ground response analysis, and deep soil-structure design in geotechnical engineering (e.g., Kramer 1996; Clayton 2011; Yang and Gu 2013). Various methods exist for measuring the stiffness of soil at small strain, including, e.g., resonant column technique (Mancuso et al. 2002; Youn et al. 2008) and bender element technique (Qian et al. 1991; Marinho et al. 1995; Blewett et al. 2000; Inci et al. 2003; Lee and Santamaria 2005; Leong et al. 2009). Resonant column test is a widely used and reliable technique for measuring small-strain shear modulus, but it is limited by the compatibility with other geotechnical testing apparatus such as triaxial, direct shear, odometer (Airey and Mohsin 2013), and its inherent electromotive force interference (Wang et al. 2003). Over the years, the bender element technique, because of its small size and nondestructive nature, has become more common and has been incorporated into various geotechnical instrumentations, combining shear wave measurement with other soil property testing such as shear strength, friction angle, and \( K_0 \) parameters (Jovičič and Coop 1998; Zeng and Ni 1998; Salgado et al. 2000; Alramahi et al. 2007; Ng and Yung 2008).

However, the accessibility of a wide range of saturation or particularly high suction range becomes the obstacle for most of the geotechnical experimentalizations for unsaturated soils. The axis translation technique, which involves high air-entry ceramic stone, is one common approach to control the suction integrated into triaxial test (Alramahi et al. 2007; Ng et al. 2009; Sawangsuriya 2009; Ghayoomi et al. 2011; Khosravi and McCartney 2012; Heitor et al. 2013; Oh and Vanapalli 2014), but it is limited to a long time duration of equilibrium and capability limitation of highest suction. In contrast, a remarkable volume change in expansive soil during drying or wetting also increases the difficulty in good control of the testing sample. A recent study by Lu and Kaya (2013) provided a good solution to tackle such problems. A Drying Cake method was established to measure the soil cake deformation and elastic modulus, and then determine the suction stress characteristic curve and soil–water retention curve. Soils can be dried under a low relative humidity environment with equivalent hundreds of MPa of suction. A zero-loading boundary condition frees the soils to deform without crack development.

In this study, we introduce a new system of measuring shear wave propagation and small-strain shear modulus for sandy, silty, and clayey soils over a wide range of saturation up to hundreds of MPa in suction without external loading. Dry air evaporation and water mist adsorption were employed to provide drying and wetting conditions. Bender element technique was used, and the determination of wave traveling time was identified for all shear wave measurements. Shear wave velocity and small-strain shear modulus were then calculated for analysis of their dependencies on soil moisture.
**Experimental Setup**

The entire system consists of two components: (1) an environmental chamber that provides controlled relative humidity for drying and wetting, and a digital balance that connects to a computer and records the change of soil weight; and (2) sensors and signal acquisition system that monitor the shear wave transmitted through the sample. Fig. 1 provides an illustrative scheme to demonstrate the setup and connections of the system. A cylinder with a top plate seated on a bottom plate forms a chamber containing soil samples. The chamber is lifted to a certain height for soil weight monitoring. Circular openings were cut on the bottom plate with slightly larger size than the sample diameter, so that soil samples can be placed exactly on the balance through the openings and be installed inside the chamber without touching the bottom plate and disturbing the weight monitoring. Lids with adjustable openings were designed on the top plate for accelerating or decelerating the natural evaporation speed for drying. A vapor diffuser connected to a humidifier was set at the center of the bottom plate and provided water mist injection for the wetting process. The entire chamber allowed two soil samples under testing separately. For simplicity, Fig. 1 shows only half capacity of the sample configurations.

A pair of bender elements with 2 mm tip length was put on the top and bottom surface of the soil specimen, respectively. The signal system consisted of an oscilloscope (Tektronix MDO3012, Beaverton, Oregon) with a built-in signal generator module (MDO3AFG) for signal emission and storage, and a digital filter (Krohn-Hite 3940, Brockton, Massachusetts) for signal conditioning. The signal flow started with the signal generator sending an excitation to the sender (bottom bender element). Then the shear wave was transmitted through the soil, and the receiver (top bender element) sensed shear wave. After that the received signal filtered off the noise and then recorded and displayed it on the oscilloscope.

**Testing Procedure**

In total, seven types of soil were tested. Table 1 lists the classifications and basic properties of the soils. These soils were chosen to represent a wide range of soil type, from sandy to silty, and clayey soils. All soils were remolded and prepared as soil cakes in a mold with diameter of 76.2 mm (3 in.), and approximately 20 mm thickness. Soil cakes were immersed in de-aired water in a desiccator with vacuum applied for sufficient time to be saturated (usually approximately 1–2 days). After saturation, the soil samples were gently transferred into the environmental chamber for drying and then wetting. Adjusting the opening of the lid size controls the evaporation rate and reduces the local relative humidity gradient between soil sample and its surrounding air. Throughout the evaporation drying process, the color of the entire soil cake surface changed uniformly, which ensured that the thin soil cakes were dried under a relatively homogeneous distribution of water content. A very thin film of Vaseline (Unilever, Englewood Cliffs, New Jersey) grease was spread on the surface of the sample holding plate to minimize the friction between soil sample and holding plate, and to prevent the soil cracking during drying or wetting. The experimental setup was maintained at a constant room temperature (25 ± 2°C). We took advantage of the low relative humidity of 31% (±10%) in local room condition, which is equivalent to a total suction of approximately 123–215 MPa, based on Kelvin’s equation (e.g., Lu and Likos 2004). This can also be achieved by using desiccants or injecting dry nitrogen gas. A digital balance with 0.01-g accuracy was used to monitor the water content, and to calculate the water content of soil under drying or wetting. After drying, an adjustable humidifier was used to provide water mist into the chamber to gradually wet the soil cakes. Low strength of the mist plume was injected to prevent water droplet condensation on the specimen for wetting. One measurement needed to be taken approximately every 12–24 h, and the duration of a single test varied from 7 to 16 days, depending on the soil type (Dong et al. 2016; Dong and Lu (2016)).

The measurement of shear wave velocity was accomplished by similar settings in previously published papers (Truong et al. 2011; Dong et al. 2016). Because of the unknown natural frequency of the soil-sensor system, a 50-Hz step-function signal was selected as the excitation, because step function covers the entire frequency range in a frequency domain. The excitation was emitted by the sending sensor, which generated a sudden pulse of vibration (50 times in a second). The excitation transmitted in the manner of shear wave through the soil skeleton. The frequency of the shear wave depends on the soil skeleton and stiffness of the bender element and its mounting system (Lee and Santamarina 2005). The tiny local vibration was sensed and captured by the receiver bender element and transferred into received signal, which was then filtered through 100-Hz high-pass, 50-kHz low-pass channels, with 20 dB of gain amplification for each. The signals were digitized at a 2.5 GHz sampling rate (100,000 data points). A stack of 256 signal-acquiring permits reduced the noncoherent noise.

In the literature, different methods are used to determine the traveling time of the shear wave: first arrival, peak to peak, cross correlation, wavelet analysis, phase detection analysis, and other frequency domain methods (Cho and Santamarina 2001; Bonal et al. 2012; Styler and Howie 2013). The first arrival under a step-function excitation is considered the most reliable method to determine the travel time of shear wave over the distance. The shear-wave velocity $V_s$ can be evaluated by dividing the known tip-to-tip distance between the two bender elements by the travel time for the first arrival $t$.

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**Table 1. Basic Properties of Tested Soils and the Classifications**

<table>
<thead>
<tr>
<th>Number</th>
<th>Soil</th>
<th>USCS</th>
<th>Porosity</th>
<th>$G_s$</th>
<th>LL (%)</th>
<th>PL (%)</th>
<th>PI (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Esperance sand</td>
<td>SP</td>
<td>0.419</td>
<td>2.65</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>Hopi silt</td>
<td>SC</td>
<td>0.429</td>
<td>2.68</td>
<td>36.0</td>
<td>23.0</td>
<td>13.0</td>
</tr>
<tr>
<td>3</td>
<td>Bonny silt</td>
<td>ML</td>
<td>0.417</td>
<td>2.65</td>
<td>25.0</td>
<td>21.0</td>
<td>4.0</td>
</tr>
<tr>
<td>4</td>
<td>BALT silt</td>
<td>ML</td>
<td>0.458</td>
<td>2.72</td>
<td>27.4</td>
<td>21.7</td>
<td>5.8</td>
</tr>
<tr>
<td>5</td>
<td>Missouri clay</td>
<td>—</td>
<td>0.490</td>
<td>2.67</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<tr>
<td>6</td>
<td>Denver claystone</td>
<td>CH</td>
<td>0.471</td>
<td>2.70</td>
<td>44.0</td>
<td>26.0</td>
<td>18.0</td>
</tr>
<tr>
<td>7</td>
<td>Georgia kaolinite</td>
<td>CH</td>
<td>0.522</td>
<td>2.66</td>
<td>118.0</td>
<td>45.0</td>
<td>73.0</td>
</tr>
</tbody>
</table>

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where $d_{tt}$ = tip-to-tip distance between the sending and receiving bender elements (assuming constant sample thickness as a result of the negligible vertical deformation in a thin cake); and $\Delta t$ = travel time of the first arrival. Then the $G_0$ values can be calculated using

$$G_0 = \rho_b \cdot (V_s)^2 = \rho_b \cdot (d_{tt}/\Delta t)^2$$

where $\rho_b$ = bulk density of soil. Specifically, Fig. 2 presents a typical shear wave signature of one single measurement. Fig. 2(a) shows the typical shear wave response under a step-function excitation, including the first major event of transmitted shear wave response in approximately 0–0.4 ms, and a second event of reflected shear wave response in approximately 0.7–1.3 ms. The received signal was magnified by a digital filter; therefore, the amplitude is not on the real scale. A zoomed-in time window in Fig. 2(b) clearly shows the features of the first event, in which the start of first negative deflection occurred at approximately 40 $\mu$s, the first negative bump maximum at approximately 70 $\mu$s, zero after the first bump at approximately 90 $\mu$s, and first major peak at approximately 125 $\mu$s. The zero recovered after first bump was chosen to be the first arrival of shear wave propagation. In this example, the travel time was determined as 87.4 $\mu$s. The major peak lasted approximately 200 $\mu$s, which is inconsistent with the result of the fast Fourier transfer of the received signal, whose primary frequency is approximately 5 kHz.

**Results**

**Wave Signature and Evolution**

After completing one cycle of drying and wetting, the received signals for soil cake specimen can be collected at different water contents. Figs. 3(a and b) show an example of typical shear wave evolution (Missouri clay) as the water content decreases under drying, and increases afterward under wetting. Fig. 3(c) gathers all wave traveling times of first arrival and plots its relationships with volumetric water content for both drying and wetting. In this

![Fig. 2. Determination of first arrival of the shear wave: (a) signature excitation and response of the bender element; (b) trail details in time window of approximately 0–500 $\mu$s](image-url)
case, when the soil sample started to dry at full saturation, the first arrival was relatively far away from the excitation at time zero (approximately 281.8 μs), and the amplitude was very small. This also indicates that the soil is very soft under zero total stress and in a full-saturation condition at water content $\theta = 0.49$. As the soil desaturates, the major peak starts to become prominent with higher amplitude. In addition, the related time response turns are significantly compacted, reflecting the velocity increases and wave front moving closer toward the time zero of excitation: 179.4 and 122.6 μs of the first arrivals at $\theta = 0.48$ and 0.46, respectively.

As the soil continues to dry, the major peak gradually moves close to time zero of the excitation and the amplitude reaches a maximum amplitude of approximately $\theta = 0.41$, then stays at the same order of magnitude but slightly decreases. At the end of drying at $\theta = 0.01$, the major peak of the first wave front moves very close to the time zero of excitation, indicating a very fast shear wave velocity compared with that under the higher water content conditions. The amplitude decreases but is still discernible. After the major peak of the first event, the succeeding events such as the second or even third arrival of the reflected shear wave—or the reflected $p$-waves by the boundary—can be identified on the trail of the response signal, because of the significantly increased soil stiffness and propagating velocity. Therefore, more signal undulation can be identified on the trail in the range of approximately 0–0.50 ms.

During the wetting process, the trend of responsive signal variation is reversed. As the water content increases from 0.01 to 0.10, the reactive range signal fluctuation slightly decreases from approximately 0–0.50 to 0–0.40 ms. The composition of the multievent response at $\theta = 0.01$ gradually evolves into a single major-event response at $\theta = 0.14$, with a prominent major peak and a first arrival in the range of approximately 0–0.15 ms and subtle response of other events in the coda range of approximately 0.15–0.35 ms. As the water content continues to increase from $\theta = 0.14$ to 0.28, the major peak becomes dominant over the others, and the first arrival time gradually increases. During the final stage of wetting at water content 0.33 and 0.38, the major peak on the response signal starts to decay, as a result of the increased amount of water and soil softening. At the end of wetting at water content 0.38, the signal almost recovers back to the same response signal at water content 0.49 of drying, but with a shorter traveling time of the first arrival, which is considered caused by the effect of hysteresis of the capillary water, and is consistent with some previous observations (Ng et al. 2009; Khosravi and McCartney 2012).

In Fig. 3(c), the quantitative curves clearly illustrate the variation of traveling time evolving with volumetric water content and its dependency on drying or wetting paths. The step-wise characteristics on curves of the first arrival time as the water content decreases under drying or increases under wetting indicates that different mechanisms are controlling throughout the entire soil–water regimes. The first arrival times of wetting path returns back along the same track of drying path until the end of the first bump as the water content increases (at $\theta = 0.33$). Then, the first arrival time starts to increase significantly and deviates from the first arrivals of drying, which suggests a hysteresis of wave propagation caused by the capillary water.

Followed by the determination of traveling times of shear waves for seven soils at different water contents, shear wave velocities can be calculated by Eq. (2) under both drying and wetting conditions, as shown in Fig. 4. As the water content decreases along the drying path, the shear wave velocity increases nonlinearly. When soils are saturated, the shear wave velocity varies from 24.4 m/s (Hopi soil) to 72.1 m/s (Georgia kaolinite), depending on, e.g., the soil type and initial void ratio, and consolidation ratio. (Shibuya and Mitachi 1994; Sorensen et al. 2010). As the soil dries and starts to form an air–water interface (around the water content of air entry), the shear wave velocity has a sharp increase (e.g., Hopi silt, Missouri clay, Georgia kaolinite). When the water content is in the range of approximately 0.15–0.35, the shear wave velocity gradually increases with a mild rate as the water content decreases. At the end of the drying stage, the shear wave velocity again significantly increases and reaches the maximum values as the soil sample dries from a water content of 0.15 to 0.01. The maximum shear wave velocity varies from 179.2 m/s (Esperance sand) to 1,793.1 m/s (Missouri clay), depending on the soil type.

Under the wetting condition, the shear wave velocity decreases in a similar pattern as its counterpart under drying. As the water content increases from room-dried condition to medium degree of saturation in the capillary water regime (approximately 0.3–0.4 of water content), the shear wave velocity of wetting is equal or less than that of drying. As the wetting continues to full saturation, the shear wave velocity of wetting is lower than that of drying, because of the effect of the capillary water hysteresis.

### G\textsubscript{0} Variation with Water Content

Given the shear wave velocity and bulk density of soil sample at various water contents, the small-strain shear modulus can be determined in terms of varying water content. Figs. 5–7 present the results of small-strain shear modulus evolution with volumetric water content for seven tested soils. All results are categorized into
three groups to demonstrate the dependency of $G_0$ on water content.

The small-strain shear modulus of Esperance sand and Georgia kaolinite were presented in Fig. 5. Although Georgia kaolinite is classified as clay, it has a very similar pattern of small-strain shear modulus development with water content as Esperance sand does, except that kaolinite has almost two orders of magnitude higher values of $G_0$ than those of sand. Starting with drying from full saturation to air entry (e.g., approximately 0.52–0.4 for kaolinite and 0.42–0.38 for sand), $G_0$ increases prominently: $G_0$ increases from approximately 3 to approximately 12 MPa as $\theta$ decreases from 0.42 to 0.38 for Esperance sand; and $G_0$ increases from 9 to 455 MPa as $\theta$ decreases from 0.52 to 0.40 for Georgia kaolinite. In the medium range of water content, $G_0$ stays at approximately 13 MPa for Esperance sand as the water content decreases from 0.35 to 0.13; $G_0$ increases up to approximately 1,500–1,700 MPa and keeps constant as the water content decreases from 0.35 to 0.04. In the low water content range, $G_0$ has an obvious abrupt jump as the soils reach the dry end: $G_0$ increases up to 57 MPa for Esperance sand at $\theta = 0.013$ and to 3,572 MPa for Georgia kaolinite at $\theta = 0.034$. For Esperance sand, a succeeding little drop of $G_0$ from 57 to 50 MPa as the sample drying from 0.03 to 0.01 was observed. This has been considered the effect of snap-off of the pendular liquid bridge at particle contacts (Cho and Santamarina 2001). The evolution of $G_0$ under wetting for these two soils basically follows the same pattern but with lower values than drying, implying that a hysteresis exists on $G_0$ evolution of this group of soils during drying and wetting.

For silty and clayey soil, the results are presented in Figs. 6 and 7. Three silty soils have similar developments of small-strain shear modulus along the drying and wetting paths. When soil starts to desaturate, $G_0$ increases around the air entry, similar to how sand or kaolinite does in Fig. 5. However, in the medium range of water content in drying, instead of keeping constant such as sand or kaolinite, $G_0$ still gradually increases: $G_0$ increases from 27 to 99 MPa as $\theta$ decreases from 0.40 to 0.10 for Hopi silt, $G_0$ increases from 21 to 281 MPa as $\theta$ decreases from 0.41 to 0.08 for Bay Area Landslide Tasks (BALT) silt, and $G_0$ increases from 57 to 404 MPa as $\theta$ decreases from 0.37 to 0.14 for Bonny silt. In the transition from medium water content range to low water content range, the trajectory of $G_0$ development changes slightly. As the soil continues to dry, $G_0$ increases slower in the low water content range than in the medium water content range. For instance, $G_0$ increases from 288 to 309 MPa as the water content changes from 0.04 to 0.01 for Hopi silt; and $G_0$ increases from 478 to 487 MPa as the water content changes from 0.03 to 0.02 for BALT silt.

The changed slope or increasing rate of $G_0$ indicates that soils are crossing over the boundary of different soil–water regimes. Comparing these three soils, Hopi silt classified as clayey sand (SC) has relatively small variation of $G_0$ over the entire range of water content (approximately 27–309 MPa), whereas the other two silty soils (ML) have large variability in $G_0$ for soils from wet to dry (approximately 21–487 MPa for BALT silt and approximately 30–1,072 MPa for Bonny silt). Additionally, Hopi silt has a similar plateau on $G_0$ in the medium range of water content from 0.2 to 0.4, which resembles the behavior of Esperance sand and Georgia kaolinite in Fig. 5. This observation suggests that silty soil with
higher fine content can develop higher $G_0$ variation between dry and saturated states than sandy soil.

The $G_0$ developments for two types of clay under drying and wetting are presented in Fig. 7. Missouri clay clearly shows a second bump in the low water content range (approximately 0.01–0.15) with a decreasing slope of the curve, in addition to the first bump around the air entry, as the soil dries from full saturation. The overall variation of $G_0$ developed from saturated to dry for clay is even larger than silty soils shown in Fig. 6. Missouri clay and Denver claystone reach their maximum $G_0$ of 1,793 and 1,788 MPa, respectively. In addition, the $G_0$ development under wetting condition follows the same curve in the low water content range as the $G_0$ development of drying. As the water content increases to high water content range, the $G_0$ decreases faster, so that $G_0$ values of wetting are always lower than those of drying at high water content.

**Analysis and Discussion**

Generally, the S-shape nonlinear development of shear wave velocity has the inverse correlation with water content: high velocity at low water content and low velocity at high water content. Sandy soil has a relatively small increment on shear wave velocity from saturation to dry state (e.g., from tens of meters per second to up to few hundreds of meters per second for Esperance sand, Hopi silt, and BALT silt). For soil containing more fine content or clayey soil, however, the shear wave velocity can increase two orders of magnitude from tens of meters per second at saturation to up to 1,800 meters per second at dry conditions (e.g., Bonny silt, Denver claystone, Missouri clay, Georgia kaolinite). The same trends apply to the $G_0$ evolution with varying water content: (1) a wide range of variability of $G_0$ for unsaturated soils from full saturation to dry state depending on soil type; (2) different types of soil developing diverse maximum $G_0$ values at dry condition; (3) a nonlinear two-stage development of $G_0$ over the entire range of saturation; and (4) hysteresis of $G_0$ primarily in medium and high water content range. These features or variability characteristics suggest that the $V_s$ or $G_0$ evolution has different principles playing the roles throughout the entire range of saturation.

Meanwhile, recent advancements in understanding soil–water retention behavior allow for better interpretation of the mechanisms behind those observations. Fig. 8 presents some typical soil–water retention curves by the Lu model (Lu 2016), which distinguishes different soil–water regimes based on their distinct soil–water interaction mechanisms. Capillary water interaction primarily dominates in the medium and high range of water content induced by surface tension of the air–water interfaces. Moreover, the adsorption water interaction primarily governs in the low water content range because of van der Waals or Coulomb forces of particle surfaces or exchangeable cations. These two soil–water regimes can now be separated quantitatively by some recent soil–water retention curve models (e.g., Lebeau and Konrad 2010; Revil and Lu 2013; Lu 2016). In Fig. 8, three types of soils (Bonny silt, Hopi silt, and Claystone) with increasing amounts of maximum adsorption water content quantitatively determine the boundaries of adsorption water interaction. Between zero and maximum adsorption water content, the adsorption water governs with capillary coexisting, and beyond that limit capillarity dominates the soil–water interaction.

Furthermore, a conceptual model of the representative elementary volume has been proposed (Dong et al. 2016) by applying the concept of different soil–water regimes to link the stiffness property with the hydrological property of soil–water retention, and to explain the mechanisms of the shear modulus dependency on water content for unsaturated soils. As shown in Fig. 9, the stiffness or shear modulus of unsaturated soils is considered to consist of two parts: the stiffness of material components in soil matrix or particle cluster (primarily responsive for the adsorption water), and the effect of interparticle contact force (primarily responsive for the
Fig. 9. Conceptual mechanisms of contributions of capillary and adsorption water to small-strain shear modulus (reprinted from Dong et al. 2016, © ASCE): (a) adsorption water regime; (b) capillary water regime.

capillary water). The first-part contribution to the shear modulus has been found in a power law in terms of the inverse of degree of saturation (Lu and Kaya 2014); the second part can be represented using suction stress concept and be correlated to soil–water retention (Dong and Lu 2016).

Therefore, the observations of $G_0$ development obey the same principle of the separation of soil–water regimes. As such, different $G_0$ development patterns indicate different soil–water interaction mechanisms. Specifically, Esperance sand and Georgia kaolinite demonstrate a good example for $G_0$ development primarily in the capillary water regime. Esperance sand has little fine soil content, and kaolinite is nonexpansive soil with only particle-surface hydration at very low water content or suction (Lu and Khorshidi 2015). Hence, in the medium and high range of water content (e.g., $\theta > 0.05$), $G_0$ shows a typical development in the capillary water as the water content varies (Fig. 5): an initial increment of $G_0$ around air entry followed by a barely changed plateau of $G_0$ as soil dries, and $G_0$ of wetting always lower than $G_0$ of drying. This feature can also be found in clayey sand Hopi silt in $\theta > 0.20$ in Fig. 6(a). The $G_0$ magnitude of Georgia kaolinite is approximately two orders higher, because of the much smaller particle size and thus stronger capillary effect. In low water content range ($\theta > 0.05$), Esperance sand and kaolinite have little increment of $G_0$ because of the gradual formation of isolated pendular liquid bridge at particle contacts. In contrast, in the medium and low water content range, three silty soils and two expansive clays (Figs. 6 and 7) clearly illustrate that another type of $G_0$ evolution in the adsorption water regime complies with the other mechanism. $G_0$ gradually increases with a decreasing rate as the soil dries. Therefore, the $G_0$ curve forms another bump in the range in which the capillary water gradually diminishes, whereas the adsorption water takes over the dominancy. The boundaries of second bump in the low water content range are also consistent with the amount of maximum adsorption water content, as shown in Fig. 8. At the dry end, $G_0$ increases to an upper-bound value that varies significantly by types of soils. Finally, $G_0$ along wetting follows the same path along drying, and no obvious hysteresis of $G_0$ between drying and wetting can be found in the adsorption water regime.

Summary and Conclusions

In this study, a new technology is presented that is capable of measuring the shear wave velocity and small-strain shear modulus for all types of soils under both variably drying and wetting conditions. Using the low relative humidity and controlled water mist injection environment, various types of soil were tested over a wide range of water content. Bender element technique was incorporated with a soil cake test to monitor the shear wave evolution and record the wave propagation velocity, as the water content varies under the zero total stress conditions. The measured shear wave velocity changes greatly with the water content, and it varies significantly from tens to hundreds of meters per second, or even up to a few thousands of meters per second, as soils change from fully wet to dry. The maximum shear wave velocity of soil at dry state also alters greatly from a few hundreds of meters per second up to 1,800 m/s, depending on the soil types. The small-strain shear moduli for seven soils at different water contents were determined along both drying and wetting paths. It is demonstrated that sandy soil has relatively small variation on $G_0$ over the saturation, whereas silty or clayey soil can develop hundreds of megapascals or even a few gigapascals on $G_0$ when soil is complete dry.

The Lu soil–water retention model, capable of separating the adsorption and capillary water regimes, provides insightful interpretation on the evolution characteristics of $G_0$ with varying water content. The particle-scale conceptual model based on different mechanisms for different soil–water regimes was employed to explain the step-wise nonlinear evolution of $G_0$ along both drying and wetting paths. In the capillary water regime, $G_0$ keeps almost constant except the initial variation around the air entry, because of the formation of the air–water interface. Unlikely, $G_0$ has a separate nonlinear relationship with the adsorption water, in which $G_0$ increases with reducing water content. $G_0$ of the adsorption regime superimposes with the capillary water contribution on $G_0$ and forms another bump on the curves. In the adsorption water regime, the $G_0$ of drying and wetting are more or less identical, whereas in the capillary regime the $G_0$ of wetting is always smaller than that of drying. Therefore, the hydraulic hysteresis of $G_0$ was found to be prominent in the capillary water rather than the adsorption water.

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