

Experimental Study on the Small Strain Shear Modulus of Unsaturated Soils

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Thang Pham Ngoc, declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology at the University of Technology Sydney. This thesis is wholly my own work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis. This document has not been submitted for qualifications at any other academic institution.

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DEDICATION

This thesis is deeply dedicated to the following people:

To my respective parents, Nguyen Thi Thanh & Pham Ngoc Hien

For their sacrifices, endless love, hard work, and inspiration

To my wonderful wife, Ngoc Nguyen Bich

For her constant love, support and caring

To my lovely daughters, Giang Pham Chau & Ha Pham Ngoc

For bringing joy and hope

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ABSTRACT

The small strain shear modulus (G_{max}) is a key parameter in analysing and predicting the dynamic response of soils. Numerous experimental studies have been conducted to investigate G_{max} of unsaturated soils during drying and wetting processes and loading and unloading stages of net stress, however, limitations still exist, requiring more research studies in this field. Specifically, the impact of hydraulic hysteresis, an important characteristic of unsaturated soil experiencing a number of drying-wetting and loading-unloading cycles of net stress, has not been captured successfully. Another issue in existing research studies is that the variation of G_{max} during an air-drying process was measured without considering the effect of matric suction equalisation, resulting in misrepresentation of the response of the material. In addition, the effects of drying-wetting and loading-unloading cycles on G_{max} of cemented soils have received little attention, and thus need to be investigated.

In this study, experimental studies were conducted to address the above-mentioned issues. To investigate the impact of hydraulic hysteresis on G_{max} of an unsaturated reconstituted soil, the specimen was subjected to a multi-stage test during several drying-wetting cycles and a loading-unloading cycle of net stress using a modified unsaturated Rowe cell apparatus. The results revealed four key factors that directly influence the magnitude of G_{max} : the void ratio, the net stress, matric suction and degree of saturation. While variations of the void ratio, net stress, and matric suction cause persistent responses of G_{max} (i.e. if all other factors remain unchanged, G_{max} would then be reversely proportional to the void ratio and directly proportional to the net stress and matric suction), variations in the degree of saturation result in different responses. A decrease in the degree of saturation may induce a reduction or growth of G_{max} since on the one hand, it reduces the effect of matric suction, while on the other hand, it increases the total effect of van der Waals attractions and electric double layer repulsions.

An analysis of the results showed that hydraulic hysteresis occurred in all the stress loops, and it directly influenced the response of G_{max} . The effect of hydraulic hysteresis can only be captured if the van der Waals attractions and electric double layer repulsions are considered. A model to estimate G_{max} while incorporating the van der Waals attractions and electric double layer repulsions has been proposed and it provided a good agreement with the experimental measurements. For practical issues, this model allows the determination of G_{max} of unsaturated soils based on the stress state, void ratio, and degree of saturation regardless of the stress and drying-wetting history, thus improving the accuracy of capturing response of G_{max} in complex loading-unloading and drying-wetting cycles.

To investigate the impact of matric suction equalisation on the measurement of G_{max} during an air-drying process, a weight-controlled bender element test was developed allowing the evolution of G_{max} at each test stage until matric suction equalisation is reached. Test results indicated that excluding matric suction equalisation causes underestimation of G_{max} measurement, especially in the middle range of the degree of saturation. This underestimation could be due to the non-uniform distribution of the water content and the corresponding matric suction across the cross section of the soil sample. The impact of matric suction equalisation on the measurement of G_{max} was rather small in the early stages of the air-drying process but accelerated when degree of saturation approached the threshold corresponding to the shrinkage limit. It was believed that water discontinuity, developed at water content smaller than the shrinkage limit, prevented the hydraulic flow from diminishing the non-uniform distribution of the water content, and thus, caused the underestimation of G_{max} . It was also found that effect of the unsaturated coefficient of permeability on the time required for matric suction equalisation is significant only at high degrees of saturation when the water phase is still continuous, while at lower degrees of saturation, when the water phase loses its continuity, effect of the unsaturated coefficient of permeability is gradually overcome by the effect of

water evaporation. Two empirical equations were proposed to determine the time required for matric suction equalisation in experiments studying behaviours of unsaturated soil after air drying and to predict G_{max} of compacted soil layers near the ground surface which can experience significant evaporation when exposed to the open environment.

To investigate effects of drying-wetting and loading-unloading cycles on G_{max} of cemented soils, a cemented sample cured under a constant stress was subjected to a multi-stage test during several drying-wetting and loading-unloading cycles using the modified unsaturated Rowe cell apparatus. The test results revealed that drying and wetting caused degradation of cementation of lightly cemented soil. The cementation degradation reduced the contribution of cementation and increased the contribution of the stress state to G_{max} . It was observed that, under constant matric suction, drying and wetting also occurred during the loading and unloading stages, respectively, due to the changes of the pore water pressure with loading-induced contraction and unloading-induced swelling. Consequently, degradation of cementation increased with increasing number of drying-wetting cycles as well as loading-unloading cycles. With an increase in the number of drying-wetting and loading-unloading cycles, G_{max} at the high stresses would intensify due to an increase in the contribution of the stress state, while G_{max} at the low stresses would decrease due to the reduction in the contribution of the cementation. In general, small strain shear modulus of lightly cemented soil was influenced by void ratio, cementation, degree of cementation degradation, and stress level. The effects of these influencing factors varied during drying-wetting cycles as well as loading-unloading cycles of net stress, thus, stress-strain history plays an important role in predicting the G_{max} of lightly cemented soils on site.

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NOTATIONS

Latin notations

A	Material constant
b_1	Fitting parameter
b_2	Fitting parameter
c	Fitting parameter
c_k	Permeability change index
$C(\psi)$	Correction function
e	Void ratio
e_{min}	The minimum void ratio at the end of the zero shrinkage stage
e_{ref}	Void ratio at a reference point
$f(e)$	Void ratio function
G_{max}	Small strain shear modulus
G_s	Specific gravity
L	Propagation distance
m	Fitting parameter
m_1	Fitting parameter
m_2	Fitting parameter
n	Soil porosity
N	Net stress
k	Fitting parameter
k_{ref}	Saturated hydraulic conductivity at a reference point
k_s	Saturated hydraulic conductivity
k_w	Unsaturated hydraulic conductivity

p_a	Atmospheric pressure
p_r	Reference pressure
p'	Mean effective stress
S_e	Effective degree of saturation
S_r	Degree of saturation
S_{rs}	Degree of saturation corresponding to the shrinkage limit
S_{r0}	Degree of saturation at saturated state
$S_{r,res}$	Residual degree of saturation
t	Propagation time
t_{se}	Time required for matric suction equalisation
u_a	Pore air pressure
u_w	Pore water pressure
$u_a - u_w$	Matric suction
V_s	Shear wave velocity
W	Gravimetric water content
W_L	Liquid limit

Greek notations

α	Fitting parameter
β	Fitting parameter
γ	Fitting parameter
ρ_{eff}	Effective dynamic mass density
σ_{vn}	Vertical net stress
σ'_v	Vertical effective stress
χ	Effective stress parameter

χ_m	Effective stress parameter for matric suction
χ_s	Effective stress parameter for solute suction
ψ	Matric suction
ψ_r	Residual matric suction

Acronyms

<i>AEV</i>	Air entry value
<i>HAEPD</i>	High air entry value porous disk
<i>LVDT</i>	Linear variable differential transformer
OCR	Over consolidation ratio
<i>SWCC</i>	Soil water characteristic curve

Chapter 1

Introduction

1.1 Background and Problem Statement

Small strain shear modulus, G_{max} , represents the shear stiffness of soils at small shear strains (e.g. 0.001% or less). It is a key parameter in analysing and predicting the response of soil in geodynamic problems. Numerous experimental studies have been conducted to investigate G_{max} of unsaturated soils (Heitor et al. 2013; Hoyos et al. 2011; Khosravi 2011; Khosravi et al. 2010; Khosravi and McCartney 2009; Khosravi and McCartney 2012; Khosravi et al. 2018; Mancuso et al. 2002; Mendoza and Colmenares 2006; Ng and Yung 2008; Oh and Vanapalli 2014; Takkabutr 2007). However, limitations in understanding the behaviour of G_{max} of unsaturated soils still exist, requiring more research studies in this field.

One of the issues which has not been successfully captured in the previous studies is the impacts of drying-wetting and loading-unloading cycles on G_{max} . The problem is that the soil water characteristic curve (i.e. the relationship between water content to matric suction) of a soil subjected to cycles of drying-wetting and loading-unloading is not unique but keep changing depending on the stress-strain history (i.e. hydraulic hysteresis) (Basile et al. 2003; Gallipoli et al. 2003; Likos et al. 2013; Pham 2001; Zakaria 1995). As a result, the matric suction-induced inter-particle force, that is proportional to the degree of saturation (Alonso et al. 2010; Gray and Schrefler 2001; Öberg and Sällfors 1997), also keeps changing with increases in the number of cycles, thus, making the evaluation of the contribution of matric

suction to G_{max} when the hydraulic hysteresis is present quite challenging.

In addition, the contributions of van der Waals attractions (i.e. the intermolecular forces between atoms of adjacent particles) and electric double layer repulsions (i.e. the forces between cations in the electric double layers in the vicinity of particle surfaces) to G_{max} were ignored in most previous studies (Heitor et al. 2013; Hoyos et al. 2011; Khosravi 2011; Khosravi et al. 2010; Khosravi and McCartney 2009; Khosravi and McCartney 2012; Mancuso et al. 2002; Mendoza and Colmenares 2006; Ng and Yung 2008; Oh and Vanapalli 2014; Takkabutr 2007). As reported by Ingles (1962) and Lu and Likos (2006), the combined inter-particle stress induced by van der Waals attractions and electric double layer repulsions is reversely proportion to the degree of saturation, and thus, might have significant effects on mechanical properties of soils in unsaturated states. As the contribution of matric suction and the combined contribution of van der Waals attractions and electric double layer repulsions to G_{max} follow opposing trends with the variation of degree of saturation, separate evaluations of these contributions are needed to capture hydraulic hysteresis effects when soils are subjected to cycles of drying-wetting. Recently, Khosravi et al. (2018) proposed to include the contribution of van der Waals attractions and electric double layer repulsions to G_{max} by adopting the concept of suction stress proposed by (Lu and Likos 2006). However, the suction stress is determined based on the corresponding soil water characteristic curve which is not unique and keeps changing in different stress loops. As a result, the prediction of G_{max} requires to repeatedly determine the soil water characteristic curves for soils subjected to a number of drying-wetting and loading-unloading cycles, which is a very time-consuming task.

Another issue is the measurement of G_{max} during an air-drying process. The problem is that a decrease in water content during an air-drying process leads to a non-uniform distribution of matric suction across the soil sample as the evaporation rate of pore water varies depending on the distance to the sample surface. Normally, a period of time is required to establish and steady

state matric suction (i.e. matric suction equalisation) (Delage et al. 2008; Mancuso et al. 2002; Rampino et al. 1999; Romero et al. 2003; Sivakumar 1993; Wheeler and Sivakumar 1995). The state of matric suction equalisation can be determined by continuously measuring matric suction, however, high matric suctions, possibly approaching hundreds of thousands kilopascal, developed at low water contents, prevents the measurement of matric suction using hydraulic tensiometers or similar devices. In previous experiments, conducted by Cho and Santamarina (2001) and Dong and Lu (2016), only relationship between G_{max} and water content during air-drying processes was investigated while the determination of matric suction equalisation time was not mentioned. As matric suction directly influences the magnitude of G_{max} , ignoring matric suction equalisation potentially leads to misrepresentation of the response of material.

The behaviour of G_{max} of structured (or cement treated) soils subjected to cycles of drying-wetting also requires further studies. A number of experiments have been conducted to investigate the effects of different factors on G_{max} of cement-treated soils including void ratio, moulding water content, confining pressure, particle properties, cement type, and cement content (Acar and El-Tahir 1986; Bahador and Pak 2012; Baig et al. 1997; Chiang and Chae 1972; Clough et al. 1981; Consoli et al. 2012; Fernandez and Santamarina 2001; Flores et al. 2009; Lovelady and Picornell 1990; Rinaldi and Santamarina 2008; Saxena et al. 1988; Trhliková et al. 2012; Yang 2008; Yang and Woods 2014; Yun and Santamarina 2005). However, the impacts of drying-wetting cycles on G_{max} have received limited attention, even though the literature review shows significant effects of these cycles on mechanical properties of cemented soils including strength and permeability (Li et al. 2014; Neramitkornburi et al. 2015; Wang et al. 2018; Zhang and Tao 2008). It was reported in the experiment conducted by Liu et al. (2018) that drying and wetting both caused the development of crack network within the soil mass due to uneven shrinkage and swelling. Formation of cracks could be the cause of

the increases in mass loss and structure failure with increasing number of drying-wetting cycles in experiments conducted by Li et al. (2014) and Neramitkornburi et al. (2015). It is evident that drying and wetting cycles can result in notable degradation of cementation, and thus, reduce the contribution of cementation on G_{max} . As in practice, a great proportion of cement-treated soils or naturally occurring structured soils are being subjected to endless drying-wetting cycles when exposed to the open air, it is of importance to understand the small strain response of cemented or structured soils to drying-wetting or loading-unloading cycles.

1.2 Research Objectives and Scope

In this research, experimental studies on the small strain shear modulus of unsaturated soils were conducted with the following specific research objectives:

1. To investigate the impacts of drying-wetting and loading-unloading cycles on G_{max} of a reconstituted soil sample in a multi-stage unsaturated test using a modified Rowe cell apparatus. The shear wave velocity was measured for the evaluation of the corresponding G_{max} at any stage of the test. The soil sample was subjected to different types of stress loops including three drying-wetting cycles and a loading-unloading cycle of net stress in an attempt to investigate the variations of G_{max} at the same stress states (i.e. the same matric suction and net stress) with the variations of void ratio and degree of saturation in these stress loops. By nullifying the effect of void ratio, the experiment was capable of investigating the effects of matric suction and degree of saturation on G_{max} simultaneously, and thus, unveiled the contributions of van der Waals attractions and electric double layer repulsion to G_{max} .
2. To establish a predictive model for G_{max} incorporating the contributions of van der Waals attractions and electric double layer repulsion to capture the effect of hydraulic

hysteresis. The proposed model was verified against the experimental results in this study as well as data available in the literature for different soils during cycles of drying-wetting and loading-unloading of net stress.

3. To investigate the impact of matric suction equalisation on the measurement of G_{max} during an air-drying process. A weight-controlled bender element setup was developed to control the exchange of water vapour between the sample and the surrounding environment. In an air-drying stage, pore water vapour was allowed to exchange freely with the surrounding environment, while in a matric suction equalisation stage, pore water vapour was allowed to redistribute in a closed soil system. Comparisons between measurements of G_{max} in air-drying and matric suction equalisation stages were conducted highlighting the importance of matric suction equalisation while conducting laboratory experiments.
4. To understand different responses of G_{max} of soil at high and low ranges of water content during an air-drying, and to determine factors impacting the time required for matric suction equalisation t_{se} . Apart from a series of weight-controlled bender element tests on soil samples with different diameters, shrinkage, filter paper, and saturated permeability tests were also conducted to capture the variations of void ratio, matric suction, and hydraulic conductivity. Results of the experiments were used to establish and verify empirical models for evaluations of G_{max} and t_{se} .
5. To understand the behaviour of G_{max} of a lightly cemented soil subjected to cycles of drying-wetting and loading-unloading of net stress. Using the modified Rowe cell apparatus, the cement-treated sample was subjected to a drying-wetting cycle before applying three loading-unloading cycles of net stress which was followed by another two

drying-wetting cycles. The main purpose of the experiment was to unveil the effects of cement degradation induced by non-uniform contractions and swellings during drying and wetting processes impacting the contribution of stresses to measured G_{max} in subsequent loading-unloading and drying-wetting cycles.

1.3 Thesis Outline

This thesis consists of six chapters and outlines of these chapters are as follows:

- Chapter 1 presents the introduction and outlines of the thesis
- Chapter 2 delivers a comprehensive literature review focusing on stress state of unsaturated soils, effects of degree of saturation, hydraulic hysteresis, and cementation on G_{max} , and predictive models for G_{max} of unsaturated soils.
- Chapter 3 reports the experimental results for the impacts of drying-wetting and loading-unloading cycles on G_{max} of unsaturated soils. The development and verification of the predictive model for G_{max} are also presented.
- Chapter 4 describes the laboratory test results concerning the impacts of matric suction equalisation on G_{max} of soils during air-drying. New empirical models for predictions of G_{max} and the time required for matric suction equalisation, t_{se} , are also presented.
- Chapter 5 presents the results of a series of experiments to evaluate G_{max} of unsaturated lightly cemented soil subjected to cycles of drying-wetting and loading-unloading of net stress.
- Chapter 6 presents the summary and conclusions from this experimental study, and provides some recommendations for future research.

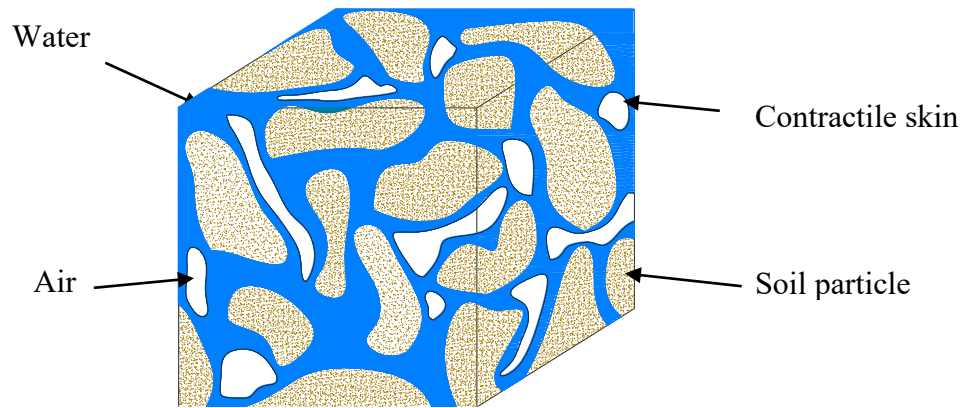
Chapter 2

Literature Review

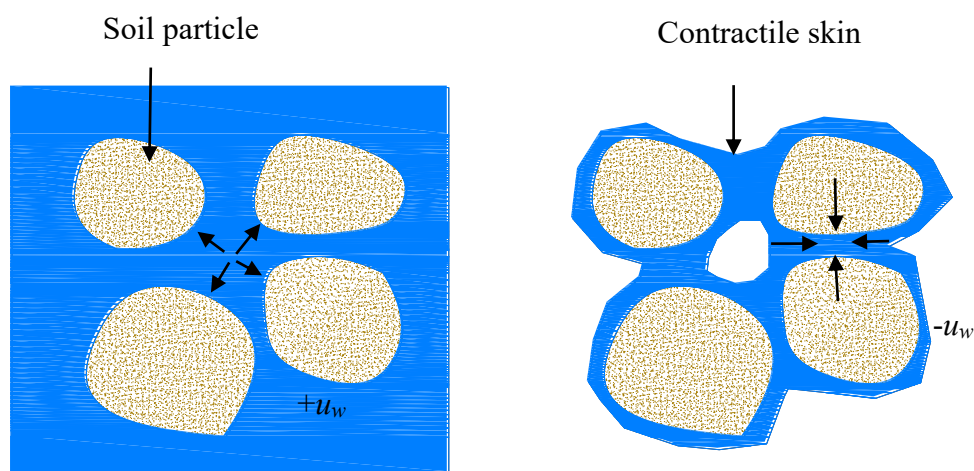
2.1 Stress state variables for unsaturated soils

2.1.1.State of stress of unsaturated soils

The characterisation of stress state is needed to model the mechanical behaviour of soils. Soil is a multi-phase porous medium and therefore various phases influence the soil stress state (Alonso et al. 2010; Fredlund et al. 1993; Khalili and Khabbaz 1998; Wulfsohn et al. 1996). Unlike two-phase saturated soils with solid and liquid phases denoting soil particles and pore water, unsaturated soil was initially considered as a three-phase system (Fredlund et al. 1993; Lambe and Whitman 1969) with the additional presence of air within the pore network, or a four-phase system (Fredlund and Morgenstern 1977) when considering the influence of the air-water interface (i.e. the contractile skin). As pore water pressure is smaller than pore air pressure in unsaturated soils (i.e. negative pore water pressure), the difference between pore water and pore air pressure (i.e. matric suction) applies a tensile pull at contractile skins. The surface tension on the contractile skins resists the force and consequently tends to pull soil particles together, providing additional normal stresses between particles (Fredlund et al. 1993). Elements of four-phase unsaturated soil and the effect of negative pore water pressure in comparison with that of positive pore water pressure are presented in Fig. 2. 1.



(a)



Positive pore water pressure reduces
strength of saturated soil

Suction increases strength
of unsaturated soil

(b)

Fig. 2. 1 (a) Elements of unsaturated soil (modified after Fredlund and Morgenstern 1977) and (b) effect of pore pressure on stress state of unsaturated soil (modified after Wulfsohn et al. 1996)

While Terzaghi's effective stress (i.e. the difference between external stress and pore water pressure) is widely accepted for characterising stress state of saturated soil, stress state

variables of unsaturated soil is still a controversial issue with the single effective stress variable and the two independent stress state variable approaches being the most well-known.

2.1.2. Single effective stress variable approach

Many attempts have been made to introduce an equivalent single effective stress, similar to Terzaghi's effective stress used for saturated soils, with only one stress state variable to characterize the stress state of unsaturated soil. For example, Croney et al. (1958) proposed the following equation:

$$\sigma' = \sigma - \beta' u_w \quad (2.1)$$

where σ' is effective stress, σ is external stress, u_w is pore water pressure, and β' is bonding factor evaluating the number of bonds of water under tension contributing to the stress state of soil.

Aitchison (1961) suggested the following equation based on a capillary model:

$$\sigma' = \sigma + \Psi(u_a - u_w) \quad (2.2)$$

where Ψ is a parameter related to the degree of saturation of the soil with values, ranging from zero to one. Jennings (1961) proposed a similar equation with Ψ being considered as a statistical factor and measured via experiments. Some authors attempted to include osmotic suction (i.e. solute suction) into the effective stress equation, such as in Eq (2.3) by Richards (1967) and Eq (2.4) by Aitchison (1973).

$$\sigma' = (\sigma - u_a) + \chi_m(h_m + u_a) + \chi_s(h_s + u_a) \quad (2.3)$$

$$\sigma' = (\sigma - u_a) + \chi_m p_m'' + \chi_s p_s'' \quad (2.4)$$

where h_m and p_m'' are matric suction, h_s and p_s'' are osmotic suction, χ_m and χ_s are effective stress parameters for matric and osmotic suctions, respectively.

To date, the most widely adopted effective stress equation was introduced by (Bishop 1959):

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \quad (2.5)$$

where u_a is the pore air pressure, and χ is a parameter related to the degree of saturation of the soil, with a value of unity for saturated soils and zero for dry soils, and $u_a - u_w$ is matric suction. A number of equations have been proposed to estimate χ , such as Eq (2.6) by Schrefler (1984), Eq (2.7) by Vanapalli et al. (1996), Eq (2.8) by Khalili and Khabbaz (1998), and Eq (2.9) by Pereira et al. (2010):

$$\chi = S_r \quad (2.6)$$

where S_r is the degree of saturation;

$$\chi = \frac{\theta_w - \theta_r}{\theta_s - \theta_r} \quad (2.7)$$

where θ_w is the volumetric water content, θ_r is the saturated volumetric water content, and θ_r is the residual volumetric water content;

$$\chi = \begin{cases} \left[\frac{(u_a - u_w)}{(u_a - u_w)_b} \right]^{-0.55} & \text{if } s > (u_a - u_w)_b \\ 1 & \text{if } s \leq (u_a - u_w)_b \end{cases} \quad (2.8)$$

where $(u_a - u_w)_b$ is the air entry value, also called the bubbling pressure, corresponds to the matric suction, above which air starts to invade into the soil pores;

$$\chi = S_e = \frac{S_r - S_{r,m}}{1 - S_{r,m}} \quad (2.9)$$

where S_e is effective degree of saturation; $S_{r,m}$ is micro degree of saturation, corresponding to the degree of saturation of only water in micropores which has negligible influence on the capillary phenomena.

It is noted that the determination of the effective stress parameter (χ) relates to the pore size distribution of unsaturated soil which is altered during drying-wetting cycles. In addition, current single effective stress approaches exclude the presence of stresses generated by van der Waals attraction and electric double repulsion, though these stresses play an important role in the mechanical behaviour of unsaturated fine-grained soils (Lu and Likos 2006). According to Ingles (1962) and Lu and Likos (2006), the contribution of the combined inter-particle stress generated by van der Waals attraction and electric double repulsion to stress state of unsaturated soils is reversely proportional to degree of saturation. On the contrary, the contribution of a given matric suction to stress state of unsaturated soils is proportional to degree of saturation (Alonso et al. 2010; Gray and Schrefler 2001; Öberg and Sällfors 1997). This indicates that when hydraulic hysteresis presents these contributions should be evaluated separately, and thus, raising the limitation of the single effective stress approach in capturing the effect of hydraulic hysteresis.

2.1.3. Two independent stress state variable approach

Based on the argument that stress state variable should be independent of the material properties, Fredlund and Morgenstern (1977) characterised the stress state in unsaturated soils in terms of two independent variables: net stress ($\sigma - u_a$) and matric suction ($u_a - u_w$). These variables are physically measurable quantities and easily controlled in laboratory experiments. Verification of the proposed stress state variables was conducted experimentally in “null” tests by Fredlund and Morgenstern (1977). In these tests, stress components (σ , u_a , and u_w) were varied equally to maintain constant values of net stress ($\sigma - u_a$) and matric suction ($u_a - u_w$). The results showed essentially no overall volume change or water flow as expected, indicating no change in the overall equilibrium of the soil mass, and hence proved the validity of the approach in describing behaviour of unsaturated soil.

Since the two independent stress state variable approach evaluates effects of net stress and matric suction separately, it is convenient to evaluate the effect of matric suction on the mechanical behaviour of unsaturated soils in experiments. Based on this approach, a number of empirical equations have been proposed to capture the contribution of matric suction to G_{max} of unsaturated soils by Sawangsuriya (2006), Sawangsuriya et al. (2009), and Heitor et al. (2013). However, these equations still fail in capturing the hydraulic hysteresis due to not evaluating the contribution of van der Waals attraction and electric double repulsion to G_{max} . One of the objectives of this study is to expand the two independent stress state variable approach to separately evaluate not only the contributions of net stress and matric suction but also the combined contribution of van der Waals attraction and electric double repulsion to G_{max} of unsaturated soils subjected to a number of cycles of drying-wetting and loading-unloading.

2.1.4. Summary

As one of the objectives of the study was to investigate behaviour of G_{max} of soil subjected to drying-wetting cycles with the presence of hydraulic hysteresis, two independent stress state variable approach was used to interpret experimental data as well as establish the predictive model.

2.2 Measurement of soil suction using filter paper test

2.2.1 Components of soil suction

According to Krahn and Fredlund (1972), soil suction, i.e. total suction, is the negative gauge pressure relative to the external gas pressure on the soil water, to which a pool of pure water must be subjected in order to be in equilibrium with the soil water through a semipermeable membrane (i.e., allows only water molecules going through). Soil suction consists of two components, including osmotic suction (ψ_o) and matric suction (ψ_m).

When the soil water is pure water, matric suction is equal to the total suction, and therefore can be computed as the difference between pore air and pore water pressures. Matric suction is commonly associated with the capillary phenomenon within pores with small radii due to the surface tension on the air-water interface. An increase of matric suction causes a decrease in the curvature of the air-water interface, extracting water from soil pores, and vice versa.

When pore air and pore water pressures are equal, osmotic suction is equal to the total suction, and can be defined as the negative gauge pressure, to which a pool of pure water must be subjected in order to be in equilibrium through a semipermeable membrane with a pool containing a solution identical in composition with the soil water. Osmotic suction is related to the salt content in the soil water; its presence causes decrease in the water vapour pressure and has no contribution to the capillary phenomena (Fredlund et al. 1993).

2.2.2 Effect of matric and osmotic suctions on mechanical behaviour of unsaturated soils

Soil suction directly impacts stress state of water phase and air-water interface in the soil mass (Fredlund et al. 1993). Hence, any changes in matric and/or osmotic suction will result in new equilibrium states through the interaction between all phases in the system. In an experiment on unsaturated dense sand-bentonite by Tang et al. (1997), opposing effects on shear strength of matric suction and osmotic suction were observed. Specifically, increases of osmotic suction produced small decreases of shear strength and stiffness, whereas the same increases of matric suction lead to larger increases in shear strength and stiffness.

Krahn and Fredlund (1972) investigated the variation of matric suction, osmotic suction, and total suction when water content was varied. Fig. 2.2 shows negligible changes of osmotic suction with variations of water content, indicating that the change of total suction can be substituted by the change of matric suction, and vice versa. For most practical issues, osmotic suction can be ignored except for cases where the salt content of the soil is varied by chemical contamination (Fredlund et al. 1993).

In general, the presence of soil suction and its dependence on water content makes mechanical properties of unsaturated soil, including strength, stiffness, permeability, shrinkage, and swelling become water content dependent. As there is no unique relationship between matric suction and water content for a given soil, both matric suction and water content need to be taken into account in studying the mechanical behaviour of unsaturated soils.

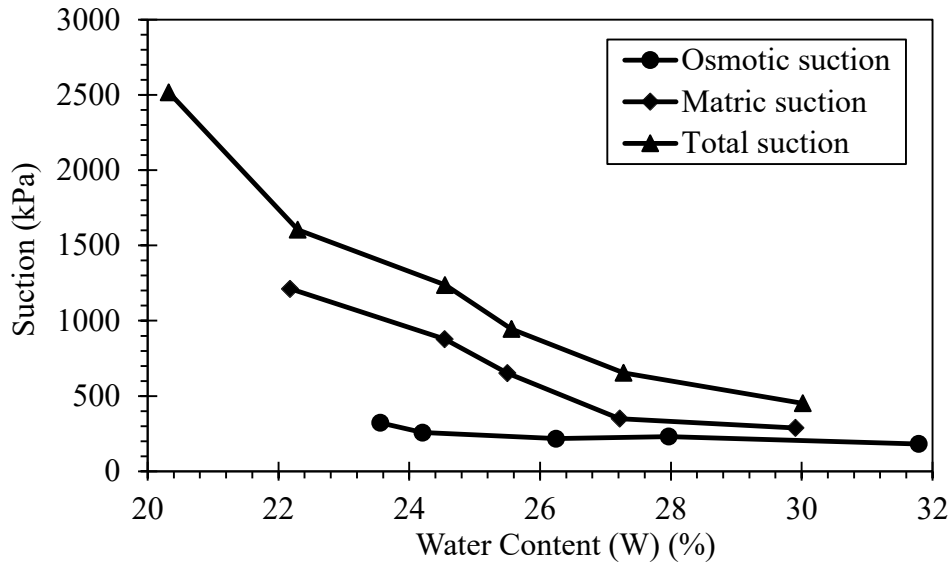


Fig. 2. 2 Total, matric, and osmotic suction measurements on compacted Regina clay (after Krahn and Fredlund 1972)

2.2.3 Filter paper test

Filter paper test is an indirect method of measuring soil suction using a filter paper calibration curve of water content versus suction. It is inexpensive, relatively simple and the only method that covers the full range of suction, in comparison with other tests such as thermocouple psychrometers, tensiometer, thermal conductivity sensors and the axis-translation apparatus (Leong et al. 2016; Likos and Lu 2002). Filter paper test can measure both total and matric suctions. Total suction is measure if the filter paper is allowed to absorb water through vapour flow until equilibrium with the soil specimen is obtained without any contact (non-contact method) within a small moisture-tight jar under constant temperature. If the filter paper is allowed to absorb water through fluid flow by sandwiching the filter paper between two specimens (contact method), only matric suction is measured (Fig. 2.3). After equilibrium is established between the filter paper and the specimen, the water content of the filter paper is measured, and the corresponding suction value is determined from the filter paper calibration curve for the used type of filter paper. Osmotic suction is then computed as the difference

between total and matric suction. The experimental procedure of the test is provided in ASTM D5298–16 (2016) with the filter paper calibration curves for Whatman No. 42 and Schleicher & Schuell No. 589 filter papers being presented in Fig. 2.4.

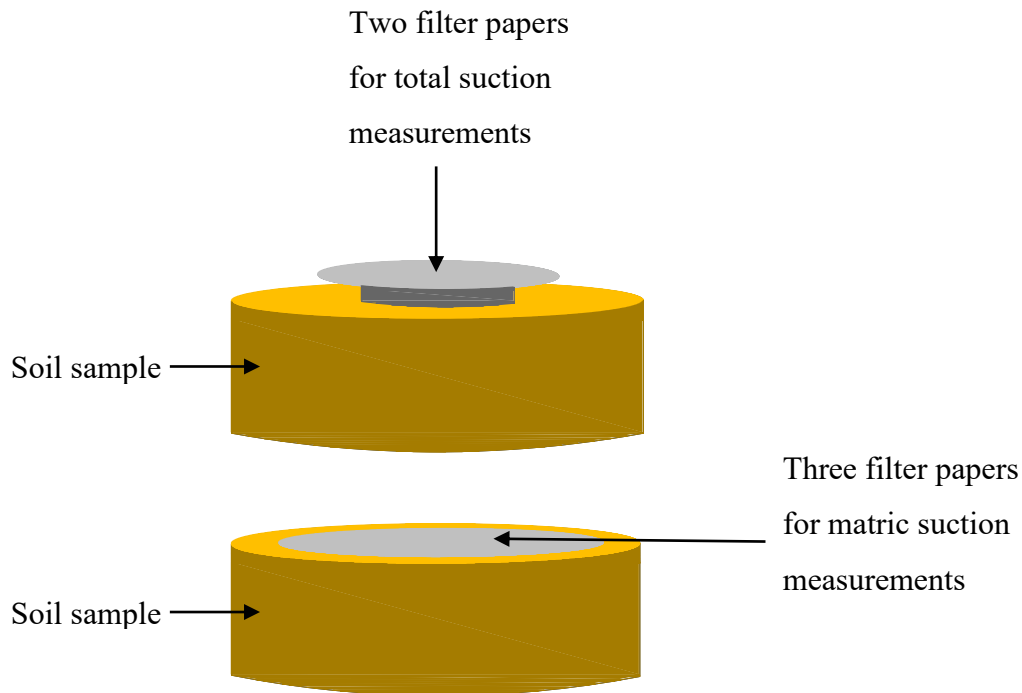


Fig. 2. 3 Contact and non-contact filter paper methods for measuring total and matric suction
(after Bulut et al. 2001)

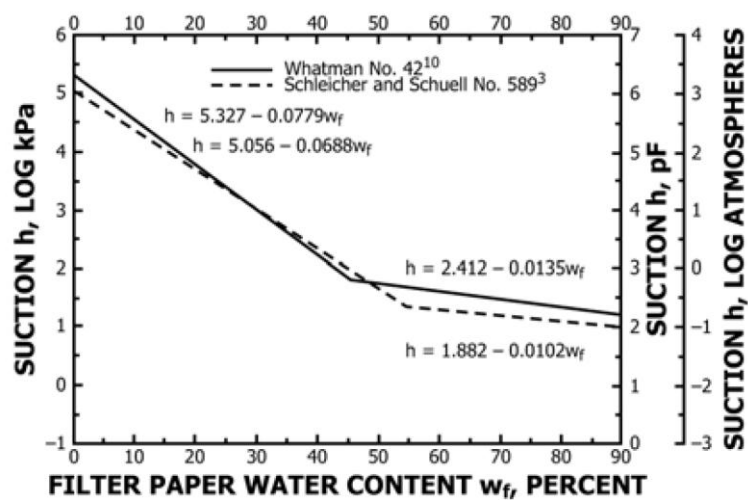


Fig. 2. 4 Calibration curves for two types of filter papers (ASTM D5298 2016)

2.3 Measurement of G_{max} using bender elements test

A basic bender element test uses two bender elements to generate and receive shear or compression waves. A bender element consists of two piezoceramic plates that are rigidly bonded to a central metallic plate. Two thin conductive layers (electrodes) are applied externally to the bender element. As explained by Strassburger (1982), applying a voltage will cause the polarization of them, causing one plate to elongate and the other to shorten so that the element bends and shear waves are generated at the free end of the bender element as illustrated in Fig. 2.5.

In order to measure small strain shear modulus of soil sample using bender elements test, two bender elements are put at the top and bottom of the sample; one acts as shear wave transmitter, while the other acts as the receiver. The shear wave velocity is determined using Eq (2.10):

$$V_s = \frac{L}{t} \quad (2.10)$$

where L is the effective distance between two signal measurement points and can be taken as the distance between the tips of the bender elements, t is the travel time (propagation time) for the shear wave. Small strain shear modulus is then computed using Eq (2.11):

$$G_{max} = \rho_{eff} V_s^2 \quad (2.11)$$

where, ρ_{eff} is soil effective dynamic mass density.

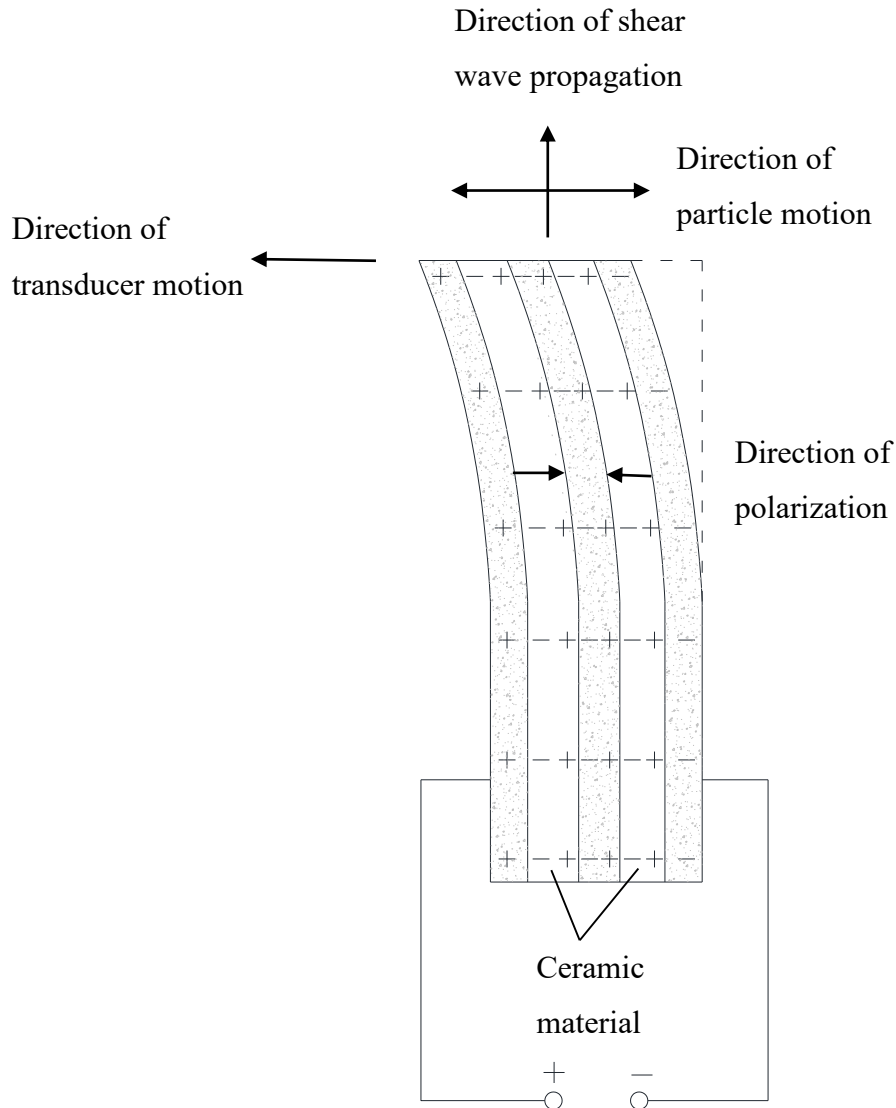


Fig. 2. 5 Schematic diagram for a bender element (after Strassburger 1982)

2.4 Axis-translation apparatus used in investigating unsaturated soil

One of the problems in applying negative pore water pressures to create high matric suction under atmospheric pressure is to avoid cavitation phenomena, i.e. the formation of vapour bubbles in a body of water, within the pore water measurement system at negative pore water pressure. The state of water under tension is thermodynamically metastable (Debenedetti 1996), at which tiny amounts of pre-existent gas would be rapidly separated forming air bubbles. As it is impossible to completely remove air, which possibly exists in crevices of soil

particles, crevices of the wall of the water container, porous stone, etc., from water in a test system, cavitation is unavoidable at high negative pore water pressures. According to Fredlund et al. (1997), cavitation of water occurs at a negative pressure approaching 1 atmosphere (i.e. 101.3 kPa). Axis-translation technique was proposed by Hilf (1956) enabling the application of high matric suction under positive pore water pressure, and therefore preventing the occurrence of cavitation phenomena. The method involves the translation of the reference pore air pressure from standard atmospheric conditions to a higher air pressure value. By increasing pore air pressure, pore water pressure will also increase correspondingly, keeping the difference between the pore air and pore water pressure (i.e. matric suction) constant, provided that pore water is essentially incompressible (Bocking and Fredlund (1980). This technique has been experimentally evaluated by Fredlund and Morgenstern (1977) and Tarantino et al. (2000), and proven to be a reliable method for controlling matric suction.

In order to keep matric suction constant during tests, a high air entry value ceramic disk, which allows water to flow through while preventing the air flow provided that its air entry value pressure is not exceeded, is placed at the bottom of the sample to separate water source from pore air pressure. When matric suction exceeds the air entry value of the disk, air starts to freely flow through the disk, altering pressure and volume of the source water. Hence, the maximum matric suction can be applied using axis-translation technique depends on the air entry value of the ceramic disk. Typical high air entry value disks used in unsaturated soil testing devices are rated for air entry value of 1, 3, 5, and 15 bar.

Axis-translation setups are devices used to apply and control matric suction during testing for unsaturated soils based on axis-translation technique. As reported by Hilf (1956), Vanapalli et al. (2008), Ng and Yung (2008), and Kawajiri et al. (2010), in order to investigate shear modulus at small strain for unsaturated soils under different net stresses and matric suctions,

conventional triaxial cell and oedometer cell were modified by replacing the normal porous stone at the bottom of the sample by a high air entry value ceramic disk, and providing an air source at the top of the sample. In these setups, pairs of bender elements could be fixed at the two ends and/or at the mid-height of the sample. Examples of modified triaxial cell and modified oedometer cell are depicted in Fig. 2.7, and Fig. 2.8, respectively.

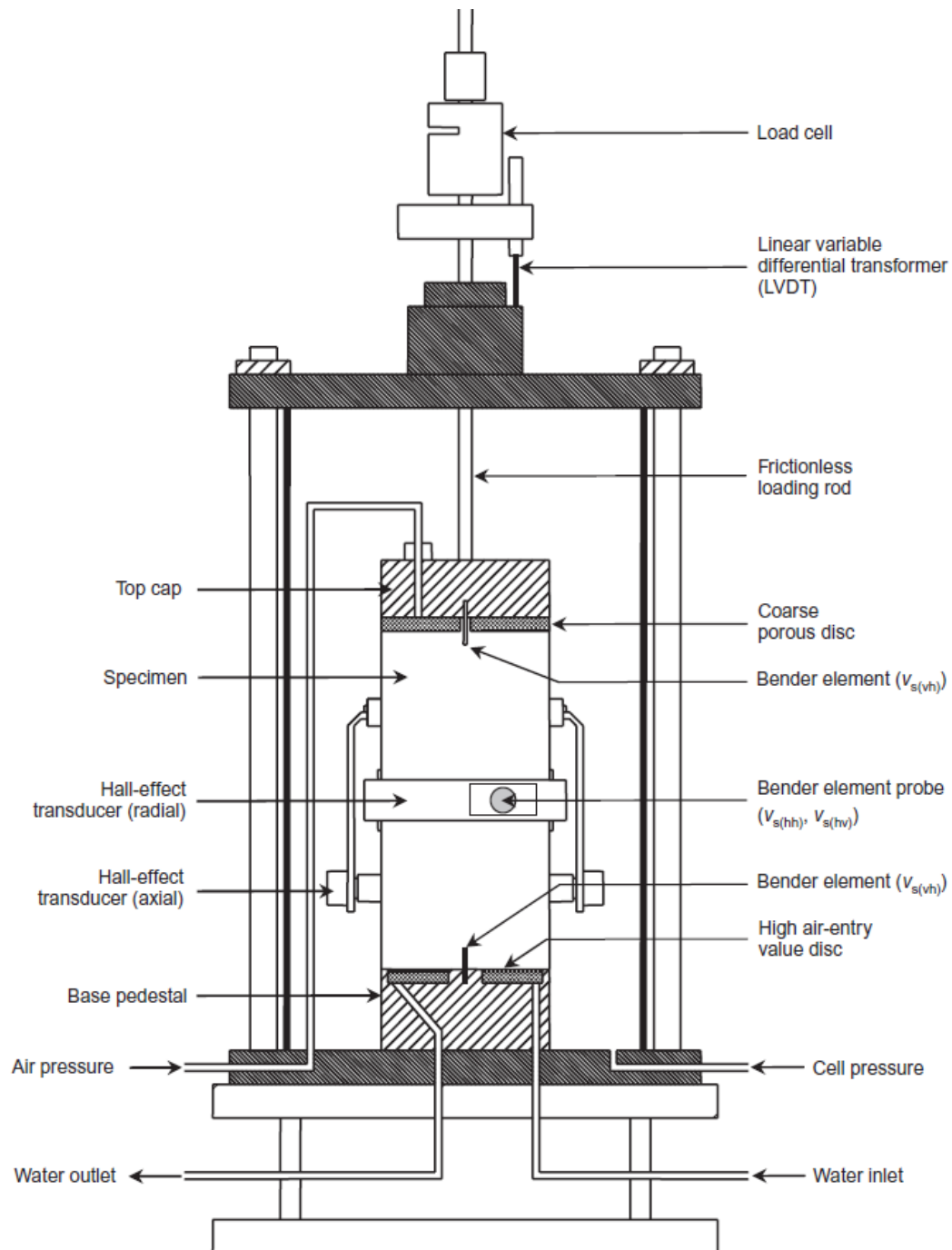


Fig. 2.6 Schematic diagram of modified triaxial apparatus (Ng and Yung 2008)

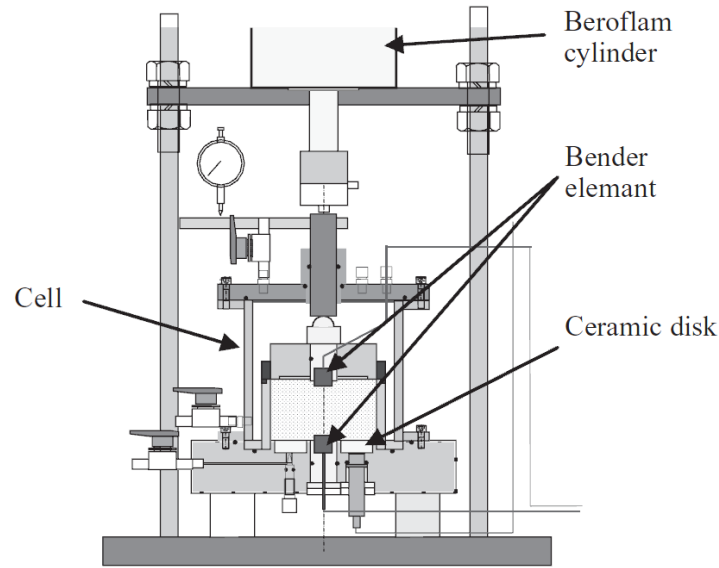


Fig. 2. 7 An oedometer type apparatus (Kawajiri et al. 2010)

2.5 Hydraulic hysteresis behaviour of unsaturated soils

Hydraulic hysteresis of unsaturated soil denotes the dependence of water content on the stress state history. It has been widely observed during wetting-drying cycles in numerous experiments on various types of soils (e.g. Bear and Bachmat 1991; Gallage et al. 2013; Gillham et al. 1976; Pham et al. 2005). A typical relationship between water content and matric suction during wetting-drying cycles is presented in Fig. 2.9.

Observations of hydraulic hysteresis under a loading-unloading cycle at constant suction were also reported by Zakaria (1994) and Gallipoli et al. (2003) for compacted speswhite kaolin in suction-controlled triaxial tests, and by Pham et al. (2004) for slurry processed silt in one-dimensional tests using GCTS pressure plate. In these tests, loading (unloading) stages were conducted by increasing (decreasing) the external stress (i.e. cell pressure in triaxial tests and vertical pressure for GCTS pressure plate tests), while pore water and pore air pressure were kept unchanged. For both speswhite kaolin and processed silt, degree of saturation experienced remarkable increases in loading stages, and slight rises in unloading stages, whereas

gravimetric water content experienced substantial declines in loading stages, and slight increases in unloading stages.

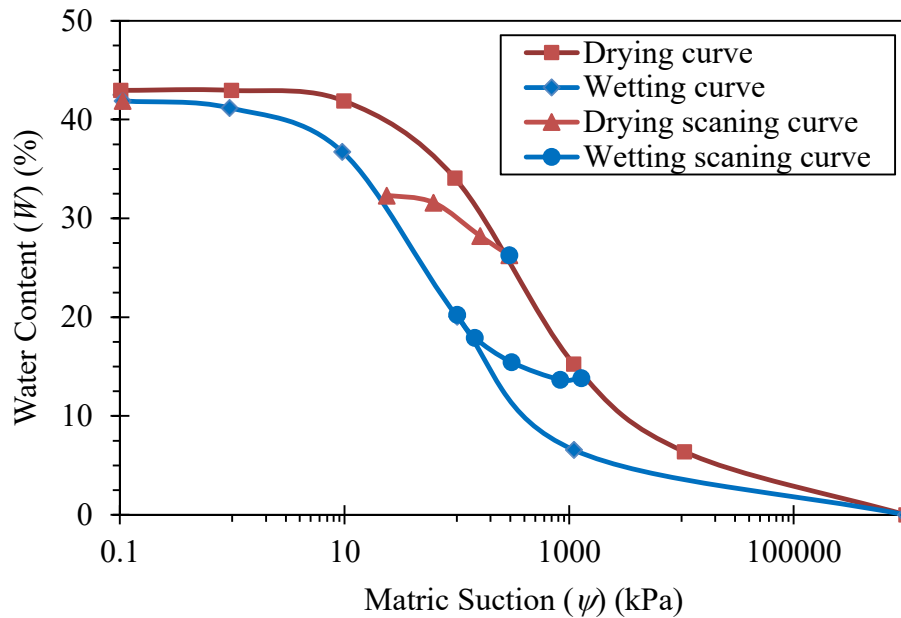


Fig. 2. 8 Soil water characteristic curves during wetting-drying cycles (after Fredlund 2000)

2.5.1 Causes of hydraulic hysteresis

Several possible causes have been proposed to explain the hydraulic hysteresis behaviour of unsaturated soils during a wetting-drying cycle. The first, called the ink-bottle effect, as explained by Tuller and Or (2004) and Fredlund et al. (2012), stems from the nonhomogeneous pore size distribution, with numerous pores connecting to each other through smaller ones (throats). In capillary phenomena, it is well established that the smaller the pore diameter, the higher matric suction it can hold. Thus, during drying, the highest matric suction that a pore can hold depends on the diameter of its throat; on the other hand, to refill the pore, matric suction needs to reduce to a lower value corresponding to the largest diameter of the pore. As a result, during wetting some pores will no longer be filled with water even though they had been filled at the same matric suction in the previous drying (Fig. 2.10a).

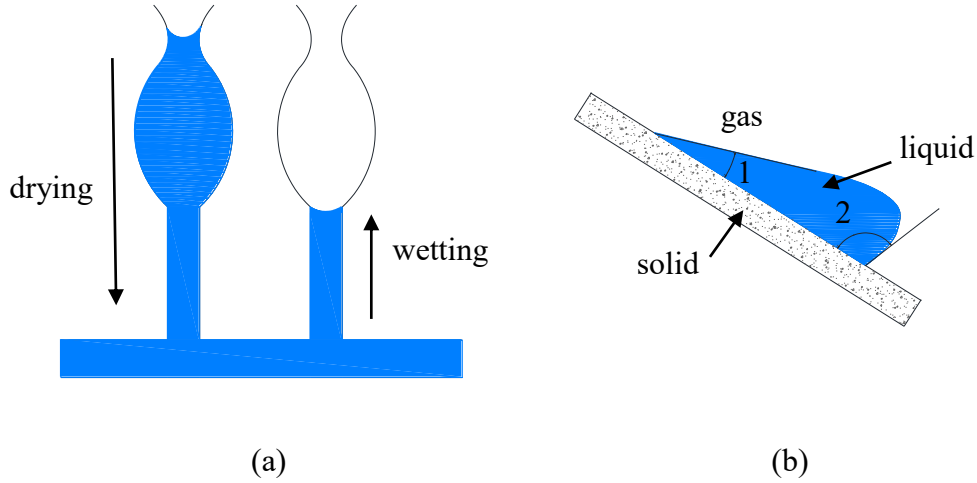


Fig. 2. 9 Causes of hydraulic hysteresis: (a) ink bottle effect and (b) contact angle effect (after Tuller and Or 2004)

The second cause is the difference between drying and wetting contact angles of water with soil particles (Fig. 2.10b), with the later always greater than the former, which has been attributable to the roughness of particle surface and the existence of surface active substances (Marshall et al. 1996). Hysteresis of contact angle leads to variations of curvature of the water meniscus, and of corresponding water content. Air entrapment during rewetting also results in reductions of water content in comparison with that in the previous drainage. Due to the formation of occluded air bubbles, unsaturated states have been observed even at zero matric suction on the main wetting curve in experiments by Fredlund and Pham (2006), Alsherif et al. (2015), and Krisnanto et al. (2016).

2.5.2 Effect of hydraulic hysteresis on G_{max}

Different responses of G_{max} during drying and wetting processes were observed in experimental studies by Ng et al. (2009), Khosravi (2011), and Dong and Lu (2016) as presented from Fig. 2.11 to Fig. 2.13. These figures reveal that response of G_{max} for most types of soils is significantly influenced by hydraulic hysteresis, especially at the high range of water content

(i.e. low range of matric suction). Interestingly, the magnitude of G_{max} during wetting stage seems always to be higher than that during the previous drying stage for tests conducted in axis-translation setup, while the opposing trend was observed in tests where matric suction was controlled by relative humidity.

Hydraulic hysteresis was also observed for unsaturated soils subjected to loading-unloading of net stresses. As reported by Biglari et al. (2012) after a cycle of loading-unloading, degree of saturation was reported to obtain significant increases that might have contributed to the variation of G_{max} as shown in Fig. 2.14. The increases of degree of saturation should be attributed to the change in the pore size distribution induced by the irreversible reductions of the void ratio during the loading-unloading cycle as reported by Ho et al. (1992), Alonso et al. (2005), and Biglari et al. (2012).

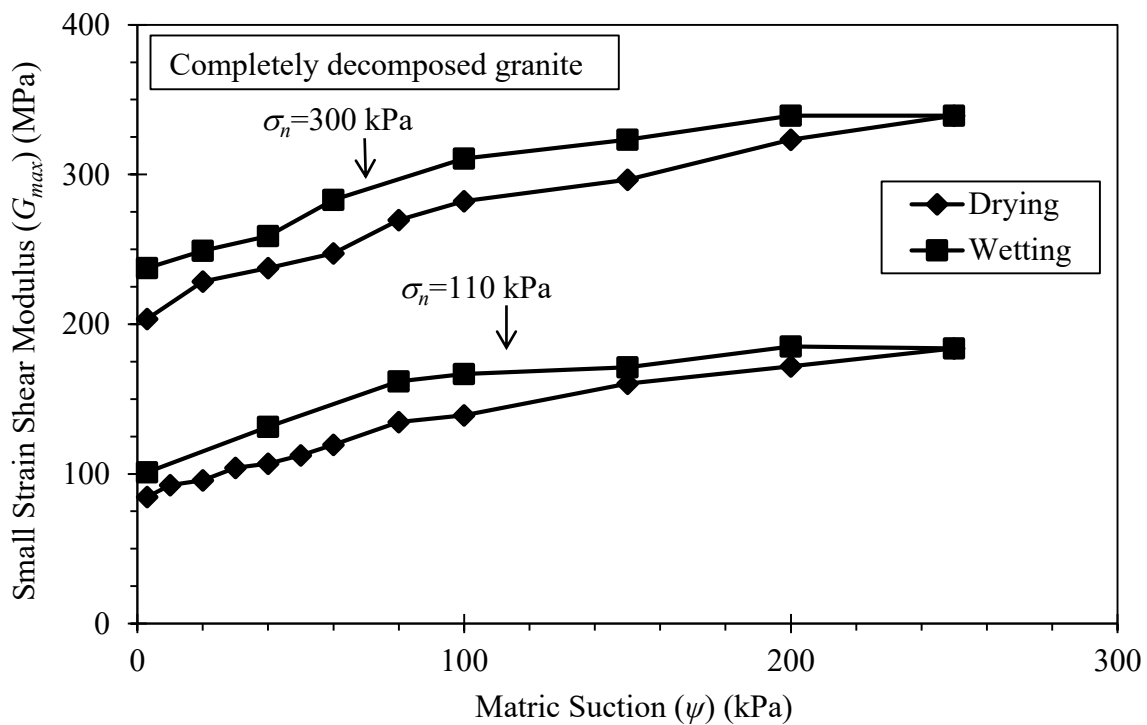


Fig. 2. 10 Responses of G_{max} of Completely decomposed granite subjected to drying-wetting cycles at different net stress (plotted using data from Ng et al. 2009)

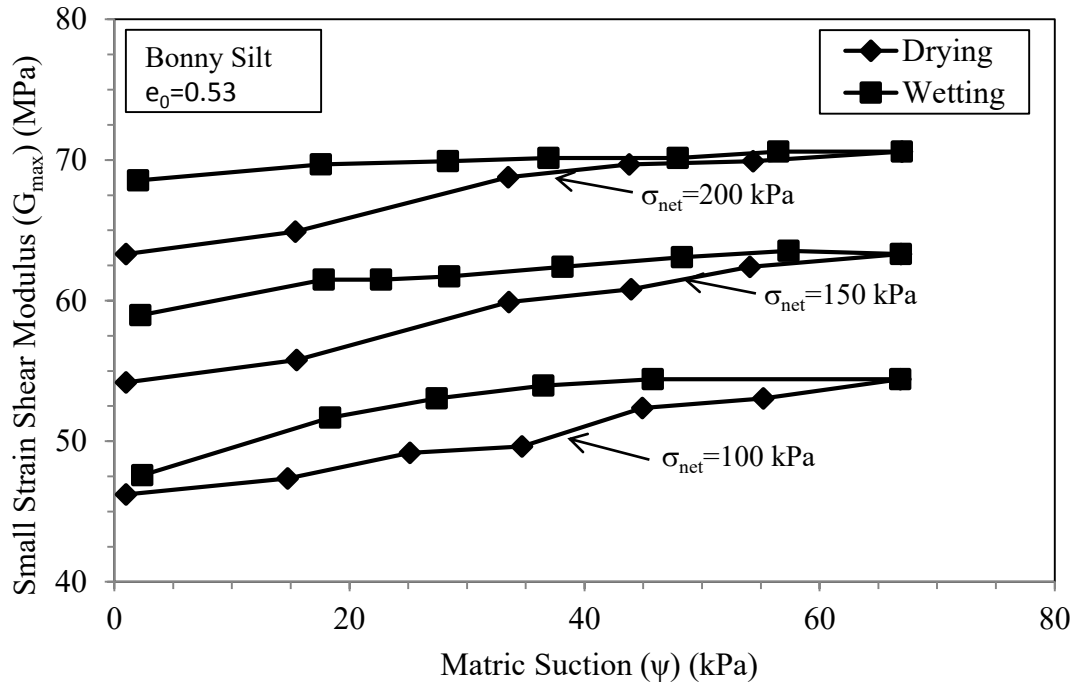


Fig. 2. 11 Responses of G_{max} of compacted Bonny silt subjected to drying-wetting cycles
(plotted using data from Khosravi 2011)

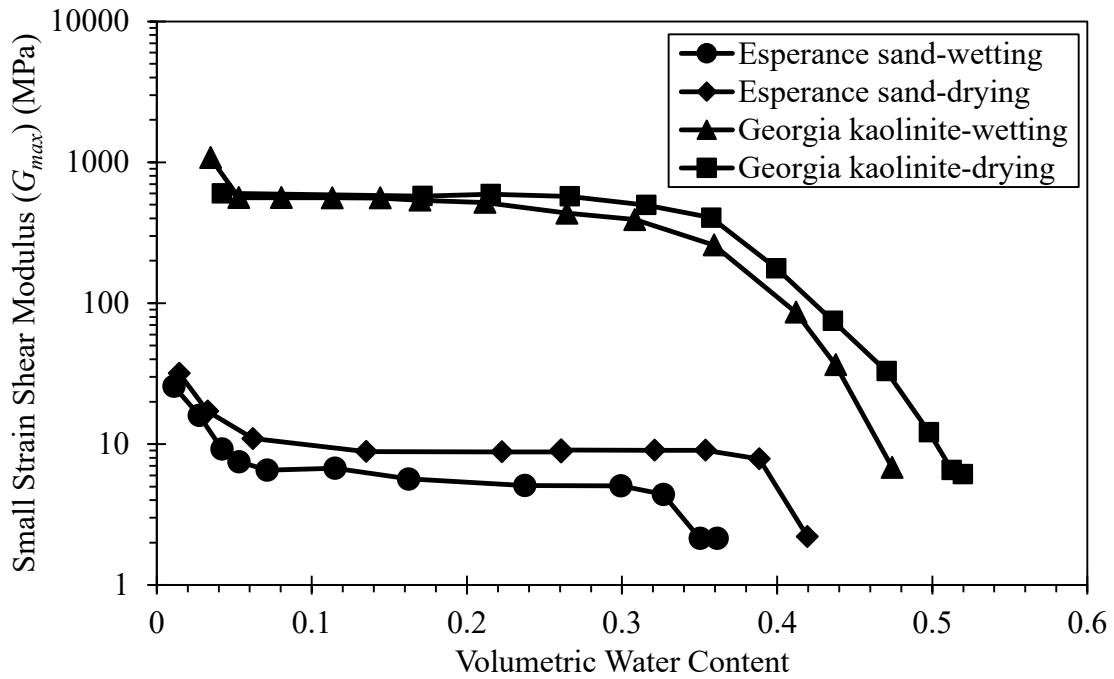
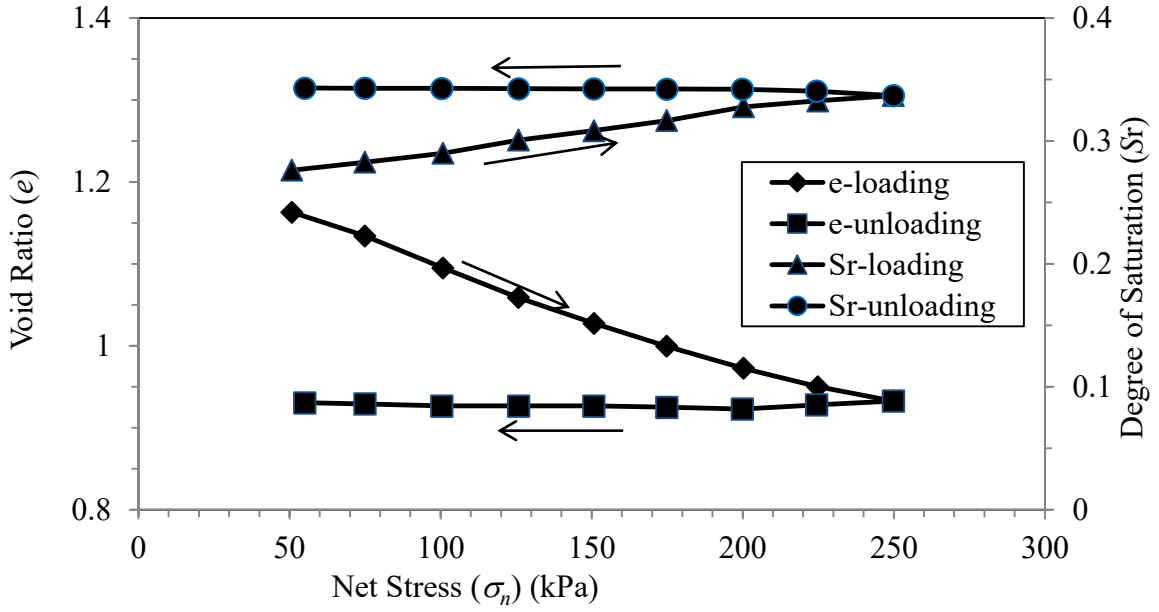
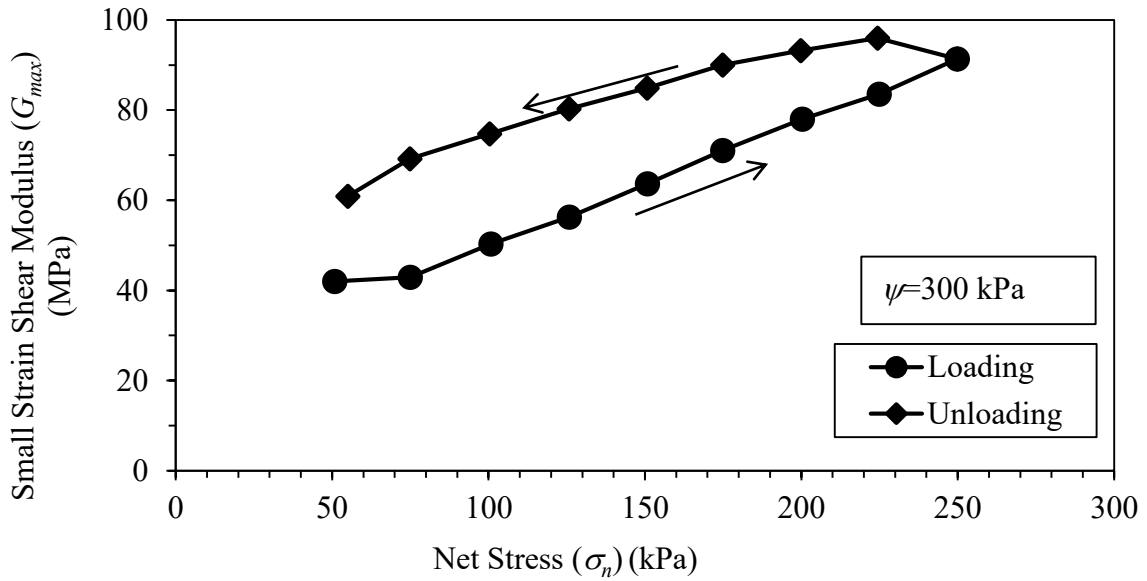


Fig. 2. 12 Responses of G_{max} of Esperance sand and Georgia kaolinite subjected to a drying-wetting cycle (plotted using data from Dong and Lu 2016)



(a)



(b)

Fig. 2. 13 (a) Hydraulic hysteresis and (b) responses of G_{max} of Zenoz kaolin subjected to a loading-unloading cycle of net stress (plotted using data from Biglari et al. 2012)

2.6 Experimental studies on the effect of degree of saturation on G_{max}

Wu et al. (1984) investigated the variation of G_{max} from saturated to dry state using a resonant column device under three confining pressures. Five fine-grained cohesionless soils were

studied in the test with different effective grain sizes (D_{10}), varying from 0.0024 mm to 0.17 mm, and different shapes of particles (namely, angular, flaky, angular to sub-rounded). Results of all the tests showed that the magnitudes of G_{max} at completely saturated state and dry state are approximately the same, while an optimum degree of saturation ($S_{r,opt}$) was observed, at which the combination of S_r and corresponding matric suction resulted in the maximum value of G_{max} (Fig. 2.15).

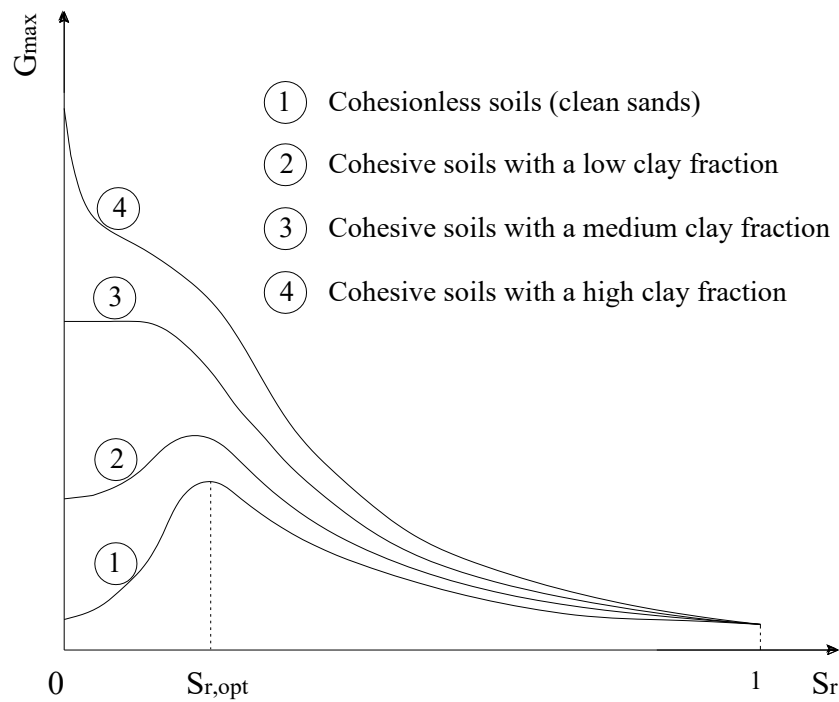


Fig. 2. 14 Possible S_r - G_{max} relationships with different clay fractions during a drying process

This behaviour can be explained by considering the contribution of matric suction to G_{max} . At matric suctions smaller than the air entry value (AEV), it can readily be assumed that there are still only two phases with pores being completely filled with bulk water and the mechanical behaviour of the soil still complies with saturated soil mechanic. As a result, an increase of matric suction can be considered as an increase of effective stress, resulting in an increase of G_{max} which can be determined by equations for saturated soils. This behaviour of G_{max} was observed in tests for a range of soils conducted by Mancuso et al. (2002), Sawangsuriya et al.

(2008), and Heitor et al. (2013). At matric suctions greater than AEV, air commences occupying larger spaces causing progressive reductions of contact area between bulk water and particle surfaces resulting in reductions in the growth rate of G_{max} with increasing matric suction. As the fraction of air volume grows, meniscus water starts forming between particles as capillary bridges (Fig. 2.16).

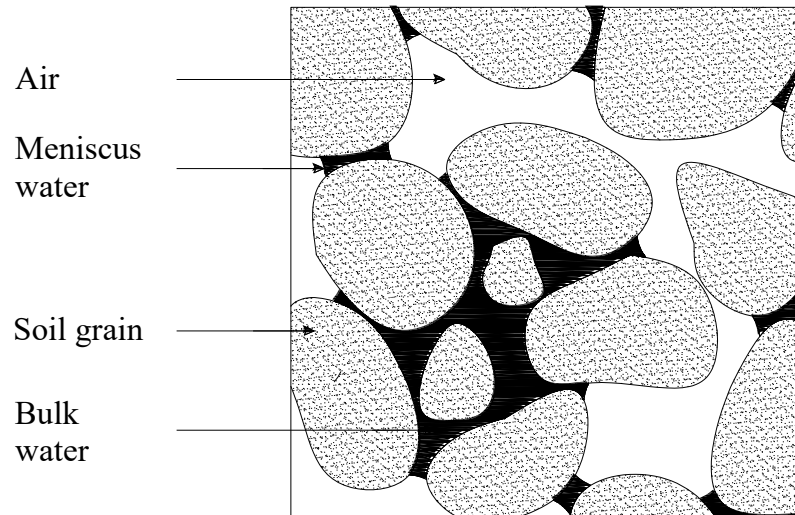


Fig. 2. 15 Bulk water and meniscus water within an RVE of unsaturated soils

Despite meniscus water and bulk water both affect the soil stiffness, their impacts on the mechanical behaviour of soils are different. Variation of matric suction within bulk water influences both normal and tangential inter-particle forces, while variation of matric suction within meniscus water affects only normal inter-particle forces (Karube et al. 1996; Ng and Zhou 2014; Wheeler et al. 2003). Herein, the normal inter-particle forces can be considered as confining pressure, which contributes to the increase in the small strain stiffness of soils. An increment of matric suction within bulk water contributes to an increase of normal inter-particle forces as an isotropic pressure does, whereas the contribution caused by the same increment of matric suction within meniscus water can be determined from equations associated with the capillary effect. The total magnitude of normal inter-particle forces within an investigated

representative volume element (RVE) is proportional to the magnitude of matric suction and the total contact area between pore water and the particle surfaces (Alonso et al. 2010; Han and Vanapalli 2016; Lu 2008; Vanapalli et al. 1996). Since it is difficult to determine the total contact area, its variation during drying and wetting processes can be represented by the volumetric variation of pore water which is tightly associated with the variation of degree of saturation. The early stages of a drying process experience reductions of bulk water volume along with the development of meniscus water. There is a gradual transition of the soil response from bulk-water to meniscus-water regulated behaviour (Mancuso et al. 2002). For higher range of matric suctions at which bulk water is nearly dried up, the amount of water loss at the same increment of matric suction will reduce significantly leading to a higher growth rate of G_{max} with decreasing degree of saturation. As desiccation progresses, the contribution of matric suction to G_{max} commences falling down due to the loss of meniscus water and finally becomes zero when meniscus water has been completely dried up at a low value of degree of saturation. There are different interpretations and methods to determine this degree of saturation. Fredlund et al. (1993) defined it as a residual degree of saturation, thus can be evaluated from the soil water characteristic curve (*SWCC*). Residual degree of saturation corresponds to the unsaturated stage which has negligible effect on the mechanical behaviour of soil, representing the state below which the liquid flow ceases, and vapour flow dominates. Alonso et al. (2010) named this degree of saturation as a microscopic degree of saturation (S_r^m), corresponding to the state at which water is held only in micro-pores and the capillary effect is negligible. S_r^m can be experimentally determined by mercury intrusion porosimetry method and for cohesionless soils, its value is approximately equal to zero.

Following experimental results, Wu et al. (1984) proposed an empirical equation for the optimum degree of saturation (i.e. the degree of saturation corresponds to the highest value of G_{max}):

$$S_{r,opt} (\%) = -6.5 \log_{10}(D_{10}) + 1.5 \quad (2.12)$$

where, $S_{r,opt}$ is the optimum degree of saturation and D_{10} is the effective grain size. Eq. (2.12) indicates that for investigated soils an increase of D_{10} causes a decrease in $S_{r,opt}$. This behaviour is attributed to the fact that the capillary effect decreases with increasing pore size.

Qian et al. (1993) conducted the same tests as those conducted by Wu et al. (1984) on thirteen cohesionless soils with different grain shapes and grain size distributions. Four of them were natural sands, namely, Glazier Way, mortar, Ottawa F-125 and Agsco sands. The presence of $S_{r,opt}$ was observed in all tests showing that $S_{r,opt}$ is proportional to void ratio and the portion of grains smaller than 400 sieve size (i.e. 38 μ m). The authors also reported that angular sands have higher values of $S_{r,opt}$ compared with that of subrounded sands with the same average grain size. The above findings could lead to a general conclusion that $S_{r,opt}$ is proportional to the fraction of small pores, which are the ideal environment for the capillary attraction.

Cho and Santamarina (2001) used a modified oedometer cell to explore the variation of shear wave velocity (V_s) against degree of saturation, reducing from a fully saturated condition to a dry condition. The cell was put inside an incubator under a constant temperature of 50 $^{\circ}$ C. Results of four tests on both cohesionless and cohesive specimens showed different relationships between degree of saturation and V_s . For clean glass bead, considered as a cohesionless specimen, an optimum degree of saturation corresponding to the maximum V_s was observed, similar to observations reported by Wu et al. (1984). For a mixture consisting of 80% glass bead and 20% kaolinite (a cohesive specimen), a different pattern was noted with a consistent increase of V_s during the drying process. Two significant increments in the slope of S_r – V_s curve are noted at two degrees of saturation including 40% and the nearly dry stage.

The same trend was observed for granite powder and Sandboil sand specimens and the magnitude of V_s at the dry condition was almost proportional to the fraction of the fine content. This trend cannot be attributed to the contribution of the increasing matric suction during drying as matric suction contribution became insignificant when meniscus water was completely desiccated at low degrees of saturation.

Three factors that possibly contribute to the stiffness of soil during drying would be cementation effects due to salt precipitation, van der Waals attraction between particles and the plastic fine content. As degree of saturation decreases, the ionic concentration in meniscus water increases until reaching saturation resulting in the formation of salt precipitation at particle contacts (bridge connection), significantly contributing to the stiffness of the soil specimen (Cho and Santamarina 2001; He and Chu 2017; Truong et al. 2012).

The results of tests conducted by Truong et al. (2012) with a wide range of salt concentration reveal that remarkable contributions of cementation to G_{max} induced by salt precipitation in the soil occur mainly near the dry state and are proportional to the salt concentration. Van der Waals forces resulting from electromagnetic field interaction between atoms of adjacent particle surfaces are the other factor that can cause the observed increase in the soil stiffness. According to Lu and Likos (2006), van der Waals attraction is active and more significant for particles smaller than $10\mu\text{m}$ (i.e., clay and silt particles) and depends on the properties of the medium between particle surfaces (e.g., pore water) and become greater at closer distances. At saturated state, van der Waals attraction is smallest, which is corresponding to the largest inter-particle distance, while at lower degrees of saturation, the distance is shortened and van der Waals attraction increases exponentially until reaching the upper bound at the dry state. As reported by Lu and Likos (2006), the total magnitude of van der Waals forces is known to be remarkably affected by the grain size, type of mineral and fraction of plastic fines. During the

drying process, fines accumulate at the contacts of larger particles increasing the number of inter-particle contacts. Thus, the smaller the grain size and the higher fraction of plastic fines, the higher total van der Waals forces. In addition, since the stiffness of plastic fines increases with reducing water content, the plastic fine content is expected to enhance the stiffness of the soil during drying with the highest contribution occurring at the dry state.

Fig. 2.17 schematically represents contributions of matric suction, van der Waals attraction, plastic fines and salt precipitation to G_{max} based on experimental results in the literature. As the contribution of van der Waals attraction is influenced by plastic fines, these two effects are combined and can be considered as only one factor. From the above discussion, it can be concluded that matric suction controls G_{max} of unsaturated soils within the high range of degree of saturation, whereas at low values of degree of saturation, the contribution of matric suction approaches zero, along with increases of the contributions of other factors (Fig. 2.17). Consequently, the small strain stiffness may vary in different ways with degrees of saturation at low range. Specifically, G_{max} may persistently increase as reported by Cho and Santamarina (2001), or remain constant, or persistently decrease mainly depending on the salt concentration, the mineral and fraction of plastic fines (Fig. 2.15).

A number of other experimental tests using different types of suction-control devices were conducted to explore the variations of G_{max} during drying and wetting processes. However, the difficulties in creating and controlling matric suction at high range and the long time required for matric suction equalisation at each stress stage, restrict those investigations only to low range of matric suctions (i.e., high degrees of saturation) with the maximum reported value of approximate 1000 kPa by Sawangsuriya (2006), while others experiments considered lower matric suctions (e.g. 400 kPa by Mancuso et al. (2002) and Hoyos et al. (2011); 200 kPa by Ng and Yung (2008); 100 kPa by Khosravi and McCartney (2012). Thus, the contribution of matric

suction to G_{max} dominates the results in those tests and conceals the contribution of other factors.

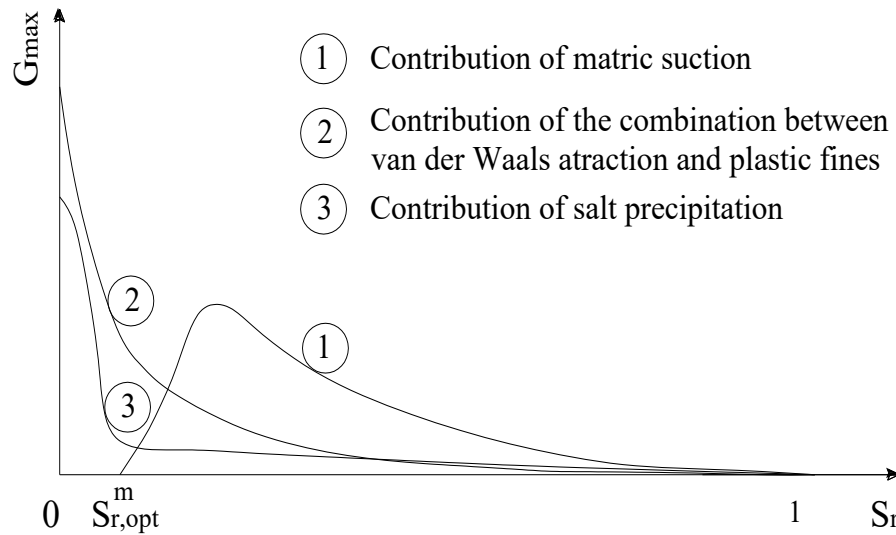


Fig. 2. 16 Schematic contributions of different factors influencing G_{max} during a drying process

From the measured values of G_{max} corresponding to varying matric suction and degree of saturation, a number of empirical equations for G_{max} prediction, considering only the contribution of net stress and matric suction, were proposed (e.g. Heitor et al. 2013; Khosravi 2011; Sawangsuriya 2006; Sawangsuriya et al. 2008). However, these equations failed to capture the effect of hysteresis observed in water retention behaviour of unsaturated soils during wetting-drying and loading-unloading cycles.

During a drying-wetting cycle, a decrease of degree of saturation at the same magnitude of matric suction causes a decrease of contribution of suction, but at the same time, it induces increments in the contributions of salt precipitation, van der Waals attraction and plastic fines. When the hydraulic hysteresis behaviour occurs, the errors caused by omitting the contributions of salt precipitation, van der Waals attraction and the plastic fines might significantly accumulate as the number of cycles increase. The accuracy of predictions can be improved by

capturing not only the contribution of matric suction but also the contribution of other possible factors in the empirical equations. A challenging issue remaining is that there are limited experimental studies on relationships between degree of saturation and those factors during drying-wetting cycles. In addition, it should be noted that different responses of excess pore air and pore water pressures during suction equalisations, as observed by Ho and Fatahi (2015) and Ho and Fatahi (2016), might affect the contributions of those factors.

2.7 Small strain shear modulus of cement treated soils

2.7.1 Mechanism of cement stabilization

Chemical stabilisation using cement is one of the most common methods in ground improvement projects due to its low price, availability and effectiveness compared to methods using other chemical stabilisers. The introduction of cement will cause the formation of artificial cement structure, and hence enhance both stiffness and strength of soft soils. Referring to Read et al. (2001), ordinary Portland Cement (OPC) consists of C_3S , C_2S , C_3A , and C_4AF with C, S, A, and F representing CaO , SiO_2 , Al_2O_3 , and Fe_2O_3 , respectively. When OPC comes in contact with water, hydration reactions of these compounds occur and form hydrated products including hydrated calcium silicates (CSH), hydrated calcium aluminates (CAH) and hydrated lime $Ca(OH)_2$. The first two are hydrated gels, the primary cementitious products, and responsible for the short-term hardening of cement treated soil, while lime reacts with silica (SiO_2) and alumina (Al_2O_3) available in clay particles in the secondary pozzolanic reactions to form CSH, and CAH contributing to the development of soil stiffness in the long term. According to Read et al. (2001), the secondary pozzolanic reactions are long-term reactivities that usually take several years. Thus, it is reasonable to ignore its contribution to G_{max} during sample preparation and curing processes measured in weeks.

2.7.2 Study on G_{max} of cement treated soft soil

Soil stabilisation with cement has wide applications in earthworks including roads, embankments, and railway tracks. It was reported that cement stabilisation increased G_{max} of treated soils (Acar and El-Tahir 1986; Chang and Woods 1987; Chiang and Chae 1972; Puppala et al. 2006; Saxena et al. 1988; Sharma and Fahey 2004; Subramaniam and Banerjee 2016; Yang 2008; Yang and Woods 2014). The study of G_{max} of cemented soils is important in predicting the response of soil subjected to dynamic loadings and during earthquakes. Chiang and Chae (1972) investigated G_{max} of a uniform sand and a silty clay treated with 2% to 6% of Type 1 Portland cement using a resonant column device. Test results showed that G_{max} of the cement-treated soils was proportional to the confining pressure, especially for the treated uniform sand. A similar observation was reported in torsional resonant column tests on Monterey sand treated with 1% to 4% of Portland cement reported by Acar and El-Tahir (1986). They believed that increases in confining pressure increased the number of inter-particle bonds, thus, resulting in enhancement of the resistance of the cement-treated sand to shear deformation.

On the contrary, Lovelady and Picornell (1990) and Baig et al. (1997) believed that G_{max} of cement-treated soils was affected by the confining pressure only when confining pressure was high enough to destroy the cementing bonds. They have proved that the notable effect of confining pressure on G_{max} of cement-treated soils, observed in previous resonant column tests, resulted from loose connections between the sample and the end platens, and that the shortcomings of the coupling technique can be overcome by using a rigid connection. With the cement treated samples being glued to the end platens with epoxy, measurements of G_{max} in resonant column tests conducted by Lovelady and Picornell (1990) and Baig et al. (1997) showed negligible effects of confining pressure at the low range of stresses. The independence

of G_{max} to confining pressure at the low range of stresses was confirmed in later experiments by Yang (2008) as shown in Fig. 2.18, Trhlíková et al. (2012), and Yang and Woods (2014) for cement treated kaolinite, bentonite, and sand.

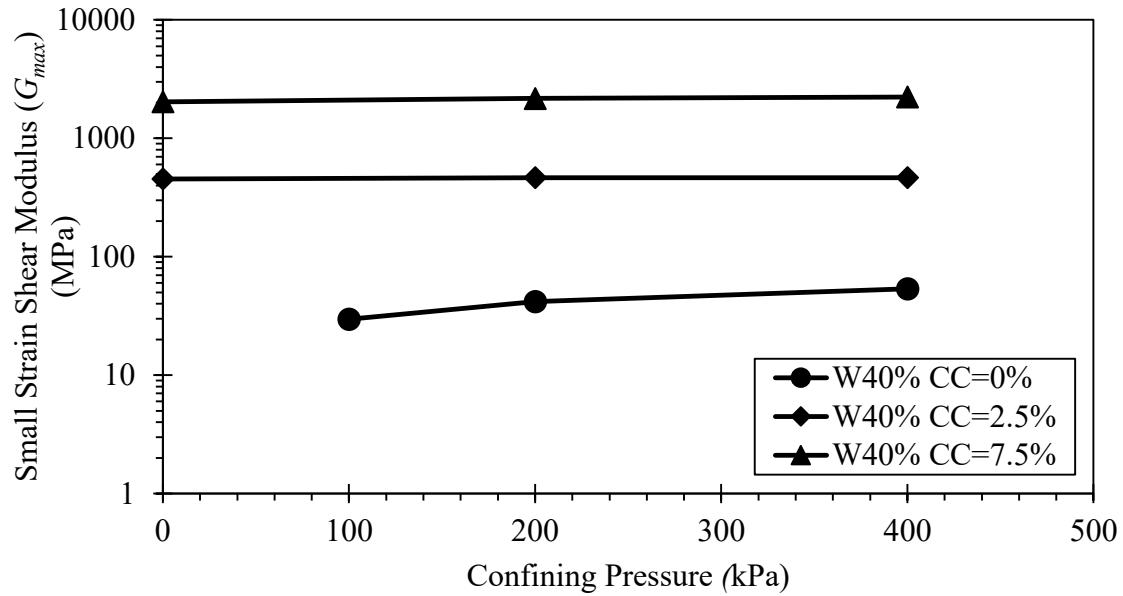


Fig. 2. 17 Effect of confining pressure on G_{max} of Kaolinite treated with 2.5% and 7.5% moulding at water content of 40% (plotted using data from Yang 2008)

Rinaldi and Santamarina (2008) classified the relationship between shear wave velocity and confining pressure into two regions: cementation-controlled region at low confining pressures and stress-controlled region at high confining pressures. Specifically, in the cementation-controlled region, the shear stiffness is determined by the degree of cementation, and confining pressure has no effect on soil stiffness, while in stress-controlled region soil stiffness increases with confining pressure as in untreated soils.

In most experiments mentioned above, investigations of G_{max} were conducted on samples after curing age, while a large proportion of cement treated soils are subjected to drying and wetting in real condition. Results of durability tests conducted by Zhang and Tao (2008) on a clayey silt, stabilised with 2.5% to 12.5% of Type 1 Portland cement, showed that the

volumetric swelling and mass loss induced by wetting-drying cycles increased with the decrease in cement dosages, and after 12 cycles, failures of samples with low cement dosages was recorded with mass losses even surpassing value of the durability criterion. Increases of mass loss, cracking, and structural failure with increasing number of drying-wetting cycles were also reported in an experiment on cement solidified lead contaminated silty clay conducted by Li et al. (2014).

Liu et al. (2018) studied the development of cracks of Cd-contaminated lean clay samples treated with 2% to 10% of Portland cement during drying-wetting cycles. Variations of cracking intensity factor, defined as the ratio of the cracked area to the total surface area, revealed that cracks induced by drying surpassed cracks induced by subsequent wetting, and that wetting not only caused further development of cracks due to non-uniform swelling but also healed some cracks owing to cement hydration reaction.

Obviously, drying and wetting have significant effects on mechanical properties of cement treated soils, including G_{max} , however, the understanding of the behaviour of G_{max} of cement treated soils subjected to cycles of drying-wetting is still limited.

2.8 Modelling of small strain shear modulus of unsaturated soils

A number of empirical equations have been proposed to evaluate G_{max} of unsaturated soils, using soil properties and empirical constants. Most of them were established based on the common knowledge that G_{max} is proportional to the stress level, and reversely proportional to the magnitude of void ratio. In some equations, the over consolidation ratio (OCR) was used as the replacement for the effect of void ratio. All proposed equations can be categorised into two groups, depending on whether the effect of degree of saturation on the contribution of stress state to G_{max} was included or not. In the first group, only contribution of net stress and

matric suction were considered, while the effect of degree of saturation was omitted (Table. 2.1). Consequently, the hydraulic hysteresis cannot be captured. In the second group, net stress, matric suction, and degree of saturation (or effective degree of saturation) were all considered in equations (Table. 2.2). Well agreements between test data and predictions using equations of the second group during a drying process have been obtained for the low range of matric suction (i.e. smaller than 1000 kPa). However, the magnitude of G_{max} under zero net stress was predicted to approach zero at the dry state that has never been captured in experiments. In fact, the magnitude of G_{max} at dry state was observed to be extremely high and proportional to the fraction of clayey material (Dong and Lu 2016). Thus, these equations also fail to capture the response of G_{max} at low degrees of saturation (i.e. high matric suctions). Additionally, the prediction of G_{max} during drying-wetting cycles was not very successful, requiring more research addressing this aspect.

Table 2. 1 Summary of the equations to estimate G_{max} of unsaturated soils omitting the effect of degree of saturation

Author(s)	Sample	Testing method	Proposed equation
Mancuso et al. (2002)	Silty sand	Resonant Column Test	$\frac{G_{max}}{p_a} = A \left[\frac{(p-u_a)+(u_a-u_w)}{p_a} \right]^n OCR^m \text{ for } u_a - u_w \leq AEV$ A is stiffness index; $(p - u_a)$ is the mean net stress of the drying path under consideration; OCR is over consolidation ratio; p_a is the reference pressure (atmospheric); n is the stiffness coefficient representing the stiffness of the material under the reference pressure (at $OCR=1$); m is the stiffness coefficient representing the sensitivity of the stiffness to stress state and history; AEV is the air entry value
Mendoza et al. (2006)	Kaolinite clay	Bender Element Test	$G_{max} = 30000 \frac{(2.3 - e)^2}{1 + e} [\ln(u_a - u_w)]^{1.35}$ e is void ratio; $u_a - u_w$ is matric suction
Takkabutr (2006)	Sand and Clay	Bender Element Test, Resonant Column Test	$\frac{G_{max}}{\sigma_0} = A \sigma_0^B [\psi^{C \exp(D \sigma_0)}] \exp(E \psi)$ ψ is matric suction; σ_0 is confinement; A, B, C, D, and E are constants

Ng and Yung (2008)	Clayey silt	Bender Element Test	$G_{max} = C_{ij}^2 f(e) \left(\frac{\sigma_i - u_a}{p_r} \times \frac{\sigma_j - u_a}{p_r} \right)^n \left(1 + \frac{u_a - u_w}{p_r} \right)^{2b}$ C_{ij} is inherent material constant related to the i-j plane; $f(e)$ is void ratio function; $(\sigma_i - u_a)$, $(\sigma_j - u_a)$ are net normal stresses related to i-j plane; p_r is reference stress, b is empirical component
Hoyos et al. (2011)	Silty sand	Bender Element Test, Resonant Column Test	$G_{max} = A(p - u_a)^B$ $p - u_a$ is net confining pressure; A, B are fitting parameters

Table 2. 2 Summary of the equations to estimate G_{max} of unsaturated soils considering the effect of degree of saturation

Author(s)	Sample	Testing method	Proposed equation
Sawangsurinya (2006)	Clayey sand, silt, lean clay, and fat clay	Bender Element Test	$G_{max} = Af(e)(\sigma_0 - u_a)^n + C \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^k (u_a - u_w)$ A is a material constant; $\sigma_0 - u_a$ is net confining stress; $f(e)$ is a void ratio function, $f(e) = 1/(0.3+0.7e^2)$; n is a stress exponent which is approximately 0.5 at small strains; C is a linear fitting coefficient; k is fitting parameter; θ, θ_r, θ_s are volumetric water content at investigated, residual and saturated states, respectively.
Sawangsurinya (2009)	Clayey sand, silt, lean clay, and fat clay	Bender Element Test	$G_{max} = Af(e) \left[(\sigma_0 - u_a) + C \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^k (u_a - u_w) \right]^n$ A is a material constant; $\sigma_0 - u_a$ is net confining stress; $f(e)$ is a void ratio function, $f(e) = 1/(0.3+0.7e^2)$; n is a stress exponent which is approximately 0.5; C is a linear fitting coefficient; k is fitting parameter; θ, θ_r, θ_s are volumetric water content at investigated, residual and saturated states, respectively.

Khosravi (2011)	Bonny silt	Resonant Column Test	$G_{max} = A(OCR)^k p_a^{1-n} [p_n + S_r(u_a - u_w)]^n$ $OCR = \frac{p'_0}{p_n + S_r(u_a - u_w)}$ A and n are fitting parameters: p_a is atmospheric pressure; k is consistency constant; OCR is over consolidation ratio; p'_0 is apparent mean preconsolidation stress; p_n is net confining stress; and S_r is degree of saturation.
Heitor et al. (2013)	Silty sand	Bender Element Test	$G_{max} = G_{max,s} A f(e) \left[\frac{(p - u_a) + S_r^k (u_a - u_w)}{p_r} \right]^n$ $G_{max,s}$ is G_{max} at saturated condition; A is parameter associated with soil structure, $f(e)$ is function of void ratio; $(p - u_a)$ is mean net stress; p_r is reference pressure (i.e. atmospheric pressure); $(u_a - u_w)$ is matric suction; k is parameter related to plasticity index; n is fitting parameter associated with the state of stress.

2.9 Summary

This chapter provided a comprehensive literature review about the selection of stress state variables in investigation of unsaturated soils, components of soil suction and their variations with changes of water content, measurements of soil suction and G_{max} , axis-translation setup used in investigating unsaturated soil behaviour, studies on the effects of degree of saturation, hydraulic hysteresis and cementation on G_{max} . Finally, proposed empirical equations in the literature were summarised and investigated to identify existing gaps requiring further research studies. Key observations and knowledge gap requiring further research can be summarised as follows:

- Independent stress state variable approach is capable and convenient to capture the response of G_{max} considering hydraulic hysteresis, especially during drying-wetting cycles.
- Unsaturated soils also exhibit hydraulic hysteresis behaviour under loading-unloading cycles due to irreversible reductions of the void ratio.
- The presence of matric suction and its dependence on water content makes mechanical properties of unsaturated soils become water content dependent.
- There is no unique relationship between matric suction and water content for a given soil, therefore both matric suction and water content need to be considered in the study of mechanical behaviour of unsaturated soils.
- The magnitude of G_{max} of both saturated and unsaturated soils is proportional to the stress level and reversely proportional to the magnitude of void ratio.

- The magnitude of G_{max} at dry state is extremely high in some cases and proportional to the fraction of clayey material.
- Empirical or semi-empirical equations proposed in the literature cannot capture the response of G_{max} at the low range of degree of saturation (or high range of matric suction) during a drying process.
- Prediction of G_{max} during drying-wetting cycles when hydraulic hysteresis is present is not well established.
- The effect of degree of saturation on the contribution of stress state to G_{max} has not yet been successfully evaluated, requiring further research to be addressed.

Existing laboratory studies explaining the techniques to measure matric suction and G_{max} were also presented, including filter paper test, bender elements test, and suction-controlled devices adopting axis-translation technique. Considering merits of these systems validated for unsaturated soil testing by numerous researchers, these systems have been used in this study to investigate responses of G_{max} under air-drying processes, drying-wetting cycles, loading-unloading cycles of net stress, and general stress application considering variations of both net stress and matric suction.

Chapter 3

Impacts of Drying-Wetting and Loading-Unloading Cycles on Small Strain Shear Modulus of Unsaturated Soils

3.1 Introduction

Responses of G_{max} when hydraulic hysteresis presents were reported during drying-wetting cycles and loading-unloading cycles of net stress. Khosravi (2011) investigated effects of void ratio, degree of saturation, matric suction and net stress on G_{max} of statically compacted Bonny silt during drying-wetting cycles under three different confining net pressures of 100 kPa, 150 kPa, and 200 kPa. The experiment used a fixed-free Stokoe-type resonant column device that was modified to include suction and saturation control. It was observed that G_{max} was proportional to net stress, and at the same levels of net stress and matric suction, G_{max} was higher in wetting process than in the previous drying. A similar observation was also reported by Ng et al. (2009) in their study on recompacted completely decomposed granite samples, subjected to different net stresses of 110 kPa and 300 kPa, using a suction-controlled triaxial system with built-in bender elements. Biglari et al. (2012) measured G_{max} of Zeno kaolin (a lean clay from a mine in northwest Iran) during loading and unloading stages under a constant matric suction of 300 kPa, using a fixed-free resonant column-torsional shear device. For a given net stress, higher values of G_{max} were reported during the unloading process in comparison to the corresponding values during loading.

A number of equations for predicting the G_{max} of unsaturated soils were established and verified based on the results available in the literature. In these equations the variation of G_{max} during drying and wetting processes under a constant net stress was attributed to changes in

the matric suction, while ignoring other factors in the predictive models such as the van der Waals attractions and electric double layer repulsions, both of which contribute to inter-particle forces, and can result in disparities between predictions and measurements of G_{max} of unsaturated soils when they are subjected to several cycles of wetting and drying (i.e. hydraulic hysteresis).

Recently, Khosravi et al. (2018) proposed a semi-empirical equation to predict G_{max} of unsaturated sand during hydraulic hysteresis. The model adopted the concepts of suction stress proposed by Lu and Likos (2006) to capture the effect of hydraulic hysteresis. Six parameters were used to determine suction stress and control effects of effective stress and hydraulic hysteresis. According to Lu and Likos (2006), suction stress represents all local inter-particle forces in unsaturated soils including van der Waals attractions, electric double layer repulsions and force induced by matric suction. However, suction stress itself is not capable of capturing hydraulic hysteresis as it is based on the corresponding soil water characteristic curve (SWCC) which keeps changing during drying-wetting cycles. Indeed, to consider hydraulic hysteresis effects, different parameters corresponding to the suction stress equation would be required (Lu et al. 2010). Hence, the prediction of G_{max} when hydraulic hysteresis presents requires SWCCs and parameters related to the suction stress equation to be redetermined repeatedly. It seems that the combination of the inter-particle forces induced by matric suction, van der Waals attractions and electric double layer repulsions which possibly follow different patterns with variations of degree of saturation makes suction stress incapable of capturing hydraulic hysteresis intrinsically.

In this study, an array of laboratory experiments was carried out to investigate the magnitude of G_{max} during several drying-wetting cycles, and a loading-unloading cycle of net stress. These experiments also set out to establish a predictive model for G_{max} evaluating the combined

contribution of van der Waals attractions and electric double layer repulsions separately from the contributions of matric suction in order to capture the effects of hydraulic hysteresis on G_{max} .

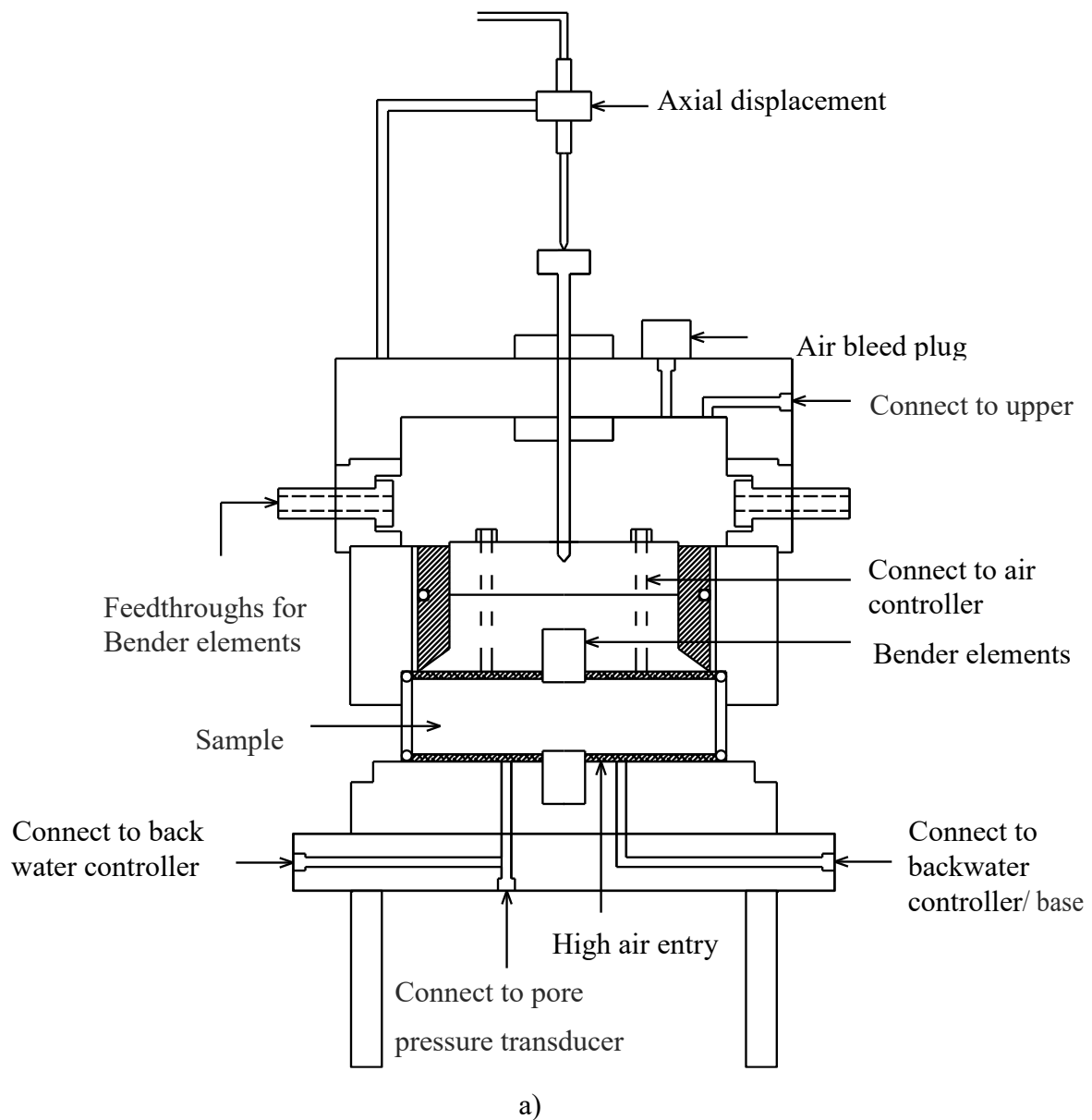
3.2 Laboratory Experiment

3.2.1 Unsaturated Rowe cell apparatus with bender elements

A modified Rowe cell was developed for testing unsaturated soil by adopting the axis-translation technique to study the G_{max} with a high degree of accuracy (Fig. 3.1). The Rowe cell apparatus was connected with three pressure/volume controllers using water or air, to simultaneously apply an upper chamber pressure p_u (the external vertical pressure), the air pressure p_a on top of the sample, and back water pressure p_b at the bottom of the sample. The two water controllers were for applying and controlling p_u and p_b , while the air controller was for applying p_a . With this system, the volume change of the sample and the volume of water entering or exiting the sample can be computed at any time during the tests.

The desired matric suction (i.e. the difference between p_a and p_b) was maintained with a *HAEPD* installed at the bottom of the sample, as shown in Fig. 3.1c, with an air entry value of 1500 kPa. However, even at matric suctions below the air entry value of *HAEPD*, some air could still diffuse through and accumulate under the disk (Padilla et al. 2006), which would result in a slight overestimation in the variation of the pore water volume from the volumetric readings of the back controller. To address this issue, water was periodically flushed from the bottom of the *HAEPD* by another water controller kept at 3 kPa lower than the corresponding back pressure; this pressure would avoid reducing the back pressure during flushing. This apparatus is also equipped with two bender elements with a maximum frequency of 100 kHz, built into the top and bottom of the sample, to measure the shear wave velocity during different applications of stress. The tip-to-tip distance between two bender elements was calculated from

the readings of a linear variable differential transformer (*LVDT*), placed at the top of the sample during the test.



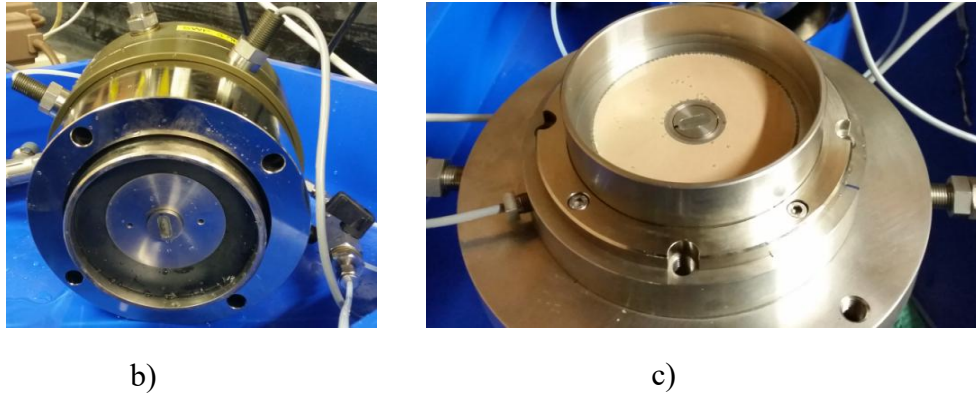


Fig. 3. 1 Modified Rowe cell apparatus with bender elements: (a) schematic diagram of the Rowe cell setup, (b) a photograph of the top loading system, and (c) a photograph of the bottom pedestal

3.2.2 Determining the shear wave velocity and selecting the input wave

Two bender elements, made from piezoelectric ceramic bimorphs, were embedded into the top and bottom of the sample (Figs. 3.1b and 3.1c). One is a transmitter to generate a shear wave when excited by a single pulse, while the other is a receiver to pick up the wave after it has propagated through the sample. Measuring the propagation distance (L) (i.e. the tip-to-tip distance between two bender elements) and the propagation time (Δt) (i.e. the time difference between the transmitted and received wave) will give the shear wave velocity by using Eq. (2.10).

The propagation distance can be computed directly and precisely from readings of the *LVDT* (see Fig.3.1a). However, the propagation time is affected by the method used to identify the arrival time of the received wave. Three approaches, currently used, are the cross correlation (Lee and Santamarina 2005), the frequency domain (Greening and Nash 2004), and the time domain (Rees et al. 2013). The first method evaluates the cross correlation between transmitted and received waves to determine the maximum amplitude, which indicates the arrival time of the first peak. This method assumes that the frequencies of the transmitted and received waves

are identical, but this assumption is improper in most cases because the receiver measures a complex interaction of incident and reflected waves (Arulnathan et al. 1998). In the time domain method, Δt is the difference in time between the starting point or the first peak point of the transmitted wave and the corresponding point in the received wave. Since the surrounding noises and near-field effect induced by the early arrival of the pressure wave frequently obscure the starting point of the real arrival, especially for short propagation distances, the first peak point is now preferred in recent studies (e.g. Ogino et al. 2015).

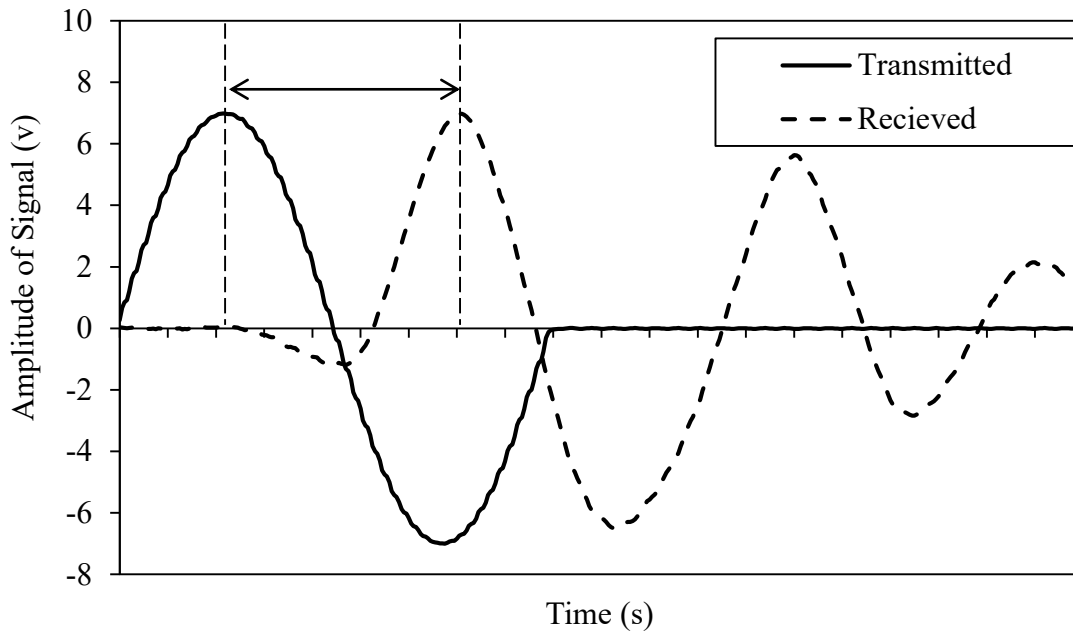


Fig. 3. 2 Determination method for the shear wave propagation time in the Rowe cell equipped with two bender elements

The propagation time can also be determined by the frequency domain method based on a phase analysis of the cross-power spectrum between transmitted and received waves to avoid the subjective visual inspection of the two waves. The cross-power spectrum is obtained using a Fast Fourier Transform, and the propagation time is then calculated from the slope of the unwrapped phase angle function using a linear regression across a defined frequency window.

However, there are more scattered measurements in this method, as Ogino et al. (2015) and Camacho-Tauta et al. (2015) have reported. For these reasons, the peak-to-first peak technique was used in this study, as shown in Fig. 3.2.

The shear wave velocity is affected by the characteristics of the input wave, particularly the wave form and wave frequency. Leong et al. (2005) examined how the two most common waveforms (i.e. square and sinusoidal waves) affect the received signal and concluded that the latter causes less distortion of the output signal than the former. Wave frequency plays even a more important role. While the best output signals occur near the resonant frequency of the sample-bender element system, the amplitude decreases at lower or higher input frequencies until they cannot be detected at extremely low or high ranges (Lee and Santamarina 2005). In addition, frequency of the input wave should be chosen so that the ratio of wave path length to wavelength is greater than 2 to prevent the near-field effect, and less than 4 to avoid attenuation (Sanchez-Salinero et al. 1986). More recently, Leong et al. (2009) found that the ratio should be at least 3.33 to minimise the near-field effect. After considering these factors, single sinusoidal waves with frequencies of 50 kHz were used in this study, and a minimum of 10 output signals were manually stacked for each determination of the propagation time to minimise electrical noises.

3.2.3 Determining the G_{max} and effective dynamic mass density

The magnitude of G_{max} is determined using Eq (2.11). For one-phase materials, the effective dynamic mass density ρ_{eff} is equal to the static mass density, but determining the dynamic mass density of water-solid composites is challenging. Even though pore water cannot transmit a shear wave, it still affects the magnitude of shear wave velocity due to the mass of a thin viscous boundary layer attached to the surface of solid particles that moves in unison as a single phase

during shear wave propagation (Biot 1956; Wu et al. 2012). The thickness of the viscous boundary layer (l_{vis}) is influenced by the wave frequency, thus as l_{vis} approaches zero at extremely high wave frequencies, there is no mass coupling and ρ_{eff} would be equal to the dry mass density ρ_d (Wu et al. 2012). However, l_{vis} approaches infinity at very low wave frequencies, which leads to full mass coupling, so ρ_{eff} would be equal to the static mass density. It is rational to believe that for mid-range wave frequencies, the degree of mass coupling in two-phase materials such as saturated soils would depend on the size of the maximum pore; hence full mass coupling would occur only when the maximum pore is smaller than $2l_{vis}$. In case, $2l_{vis}$ is smaller than the maximum pore size, there would be relative motions between the pore water and soil particles.

For partially saturated soils, which are three-phase materials, the water body may be smaller than the pore size, thus pore size cannot be used to check the mass coupling effect. To date, there are no correlations for estimating the ρ_{eff} for three-phase composites, but in practice, the ρ_{eff} of unsaturated soils is the total mass density (ρ_t) (e.g. Biglari et al. 2012, Dong & Lu 2016). In this study, the maximum effective dynamic mass density ($\rho_{eff,max}$) corresponding to the full thickness of the viscous boundary layer (or full mass coupling) was computed for a given porosity, using Eq. (3.1) for two-phase composites at low-frequency range, where the wavelength is larger than the typical pore sizes in the composite (Martin et al. 2010; Mei et al. 2007):

$$\frac{\rho_{eff,max}}{\rho_s} = \frac{\rho_s + \rho_w - n(\rho_s - \rho_w)}{\rho_s + \rho_w + n(\rho_s - \rho_w)} \quad (3.1)$$

where ρ_s is the density of the solid particles ($\rho_s = 2636 \text{ kg/m}^3$ in this study), ρ_w is the density of water ($\rho_w = 998 \text{ kg/m}^3$ at 21.5°C), and n is the soil porosity. It is assumed that the viscous layer of pore water is only removed during drainage when all the external water has been pushed

out, and during imbibition, the formation of the viscous layer occurs first. During the test when $\rho_{eff,max} \leq \rho_t$, full mass coupling occurs corresponding to the full thickness of the viscous boundary layer and thus $\rho_{eff} = \rho_{eff,max}$. However, when $\rho_{eff,max} > \rho_t$, partial mass coupling occurs corresponding to a thinner thickness of the viscous boundary layer and thus $\rho_{eff} = \rho_t$. Therefore, ρ_{eff} can always be taken as the minimum of $\rho_{eff,max}$ (Eq. (3.1)) and the corresponding ρ_t (measured during the test) for both saturated and unsaturated conditions.

3.2.4 Sample preparation and calculating the initial physical properties

A mixture of 75% fine sand and 25% kaolin clay was used for the soil sample, and its particle size distribution curve, determined based on AS-1289.3.6.1 (2009) and AS-1289.3.6.3 (2003), is shown in Fig. 3.3. The mixture was chosen in an attempt to reduce the time required for matric suction equalisation in time-consuming unsaturated Rowe cell tests. Laboratory tests provided the specific gravity, plastic limit, and liquid limit of the soil sample as showed in Table 3.1.

Table 3. 1 Basic properties of the soil sample

Specific gravity	2.64
Plastic limit	8.9%
Liquid limit	18.7

According to the Unified Soil Classification System the soil is classified as clayey sand (SC). While the sample was being prepared, the dry sand and kaolin were mixed with a spatula until it became homogeneous, and then a predetermined amount of distilled water was gradually sprayed into the mixture. The final mix of fine sand, kaolin, and water was then stored in an air-tight plastic bag, and left for 24 hours for moisture stabilization at a room

temperature of 21.5°C. The water content of the soil was determined before the mix was placed into the unsaturated Rowe cell. The initial mass of soil placed in the Rowe cell was also measured, and since its initial volume was known (i.e. 31 mm in height and 100 mm in diameter), the initial density and unit weight could be readily calculated. From three known quantities, including the gravimetric water content, specific gravity and unit weight, every other physical property at the initial state, such as void ratio and degree of saturation could be determined.

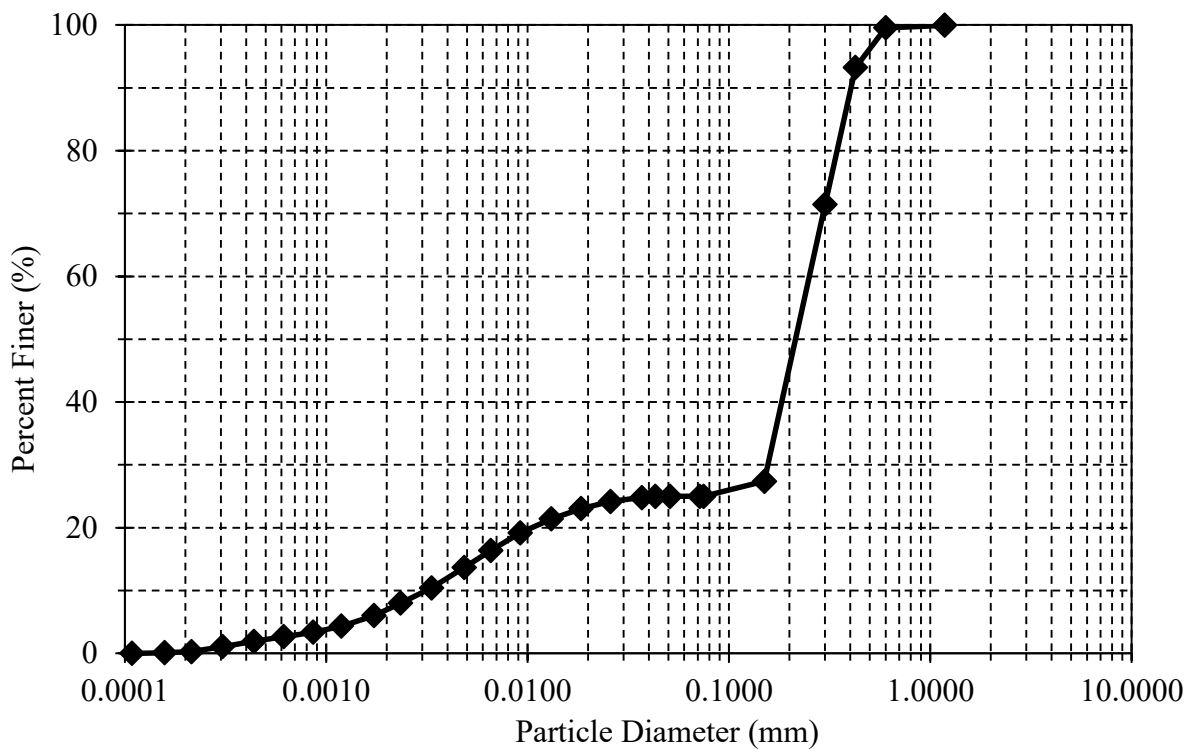


Fig. 3. 3 Particle size distribution curve for the sand and kaolin mixture

3.2.5 Procedure for unsaturated tests

Before applying a vertical net stress (i.e. $\sigma_{vn}=p_u-u_a$) and matric suction, the sample was saturated by simultaneously increasing the back pressure (p_b) and upper chamber pressure (p_u) so that the vertical effective stress remained constant at 50 kPa until the Skempton's pore pressure parameter (B -value) of 0.95 or a greater value was obtained. The initial vertical net

stress of 20 kPa and initial matric suction of 30 kPa were chosen so that the corresponding vertical effective stress remained unchanged in comparison to the stress state at the end of the saturation stage. The initial matric suction was also expected to be smaller than the air entry value (AEV) of the sample to obtain the first drying $SWCC$ from a saturated state. In each stage, the change in pore volume (i.e., the change in volume of the upper chamber), the volumetric change of pore water (i.e., the change of back volume), and the axial displacement were measured every 10 seconds. The shear wave velocity was evaluated using the built-in bender elements to monitor the development of G_{max} due to changes in the matric suction and the vertical net stress, as presented in Table 3.2.

Table 3. 2 Stress states of the Rowe cell unsaturated test with shear wave velocity measurement

Test stage	Net stress (kPa)	Suction (kPa)
Drying-wetting cycles	20	30, 50, 70, 90, 110, 130, 150, 170, 190, 210, 230, 330, 430, 530, 630, 730
	20	530, 430, 330, 90, 50, 30
	20	90, 630, 730, 830, 930
	20	630, 90, 30
	20	90, 330, 630, 930
	20	630, 330, 30
Loading-unloading cycle of net stress	50, 100, 200, 400,	30

		800	
		400, 200, 100	30
Verification exercise	Mixed applications of net stress and matric suction	400	200
		200	400
		400	200
	drying process	5	400, 800, 970

In this test, the upper chamber pressure (p_u) remained constant, while the back pressure (p_b) and pore air pressure (p_a) were changed to control the vertical net stress and matric suction. Therefore, only p_b changed in the drying-wetting cycles, but in the loading-unloading cycle of vertical net stress both p_b and p_a were altered.

3.3 Results and Discussion

3.3.1. Variation of void ratio and SWCC during drying-wetting cycles

Changes in the void ratio had a direct effect on the stiffness and physical properties of soil such as its porosity, density, and degree of saturation. Variations in the void ratio due to variations in the vertical net stress and/or matric suction can be assessed using the unsaturated Rowe cell setup. Fig. 3.4 shows the variations in the void ratio with matric suction during the three drying-wetting cycles measured in this study.

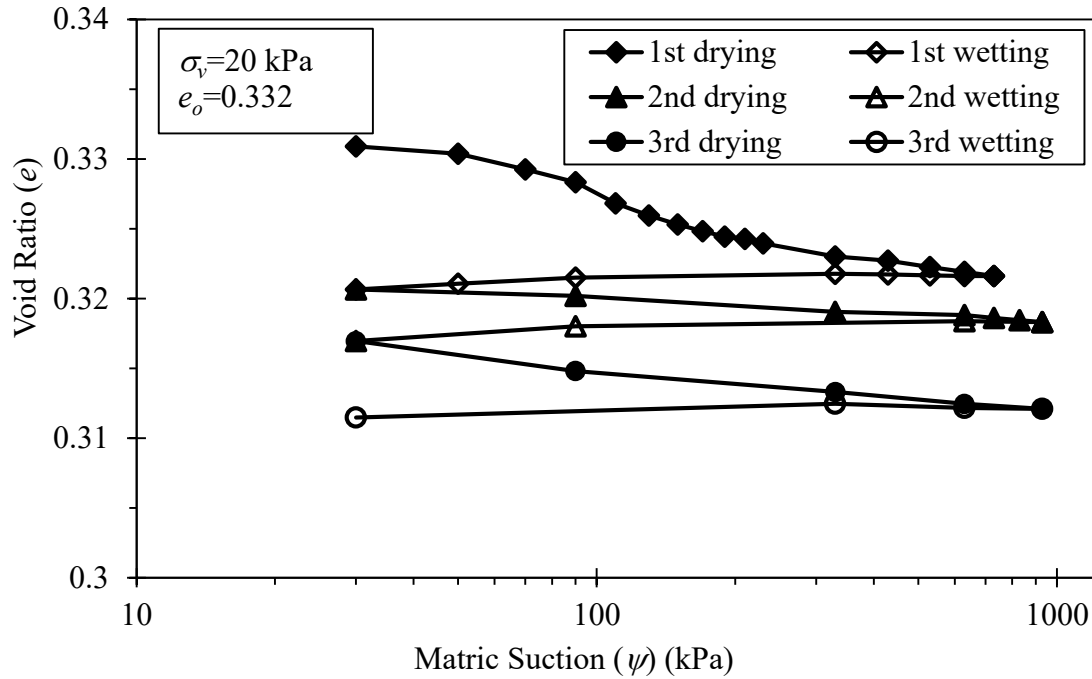


Fig. 3. 4 Void ratio and matric suction ($e-\psi$) relationship during three drying-wetting cycles

The irreversible reductions in the void ratio during the drying-wetting cycles revealed the plastic volume changes, such that the first drying caused a 3.23% reduction in the void ratio, whereas in the following wetting, the swellings were negligible, and there was a further reduction in volume (collapse) when the matric suction decreased to small values. Put simply, an 0.3% reduction in the void ratio occurred in the first wetting, whereas the induced drying (wetting) reductions in the void ratio in the second and the third cycles were 0.73% (0.43%) and 1.53% (0.2%), respectively. The reduction in the void ratio in the third cycle was higher than the second cycle probably due to previous collapses that rearranged the particles toward structures facilitating particle slippage. Clearly, apart from the plastic strain that accumulated within the drying-wetting cycles, collapse also contributed to the irreversible volumetric compressions.

The soil water characteristic curve (*SWCC*) can generally be presented in terms of the

gravimetric water content (ψ - w), the volumetric water content (ψ - θ), or the degree of saturation (ψ - S_r). Since the gravimetric and volumetric water contents of deformable soils may alter as the matric suction changes, even though the soils are still saturated, ψ - S_r is a better way to estimate the *AEV* (Fredlund and Houston 2013; Pasha et al. 2015). The variations of overall and pore water volumes were taken as variations of the upper chamber and back volumes, and since their values at the saturated state were known, these volumes and the corresponding degree of saturation could be computed at any stage of the test.

The semi-log plots of S_r - ψ shown at different drying-wetting cycles in Fig. 3.5 indicate that the degree of saturation in wetting at a given matric suction is constantly lower than that in the previous drying process. In fact, comparisons of the drying curves show a tendency to decrease in degrees of saturation when the number of cycles increases, especially between the first and second cycles; a similar tendency occurred in the wetting curves.

Ma et al. (2015) investigated the *SWCC* of unsaturated silt during drying-wetting cycles. It was reported that effects of the stress state on the *SWCC* are only attributed to changes in the void ratio. However, as can be observed in Fig. 3.6, the degree of saturation at the end of a drying-wetting cycle was smaller than the corresponding value in the previous cycle at the same matric suction (i.e. 30 kPa), even though the void ratio decreased. The phenomenon can be explained by possible alterations of pore network induced by drying, wetting processes as observed in the study by Nowamooz et al. (2016) which might be insignificant for silt used in the experiments reported by Ma et al. (2015).

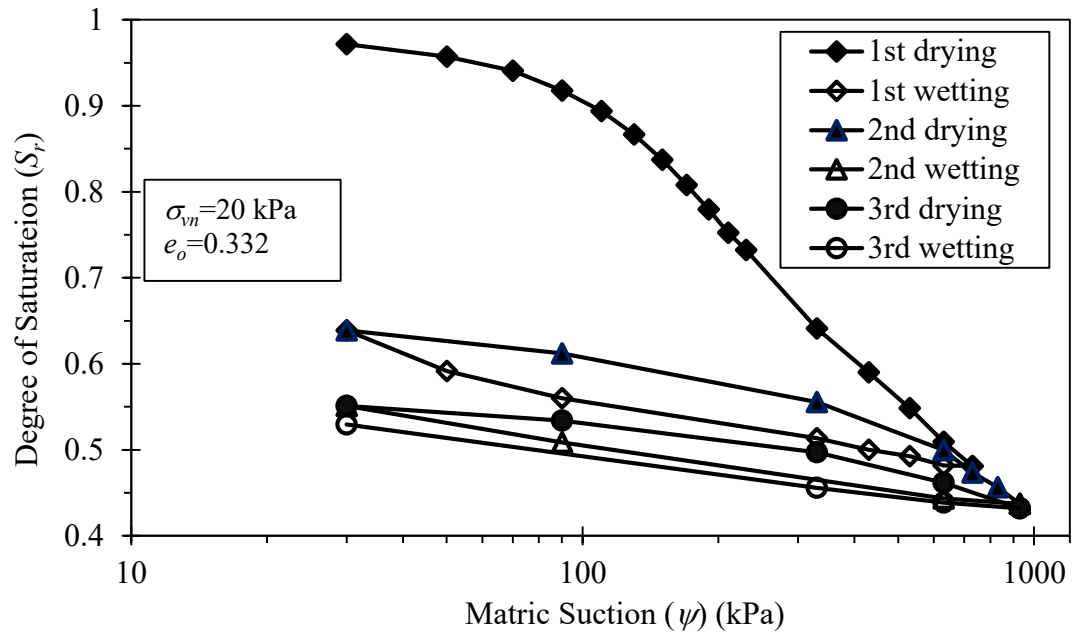


Fig. 3. 5 Degree of saturation versus measured matric suctions (*SWCC*) in three drying-wetting cycles

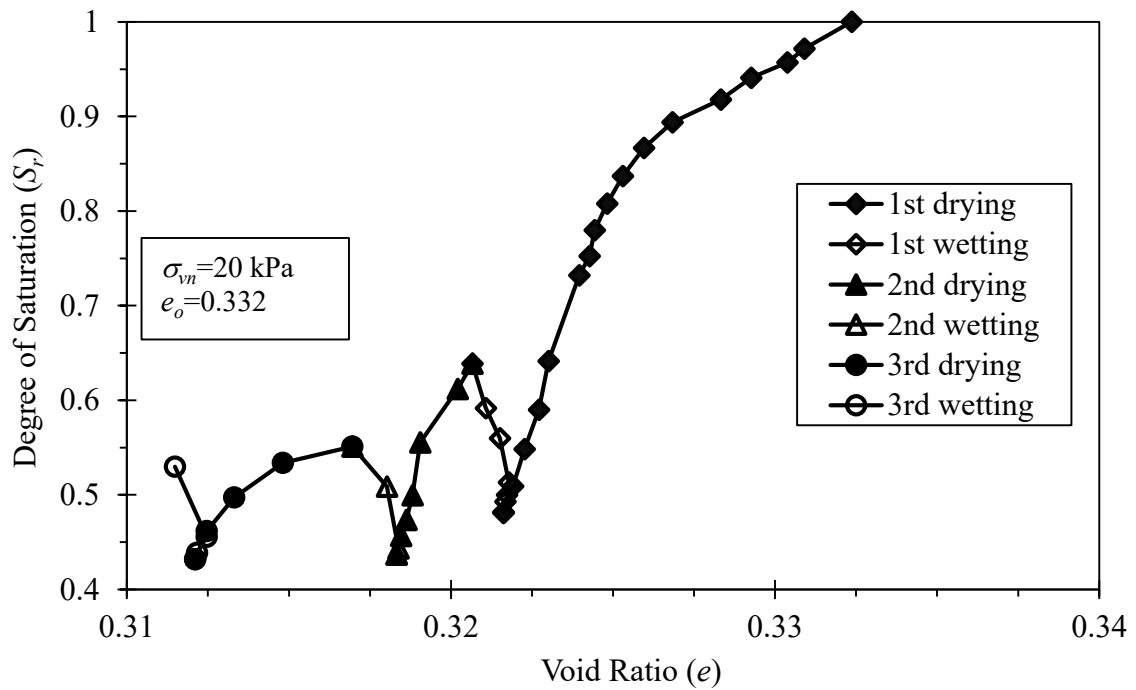


Fig. 3. 6 S_r - e relationship during three drying-wetting cycles

3.3.2. Variations of effective dynamic mass density during drying-wetting cycles

Variations of effective dynamic mass density (ρ_{eff}) with matric suction (ψ) during three drying-wetting cycles are depicted in Fig. 3.7. Persistent increases of ρ_{eff} at low matric suctions reached an upper bound in the middle range of matric suction before beginning to fall at higher matric suctions, but as the void ratio and degree of saturation decreased during drying (see Figs. 3.4 and 3.5), the void ratio dominates at low matric suctions and the degree of saturation dominates at higher matric suctions. However, Fig. 3.7 shows that a reduction of the matric suction during wetting caused a growth of ρ_{eff} .

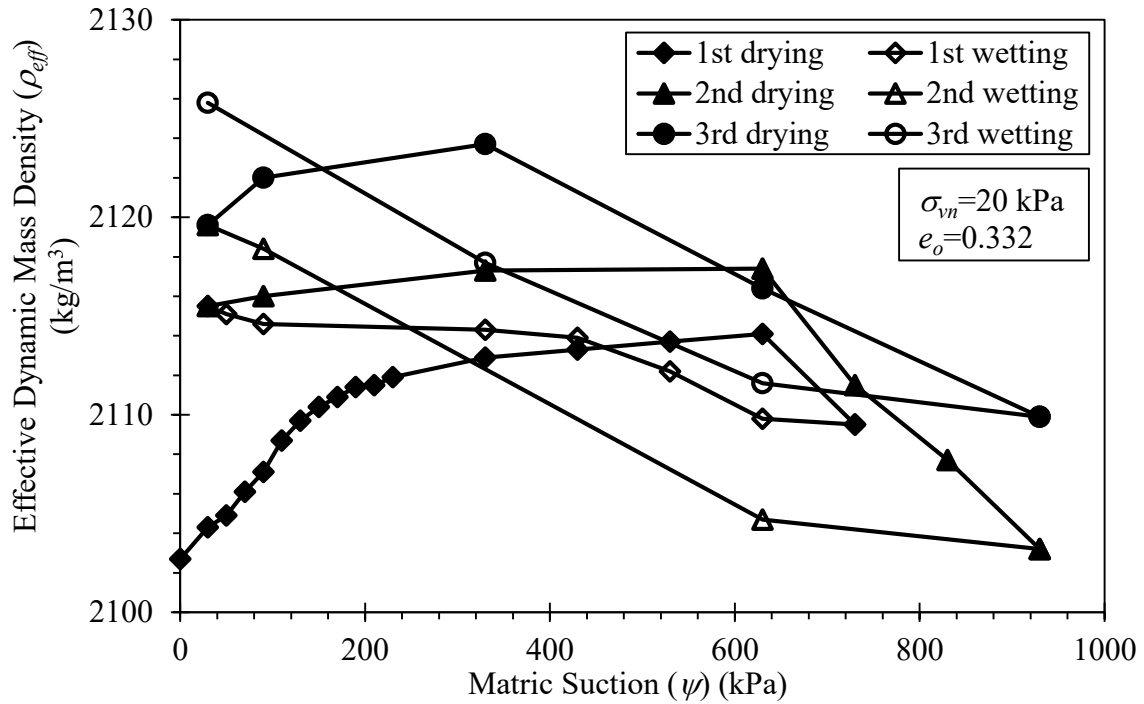


Fig. 3. 7 ρ_{eff} - ψ relationship during three drying-wetting cycles

The magnitude of effective dynamic mass density, ρ_{eff} , directly depends on the void ratio and the water content, changing considerably during the drying-wetting cycles, as reported in Figs. 3.4 and 3.5. Since the mass density of soil is inversely proportional to the specific volume ($1+e$), the relationship between $\rho_{eff}(1+e)$ and the degree of saturation is shown in Fig. 3.8 in

an attempt to investigate how the degree of saturation affects ρ_{eff} while excluding the void ratio. Obviously, a threshold of the degree of saturation $S_r \approx 0.5$ exists and it divides the range of degree of saturation into high and low ranges. Fig. 3.8 shows that at the high range ($S_r > 0.5$), variations of the degree of saturation had no or negligible effect on $\rho_{eff}(1+e)$, which indicates that changes of ρ_{eff} should be induced mainly by variations of the void ratio. In other words, the amount of viscous layer coupling with soil particles should be constant regardless of variations in the water content. However, at the low range ($S_r < 0.5$), variations in the degree of saturation contributed directly to changes of $\rho_{eff}(1+e)$, which indicates variations in the thickness of the viscous layers.

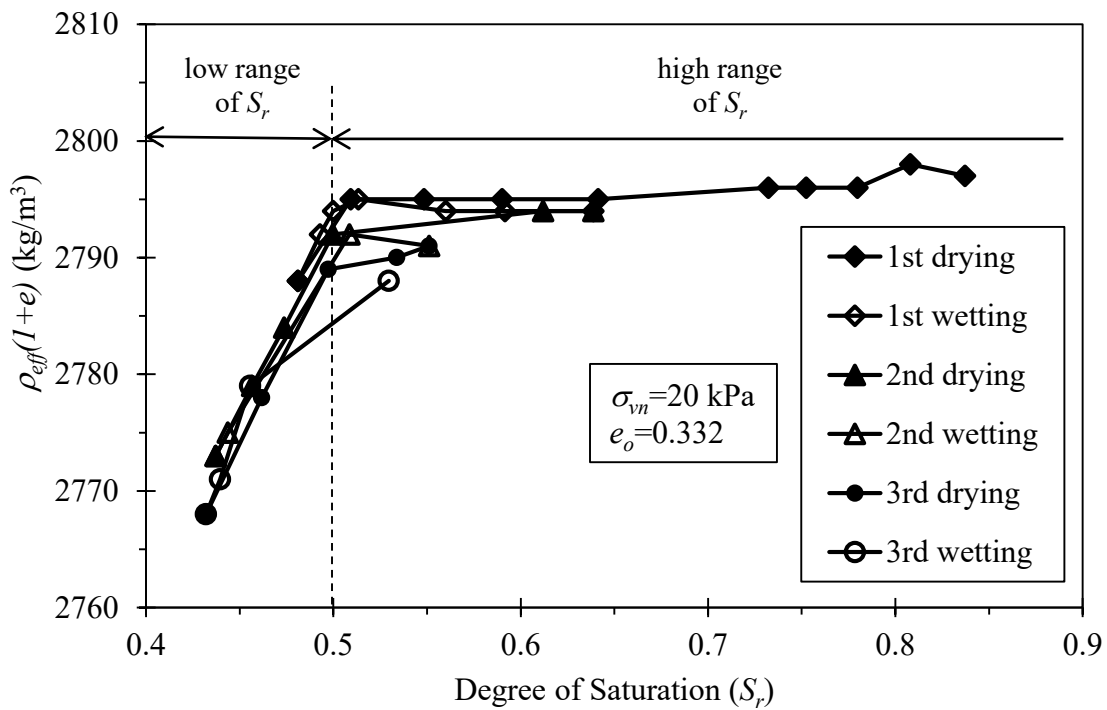


Fig. 3. 8 S_r - $\rho_{eff}(1+e)$ relationship during three drying-wetting cycles

3.3.3. Variations of G_{max} during drying-wetting cycles

The three drying-wetting cycles enable the investigation of effects of matric suction as well as degree of saturation on G_{max} as shown in Fig. 3.9, where $G_{max}/f(e)$ was used instead of G_{max} to

exclude the effect of the void ratio, and where $f(e)=1/(0.3+0.7e^2)$ is the void ratio function proposed by Hardin (1978). As expected, $G_{max}/f(e)$ increased with an increase in matric suction at a given degree of saturation. According to Wheeler et al. (2003), and Ng and Zhou (2014), an increase in the matric suction within the free water and meniscus water (i.e. pore water forms between the particles as capillary bridges) will generate extra normal inter-particle forces which enhance the soil mechanical properties. Therefore, the soil stiffness should be proportional to matric suction for the full range of degree of saturation, except for the dried state.

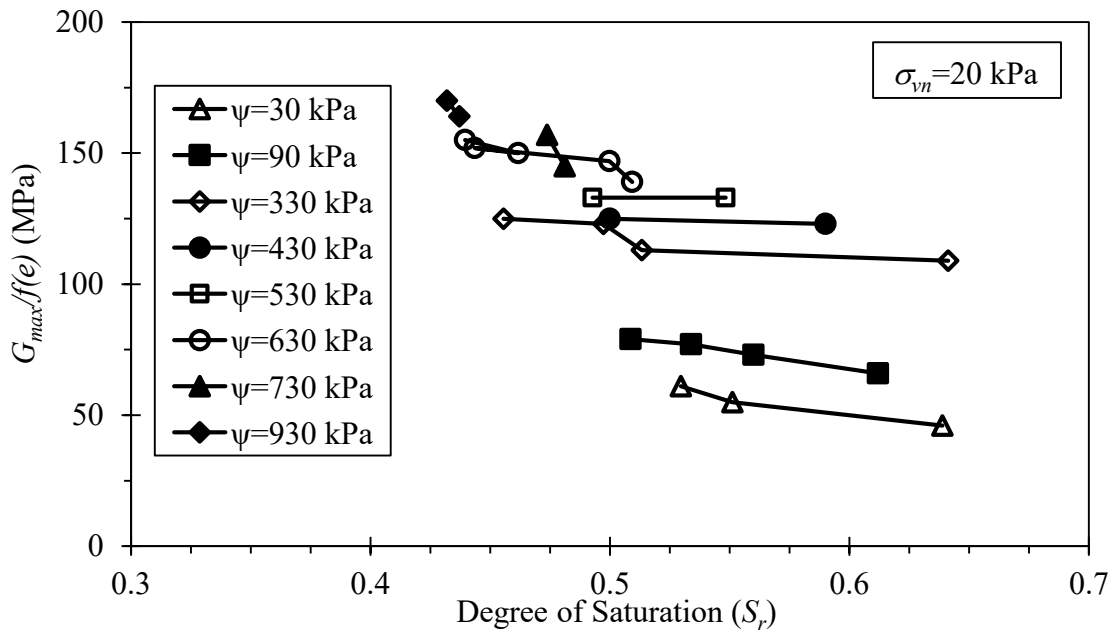


Fig. 3. 9 $G_{max}/f(e)$ - S_r relationship during three drying-wetting cycles

Furthermore, matric suction generates inter-particle forces through the contact area between pore water and particle surfaces (Alonso et al. 2010; Han and Vanapalli 2016; Vanapalli et al. 1996), and since the total contact area between the pore water and particle surfaces is proportional to the amount of water phase, the enhanced mechanical properties of soil induced by matric suction are proportional to the degree of saturation (Alonso et al. 2010; Gray and Schrefler 2001; Öberg and Sällfors 1997). However, Fig. 3.9 shows that at a given matric

suction, the values of $G_{max}/f(e)$ are higher at lower degrees of saturation; this indicates there are other influencing factors in addition to void ratio, degree of saturation, and matric suction, whose contributions accelerated as the degree of saturation decreased. Two factors that have minor effects on mechanical properties of saturated soils, but possibly play vital roles in the response of unsaturated soils, are the van der Waals attraction and electric double layer repulsion (Lu and Likos 2006; Santamarina 2002).

3.3.4. Effects of van der Waals attraction and electric double layer repulsion on G_{max} during drying-wetting cycles

The van der Waals attraction (the attractive intermolecular force) and electric double layer repulsion (the repulsive force that exists among the cations in the electric double layers at the soil/water interface) between two spheres are estimated using Eq (3.2) and Eq (3.3), respectively (Israelachvili 2011):

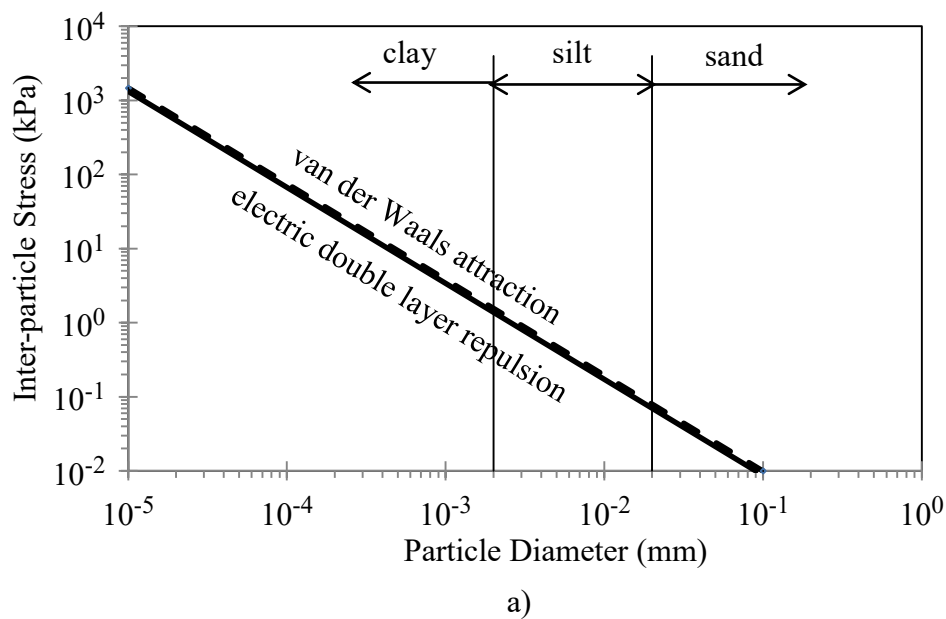
$$F_{vdw} = \frac{A}{6D^2} \frac{(R_1 R_2)}{(R_1 + R_2)} \quad (3.2)$$

$$F_{ddl} = \kappa Z e^{-\kappa D} \frac{(R_1 R_2)}{(R_1 + R_2)} \quad (3.3)$$

where R_1 and R_2 are radii of the two spheres, D is the separation between particle surfaces, A is the Hamaker constant (A is proportional to the density of interacting particles and depends on the medium between the particle surfaces), Z is the interaction constant, which is a function of the electrolyte valency and the properties of particle surfaces, and κ^{-1} is the Debye length, which is a function of the solution and on the geometry and separation. As the van der Waals attraction follows a power-law decay with separation and the electric double layer repulsion decreases exponentially, the former decays slower at short distances but faster at larger

distances than the latter. According to Tan (2010) the attractive forces dominate between particles at distances smaller than $20 \text{ \AA}$, whereas the repulsive forces dominate for particles at larger distances. Since the porosity and pore size distribution determine the distance between particles in a soil body, an increase in porosity would enhance the repulsive force and diminish the attractive force.

Even though the two forces are proportional to particle diameter as shown in Eq (3.2) and Eq (3.3), the corresponding inter-particle stresses generated within a soil body were reported to inversely proportional to particle diameter as showed in Fig. 3.10a (Ingles 1962). The inter-particle stress generated is significant for clay particle while it is minor for silt and especially for sand particles. Hence, the effect of the two forces on the mechanical properties of soils would be proportional to the proportion of clay particle.



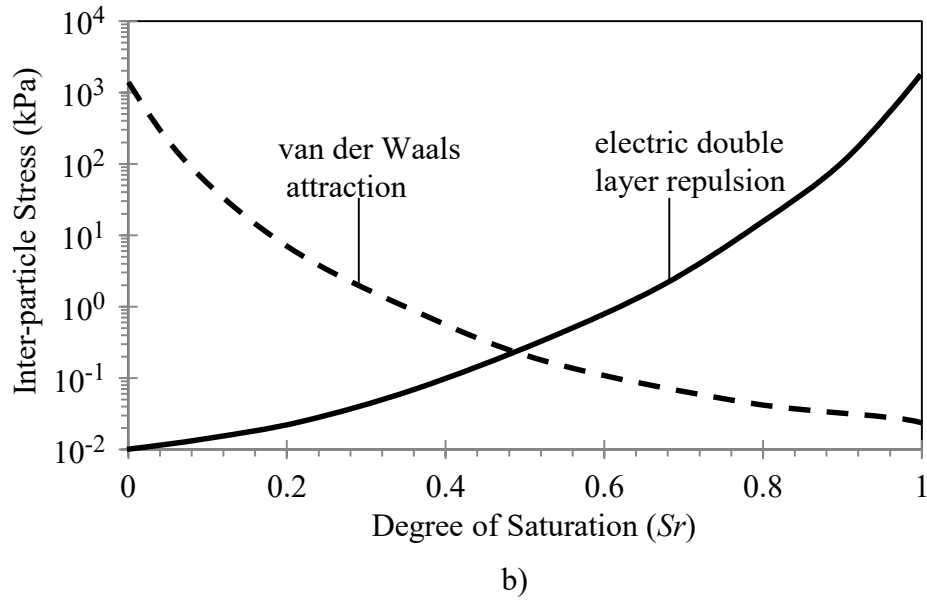


Fig. 3. 10 Dependence of inter-particle stress generated by van der Waals and electric double layer forces on (a) particle diameter (after Ingles 1962), and (b) degree of saturation (after Lu and Likos 2006)

Apart from the clay content and porosity, variations in the degree of saturation also influence the van der Waals and electric double layer forces. Fig. 10b illustrates the dependence of inter-particle stresses, generated by the two forces, on the degree of saturation. According to Visser (1995), the van der Waals attraction between clay (hectorite) particles in water is greatly smaller than in air with the Hamaker constant of 0.49×10^{-20} J in water and 7.4×10^{-20} J in air.

At the saturated state, water is the only medium existing among the particles; this corresponds to the thickest electric double layers and the minimum value of the Hamaker constant, and therefore inter-particle stresses induced by the van der Waals attraction and electric double layer repulsion reach their lower and upper bound values, respectively, as reported by Lu and Likos (2006). Effect of the attractive force on the mechanical properties of soil might dominate in case separations shorter than $20 \text{ \AA}$ hold the highest fraction (e.g. extremely dense saturated soils), whereas in most other cases effect of the repulsive forces

dominate and lead to almost no attraction or even repulsive inter-particle stresses that adversely influence the G_{max} of saturated soils.

During the drying process, the water phase decreased and the air phase increased, which led to the evolution of van der Waals attraction-induced inter-particle stress and degradation of electric double layer repulsion-induced inter-particle stress; this facilitates the aggregation of fine particles and growth in the combined contribution of the two forces on G_{max} . This phenomenon continues until the dry state is reached where the absence of water phase denotes the disappearance of electric double layer repulsion-induced inter-particle stress and the upper bound of van der Waals attraction-induced inter-particle stress. An opposing phenomenon occurs during the wetting process as water is added, cations in the electric double layers are hydrated and the electric double layers become thicker; these actions reduce the van der Waals attractions and increase the electric double layer repulsions. Therefore, the overall contribution of the forces induces a decline of G_{max} with increasing degrees of saturation.

By considering the combined effect of van der Waals attractions and electric double layer repulsions on G_{max} during drying and wetting processes, rises of $G_{max}/f(e)$ with decreasing degrees of saturation at constant matric suctions during three drying-wetting cycles shown in Fig. 3.9 can now be explained. A reduction in the degree of saturation led to a decline in the inter-particle stresses induced by matric suction, but it also led to an increase in the resultant attractive stresses induced by van der Waals attractions and electric double layer repulsions. The result is that G_{max} for a given stress state and void ratio experienced growth instead of a fall with a decrease in the degree of saturation.

3.3.5. Effects of drying-wetting cycles on G_{max}

The responses of G_{max} during three drying-wetting cycles are shown in Fig. 3.11. Similar to

observations reported in the literature, G_{max} was always larger during wetting than in the previous drying at the same level of matric suction in the first drying-wetting cycle. This trend also presented itself in the second and third cycles due to lower void ratios and degrees of saturation during the wetting processes, as shown in Fig. 3.4 and Fig. 3.5.

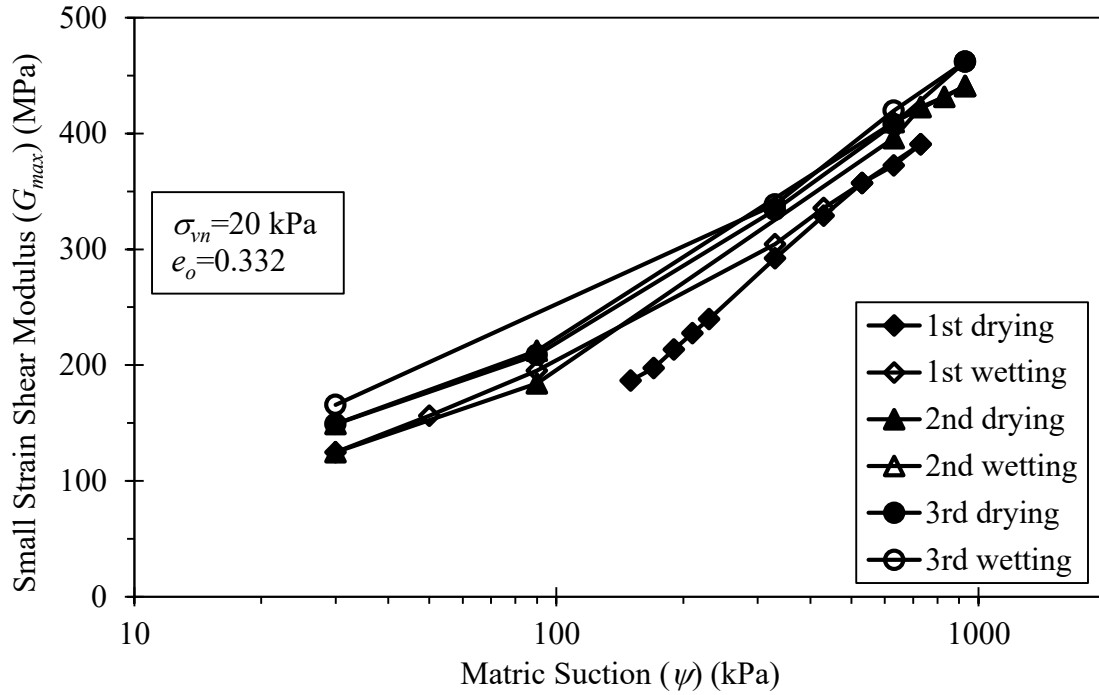


Fig. 3. 11 G_{max} - ψ relationship during the three drying-wetting cycles

As expected, G_{max} increased with increasing number of cycles, especially at the low range of matric suctions, reflecting the accumulation in irreversible changes of void ratio and degree of saturation. Therefore, the effect that the drying-wetting cycles have on G_{max} can be captured by evaluating the effects of the void ratio and degree of saturation.

3.3.6. Variation of void ratio during the loading-unloading cycle of net stress

Apart from drying-wetting cycles, irreversible compressions also occurred in the loading-unloading cycle of vertical net stress, as shown in Fig. 3.12. This observation demonstrated similar trends in the variation of void ratio with net stress as those in the literature (e.g. Alonso

et al. 2005; Ho et al. 1992). It is therefore expected that due to irreversible reductions of the void ratio, the soil sample also experienced hydraulic hysteresis during the loading-unloading cycle of net stress.

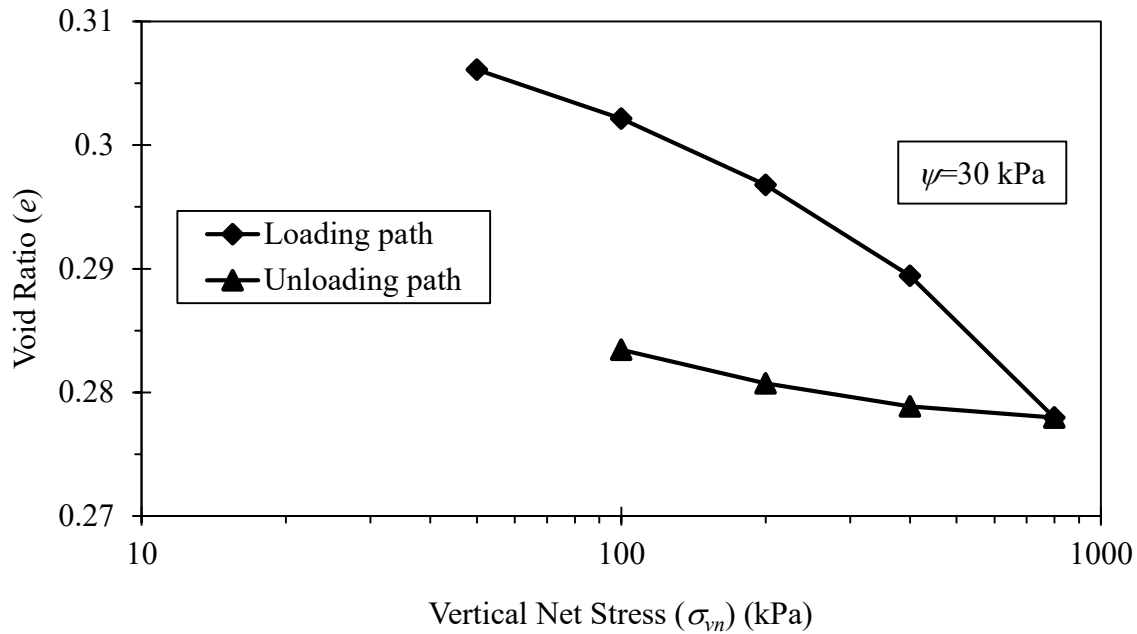


Fig. 3. 12 σ_{vn} - e relationship in the loading-unloading cycle

3.3.7. Hydraulic hysteresis behaviour during the loading-unloading cycle of net stress

While investigating hydraulic hysteresis in terms of the degree of saturation, it is of importance to consider variations of void ratio and gravimetric water content. As depicted in Fig. 3.13, during the loading stage, the void ratio dominates with consistent increases in the degree of saturation even though the gravimetric water content consistently decreased. However, during unloading, the gravimetric water content was more dominant because the degree of saturation continued to grow. Nonetheless, the plastic volumetric strain that occurred in the loading-unloading cycle of vertical net stress (see Fig. 3.12), contributed to the differences between degrees of saturation for a given vertical net stress, as shown in Fig. 3.13.

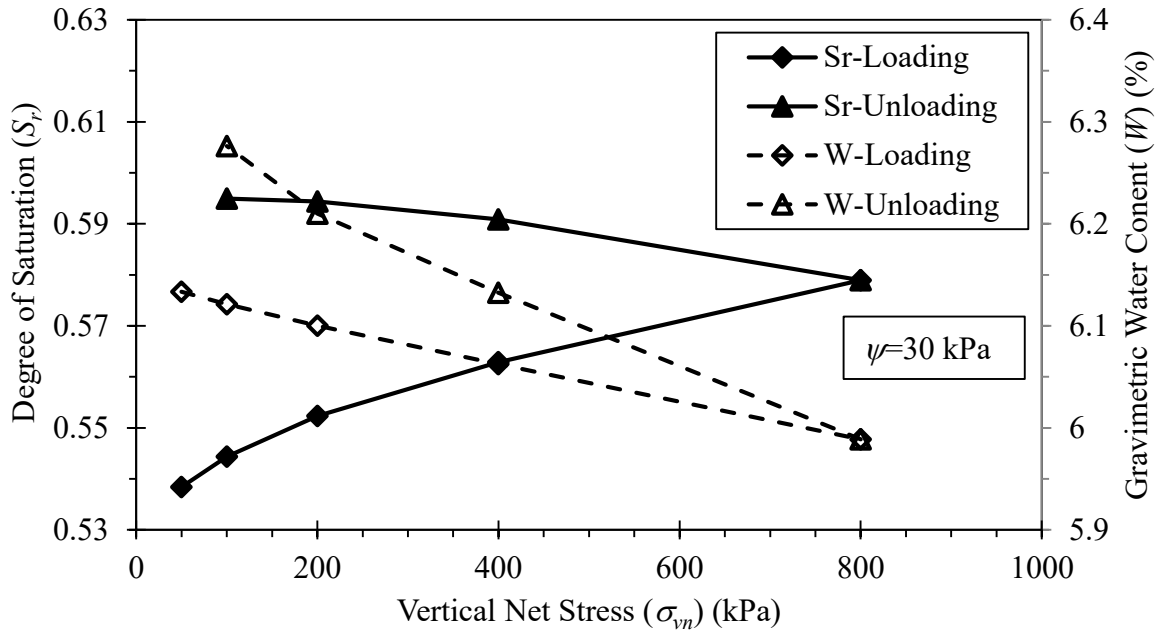


Fig. 3. 13 Hydraulic hysteresis in a loading-unloading cycle

Observations of hydraulic hysteresis under a loading-unloading cycle of net stress at constant suctions were reported by Zakaria (1995) and Gallipoli et al. (2003) for compacted speswhite kaolin tested in suction-controlled triaxial tests, and by Pham et al. (2004) for slurry processed silt in pressure plate tests. In these tests, the loading/unloading stage was conducted by increasing/decreasing the external stress (i.e. cell pressure in triaxial tests and vertical pressure for the pressure plate tests), while p_a and p_b remained unchanged. The degree of saturation of speswhite kaolin and processed silt increased considerably in the loading stage but not as much in the unloading stages, whereas the gravimetric water content decreased in the loading stages and increased in the unloading stages. The hydraulic hysteresis that occurred in the loading-unloading cycle of net stress probably resulted from the plastic volumetric strains that accumulated within the cycle, which caused irreversible changes in the pore size distribution and corresponding soil water retention, even at a constant suction. Farulla and Rosone (2012) and Rostami et al. (2013) reported that in the loading/unloading stages of net stress, the micro-pore and macro-pore volumes altered, but most changes occurred in the latter.

3.3.8. Variations of effective dynamic mass density during the loading-unloading cycle of net stress

Fig. 3.14 shows that ρ_{eff} grew consistently with the vertical net stress, but at reducing rates during loading. The opposite trend occurred during unloading where ρ_{eff} decreased at an increasing rate. The effective dynamic mass density is a function of the void ratio and gravimetric water content, so the relationship between ρ_{eff} and vertical net stress revealed that the void ratio dominated over the gravimetric water content at the stress levels investigated. Variations of ρ_{eff} (Fig. 3.14) were obviously associated with changes in the void ratio during loading and unloading (Fig. 3.12).

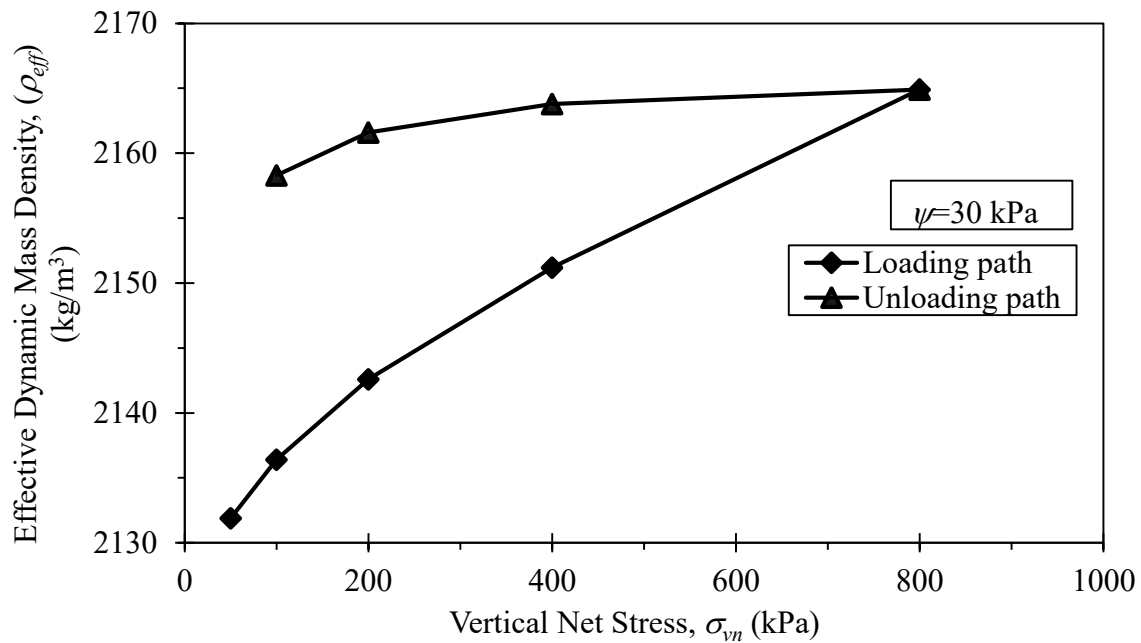


Fig. 3. 14 σ_{vn} - ρ_{eff} relationship in a loading-unloading cycle

3.3.9. Variations of G_{max} during the loading-unloading cycle of net stress

Fig. 3.15 shows the variations of G_{max} with vertical net stress at a constant matric suction; here G_{max} kept increasing with the vertical net stress during loading, and during the corresponding unloading G_{max} was less for a given vertical net stress. This response of G_{max} is the opposite of

that reported by other researchers (e.g. Fioravante et al. 2013; Zeng & Ni 1998) for saturated soils where G_{max} during unloading was higher than during loading at a given stress. For a saturated soil, at a given stress level, G_{max} depends reversely on the void ratio (Hardin 1978; Richart et al. 1970; Vucetic and Dobry 1991), therefore, the plastic volume change accumulated during a loading-unloading cycle results in higher values of G_{max} during unloading.

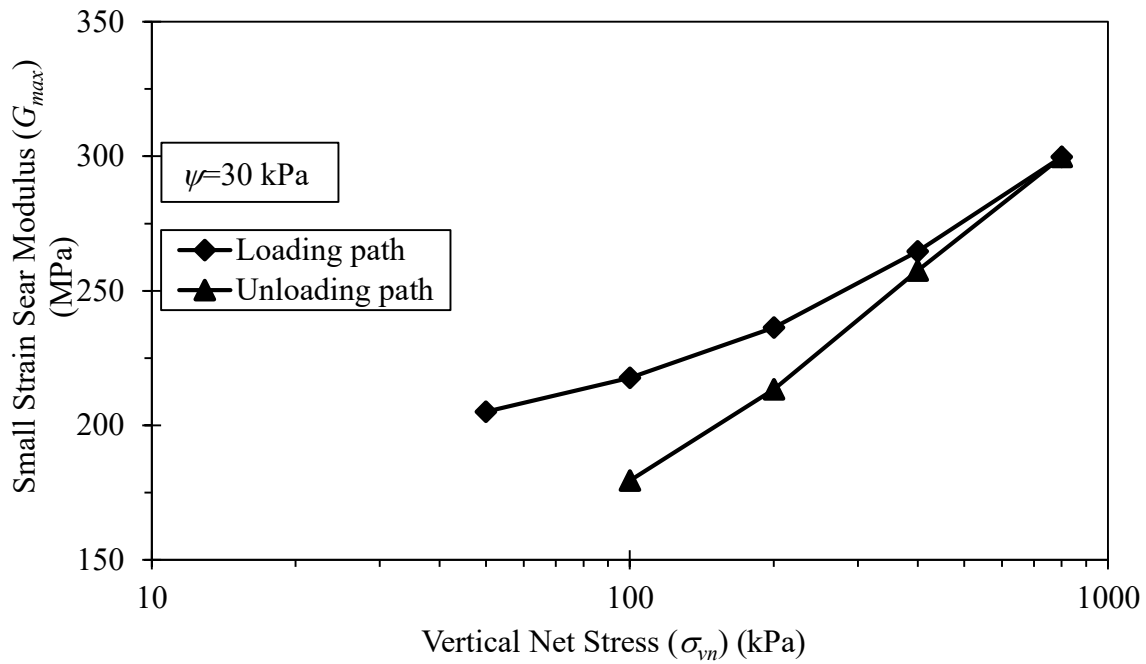


Fig. 3. 15 σ_{vn} - G_{max} relationship in a loading-unloading cycle

For an unsaturated soil, the response of G_{max} during a loop of loading and unloading of net stress depends on variations of both the void ratio and degree of saturation which follow opposite trends as shown in Fig. 3.12 and Fig. 3.13. Hence, G_{max} during an unloading process might have higher or lower values than in the previous loading process depending on which effect (i.e. reduction in void ratio and increase in degree of saturation) outweighs the other. That explains different responses of G_{max} during the unloading process between the soil investigated in this study and Zenoz kaolin reported by Biglari et al. (2012). After a stress loop, it was reported that the decrease in void ratio and increase in degree of saturation for Zenoz

kaolin were 20% and 24.3%, and for the soil in this study were 6.3% and 10.6%, respectively. It is rational to believe that for Zenoz kaolin, the large decrease of void ratio (i.e. 20%) led to the dominant effect of void ratio over the effect of degree of saturation on G_{max} ; on the contrary, for the soil investigated in this study, effects of degree of saturation outweighed influence of the void ratio (small decrease of 6.3%) on G_{max} .

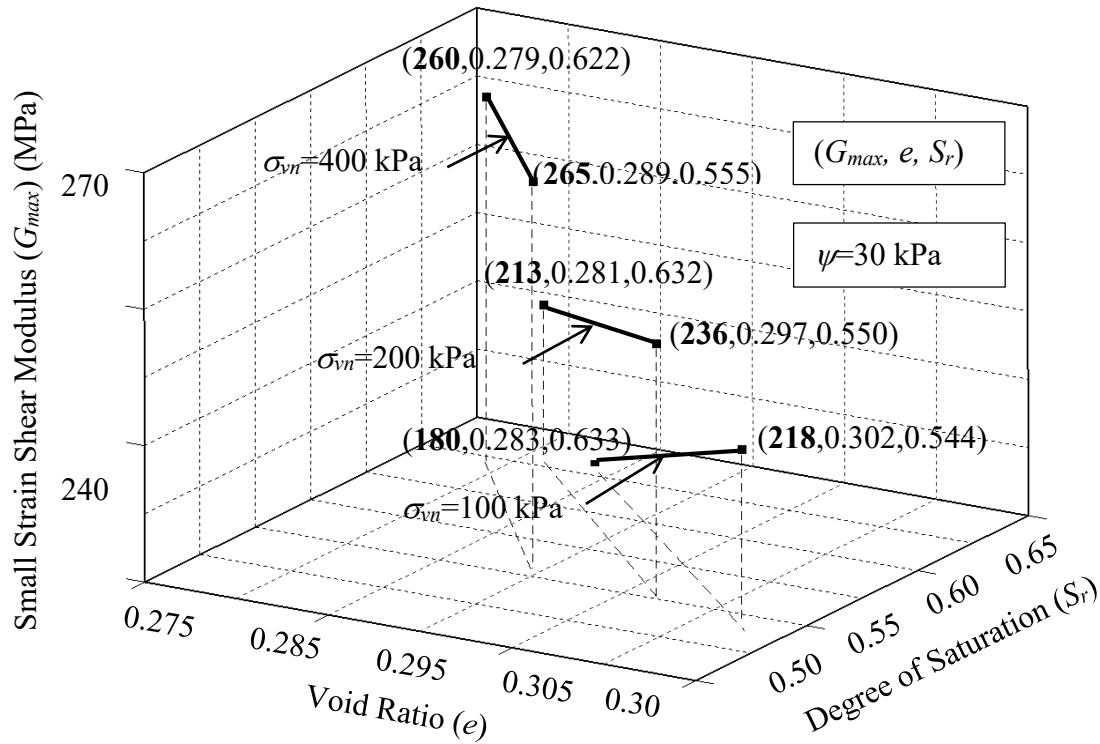


Fig. 3. 16 Variation of G_{max} with void ratio and degree of saturation

in the loading-unloading cycle

Fig. 3.16 depicts the variations of G_{max} with void ratio and degree of saturation in the loading-unloading cycle investigated. The decrease in G_{max} due to a decrease in the void ratio and an increase in the degree of saturation, as shown in Fig. 3.16, indicates how the degree of saturation affected G_{max} at the stress levels investigated. Under a constant matric suction $\psi = 30$ kPa, and at a vertical net stress $\sigma_{vn} = 100$ kPa, after a stress loop, G_{max} decreased 17.5% (from 218MPa to 180MPa) when the corresponding void ratio decreased by 6.2%, and the

corresponding degree of saturation increased by 16.2%. At higher vertical net stresses (i.e. 200 kPa and 400 kPa), after a stress loop, variations in the void ratio, degree of saturation and resulting G_{max} were smaller.

To investigate the effect that the degree of saturation has on G_{max} while excluding the influence of void ratio, variations of $G_{max}/f(e)$ with vertical net stress and degree of saturation during the loading-unloading cycle are depicted in Fig. 3.17. Under a constant matric suction $\psi = 30$ kPa, at a given vertical net stress and after a stress loop of the loading-unloading cycle, $G_{max}/f(e)$ decreased as the degree of saturation increased. The highest reduction of $G_{max}/f(e)$ of 19.2% occurred at vertical net stresses of 100 kPa; this corresponds to an increase of 16.2% in the degree of saturation.

As discussed earlier, an increase in the degree of saturation leads to a rise in the contribution of the matric suction investigated (due to an increase in the contact area between pore water and soil particles) and a fall in the combined effects of van der Waals attractions and electric double layer repulsions (due to a decrease in the resultant attractive inter-particle forces). Fig. 3.17 shows that the latter had a greater effect during the unloading stage so the effects of the van der Waals attractions and electric double layer repulsions should be captured in order to predict the G_{max} in partially saturated soils.

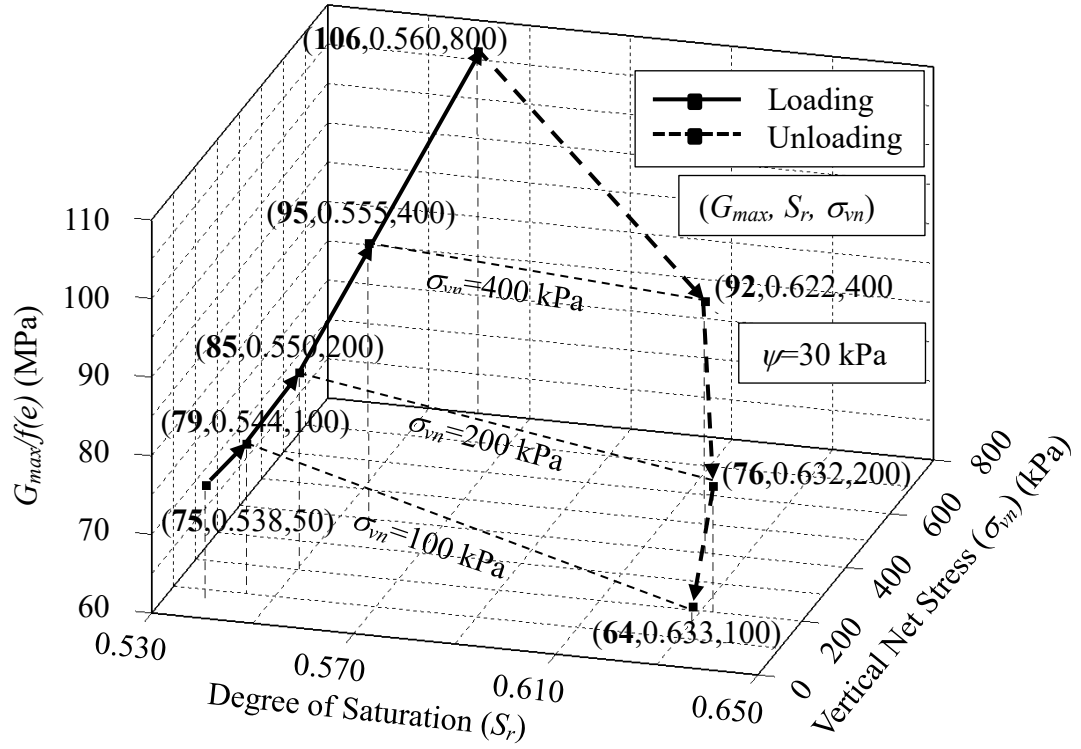


Fig. 3. 17 Variation of $G_{max}/f(e)$ with vertical net stress and degree of saturation in the loading-unloading cycle

3.4 Relationship for G_{max} incorporating the hydraulic hysteresis effect

3.4.1 Model establishment

The relationship developed to predict G_{max} for reconstituted unsaturated soils in this study was inspired by the Hardin-style equations for saturated soils (Hardin 1978; Hardin and Blandford 1989) where the void ratio function is used as an alternative to the overconsolidation ratio as shown in Eq. (3.2):

$$\frac{G_{max}}{p_r} = f(e)a \left(\frac{p'}{p_r} \right)^n \quad \text{for saturated soil} \quad (3.2)$$

where a , n are material constants; p' is the mean confining effective stress; $f(e)$ is the void ratio function presenting the properties of packing and density, $f(e)=1/(0.3+0.7e^2)$ is for saturated

sands and clays (Hardin 1978), and p_r is the reference pressure (atmospheric pressure).

The inter-particle forces for unsaturated soils are attributed to the net stress, matric suction, van der Waals attractions, and electric double layer repulsions. It is believed that the contributions of a given net stress to the mechanical properties of unsaturated soil, including the small strain shear stiffness, are independent of the water content (Bishop 1959; Khalili et al. 2004; Khalili and Khabbaz 1998; Lu and Likos 2006; Vanapalli et al. 1996), whereas contributions from a given matric suction are proportional to the degree of saturation (Alonso et al. 2010; Gray and Schrefler 2001; Öberg and Sällfors 1997). Figs. 3.9 and 3.17 show that at a given void ratio, net stress, and matric suction, an increase in the degree of saturation led to a decrease in G_{max} despite an increase in the contribution of matric suction. This indicates a decrease of the combined contribution of van der Waals attractions and electric double layer repulsions that dominates over the contribution of matric suction at the stress states investigated. Therefore, an equation to predict G_{max} while incorporating all the above-mentioned contributions was proposed in this study.

The proposed Eq. (3.3) indicates that the contribution of net stress follows a power law that is similar to saturated soils, and is independent of the degree of saturation. Effects of degree of saturation on G_{max} are evaluated in the contribution of matric suction and the combined contribution of van der Waals attractions and electric double layer repulsions. It is noted that the two contributions follow different patterns with the variation of degree of saturation. During a drying process beginning from saturated state, the combined contribution of van der Waals attractions and electric double layer repulsions increases persistently with decreasing degree of saturation, whereas the contribution of matric suction follows a rapid growth in the early stage due to fast increases of matric suction, before commencing to decrease to zero when approaching the dry state due to the loss of pore water. The reverse patterns occur during a

wetting process. In addition, at the same stress state, while the former is proportional to the degree of saturation, the latter is reversely proportional to the degree of saturation, as Figs. 3.9 and 3.17 show. Thus, the two contributions need to be evaluated separately to capture hysteresis. In Eq. (3.3), variations of the two contributions with degree of saturation are captured through parameters m and k , while parameters b and c are for evaluating their magnitudes. The proposed equation can be presented as follows:

$$G_{max} = p_r f(e) \left[a \left(\frac{\sigma_n}{p_r} \right)^n + b \left(\frac{\psi S_r}{p_r} \right)^m + c (1 - S_r)^k \right] \quad (3.3)$$

where a , n , b , m , c and k are the material constants, $p_r = 100$ kPa is the reference pressure, $\sigma_n = p - u_a$ is the net stress, $\psi = u_a - u_w$ is the matric suction, and S_r is the degree of saturation. All the material constants can be determined using the nonlinear least-square data fitting method with at least six observations. At saturated state, when $u_a = u_w$, $\psi = 0$, and $S_r = 1$, Eq. (3.3) returns to Eq. (3.2) which is for saturated soils.

3.4.2 Model Calibration

Six model parameters (i.e. a , n , b , m , c , and k) were determined by using the least-squares data fitting method (Coleman and Li 1996; Marquardt 1963). This determination was based on the values of two independent variables (i.e. the net stress and the matric suction) and two dependent variables (i.e. the void ratio and the degree of saturation) during the three drying-wetting cycles and the loading-unloading cycle of net stress. The objective function $f(x)$ of the least squares problems is the sum of the squares of residuals that represent the absolute differences between the measured and corresponding computed values of G_{max} . By solving the minimisation problem presented in Eq (3.4), the model parameters which are variables of the function could be obtained:

$$\min_x f(x) = \min_x \sum_{i=1}^j (G_{maxi} - G_{maxi}(x))^2 \quad (3.4)$$

where $x = [x_1, x_2, x_3, x_4, x_5, x_6] = [a, n, b, m, c, k]$ is the vector of the model parameter, G_{maxi} and $G_{maxi}(x)$ are the i^{th} measurement and corresponding prediction of G_{max} , and j is the number of observation/measurement points.

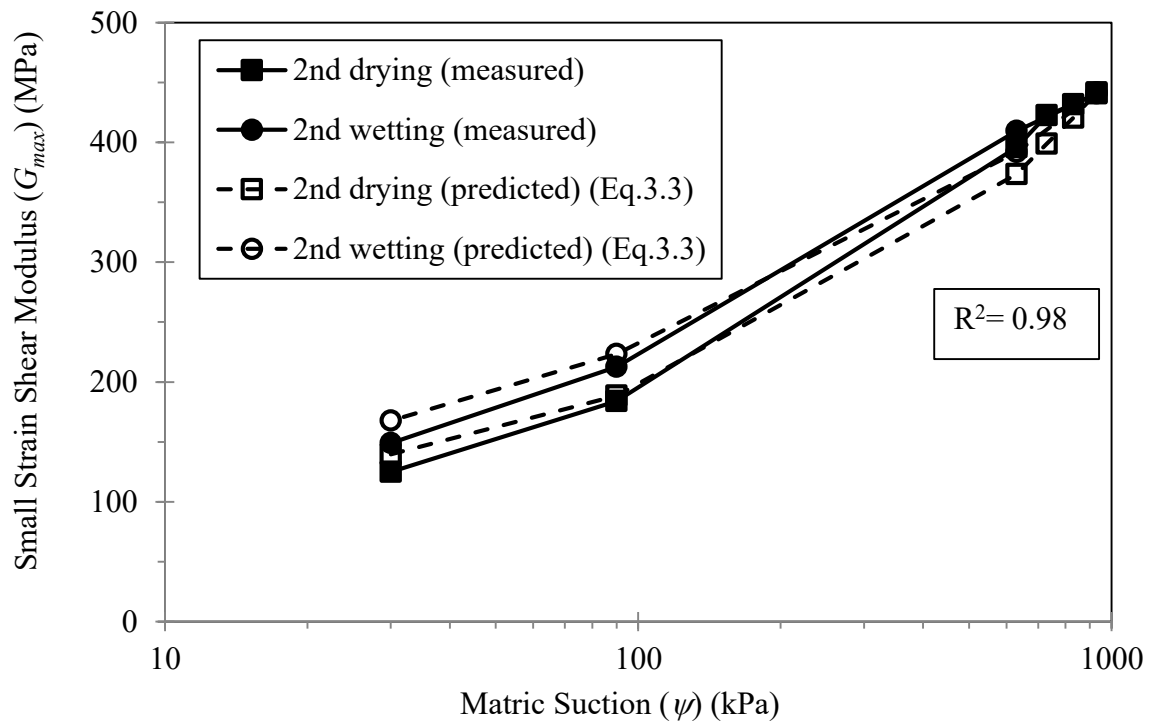
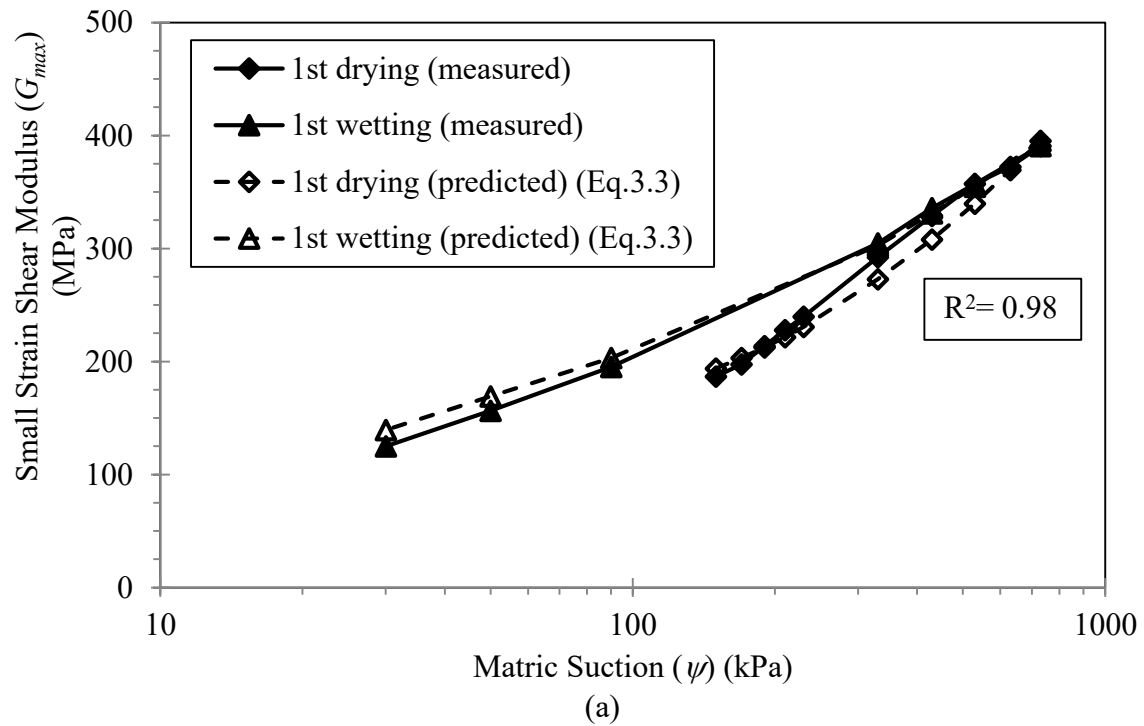
This mathematical model is nonlinear in terms of the parameters n , m , and k , and therefore determining the model parameters requires a set of initial values and an effective algorithm for iterations. The trust-region reflective optimisation algorithm utilised in this study has strong convergence properties proven to provide reliable and robust solutions (Yuan 2000). One advantage of the trust-region reflective algorithm is its ability to reduce the number of iterations (Coleman and Li 1996). This algorithm was coded in the MATLAB software package using the “lsqnonlin” function.

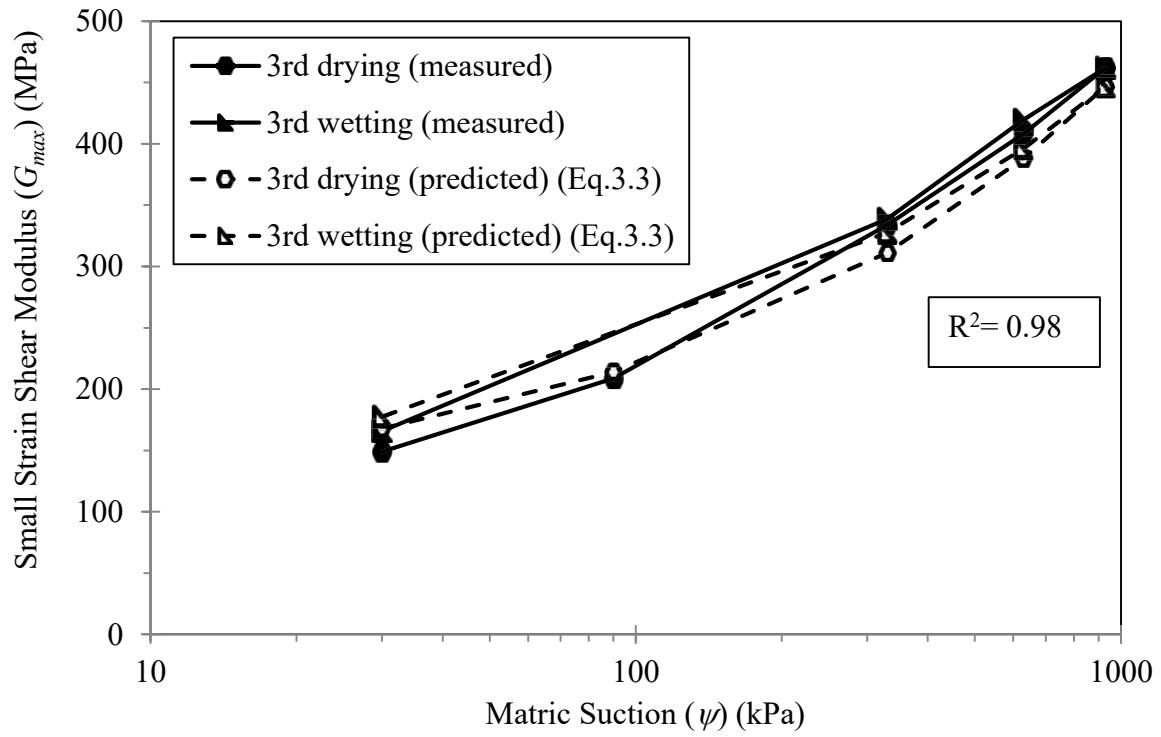
As (b, m) and (c, k) are coupled parameters, proposed to capture the effect of hydraulic hysteresis on G_{max} , the model calibration requires observations of at least one drying-wetting cycle to ensure the uniqueness of these parameters for the soil investigated. Table 3.3 is a summary of the calibrated model parameters. As shown in Figs. 3.18a-d, the predicted G_{max} values adopting the calibrated model parameters were in good agreement with the measurements during the three drying-wetting cycles and the loading-unloading cycle of vertical net stress.

In practice, magnitudes of the model parameters can also be obtained by building a Microsoft Excel spreadsheet to solve the minimisation problem presented in Eq (3.4) using the Solver Add-in. However, the procedure requires much more time.

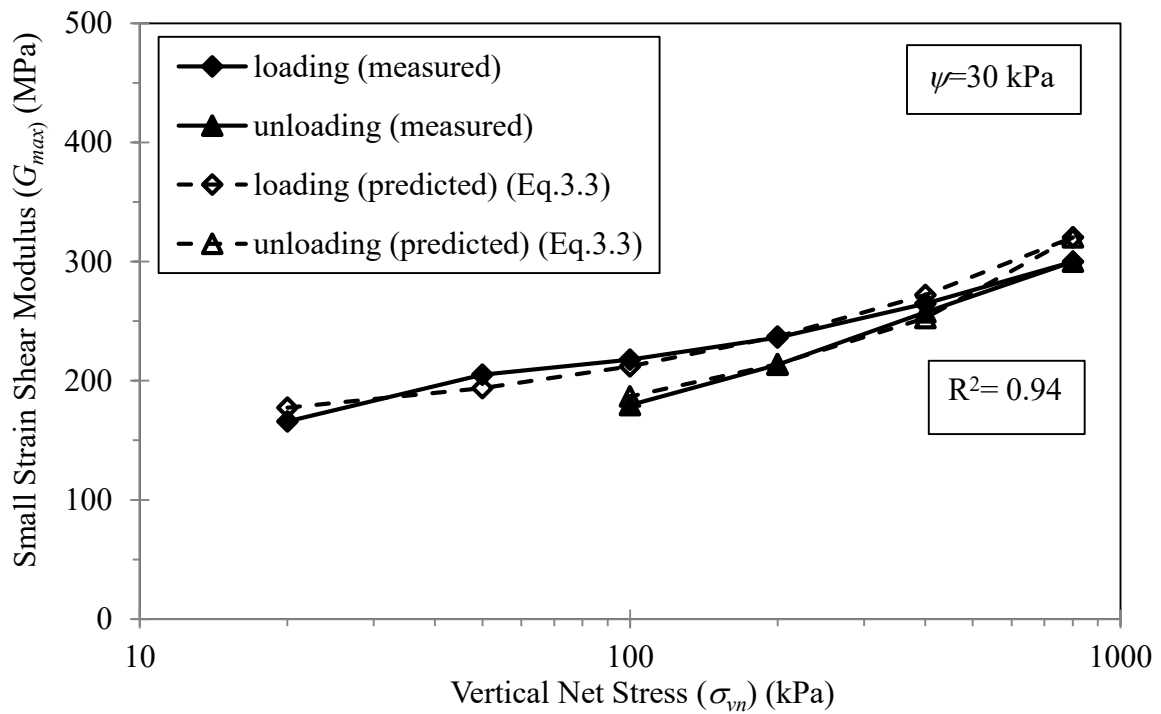
Table 3. 3 Values of calibrated model parameters for the soil tested in this study

Model parameter	a	n	b	m	c	k
Value	296	0.4	493	0.5	2307	2.7





(c)



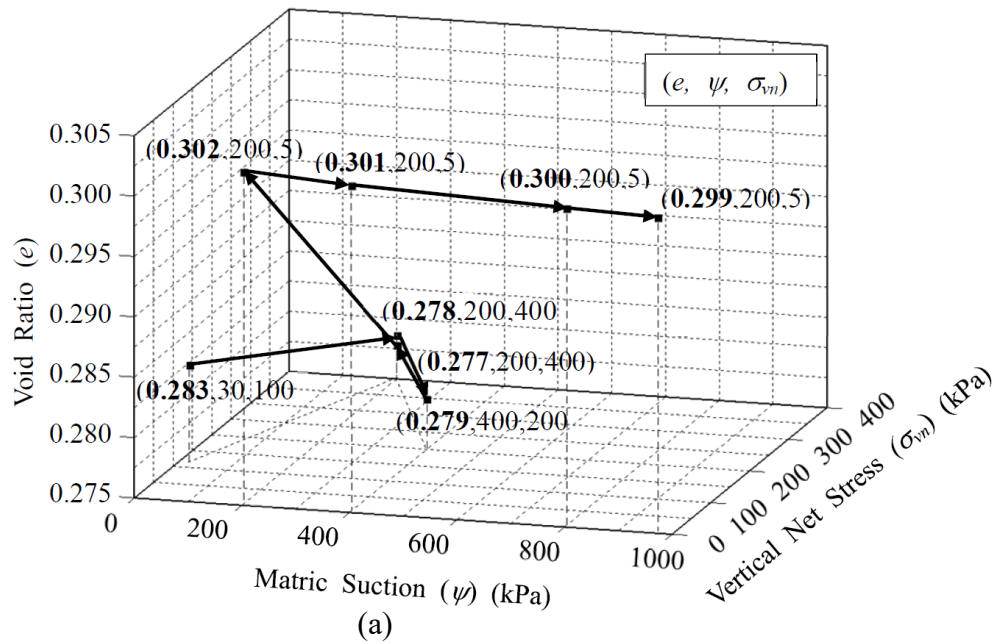
(d)

Fig. 3. 18 Measured and predicted G_{max} values during (a) the 1st, (b) the 2nd, (c) the 3rd drying-wetting cycles, and (d) the loading-drying cycle

3.4.3 Model Verification

Model verification via laboratory tests with complex loading paths

To verify the proposed model for the investigated soil, further experiments were conducted in the laboratory considering three mixed applications of matric suction and net stress, and a drying process as demonstrated in Table 3.2. Variations of the void ratio and degree of saturation with matric suction and net stress are shown in Figs. 3.19a, b. During the mix saturation with matric suction and net stress are shown in Figs. 3.19a, b. During the mix applications, responses of the void ratio and degree of saturation reveal different effects of the two stress state variables. During the stress loop with changes of 200 kPa of both matric suction and vertical net stress, while the response of void ratio shows dominant effect of net stress over matric suction as reported by Bagherieh et al. (2009) and Mašin (2010), response of degree of saturation shows dominant effect of matric suction.



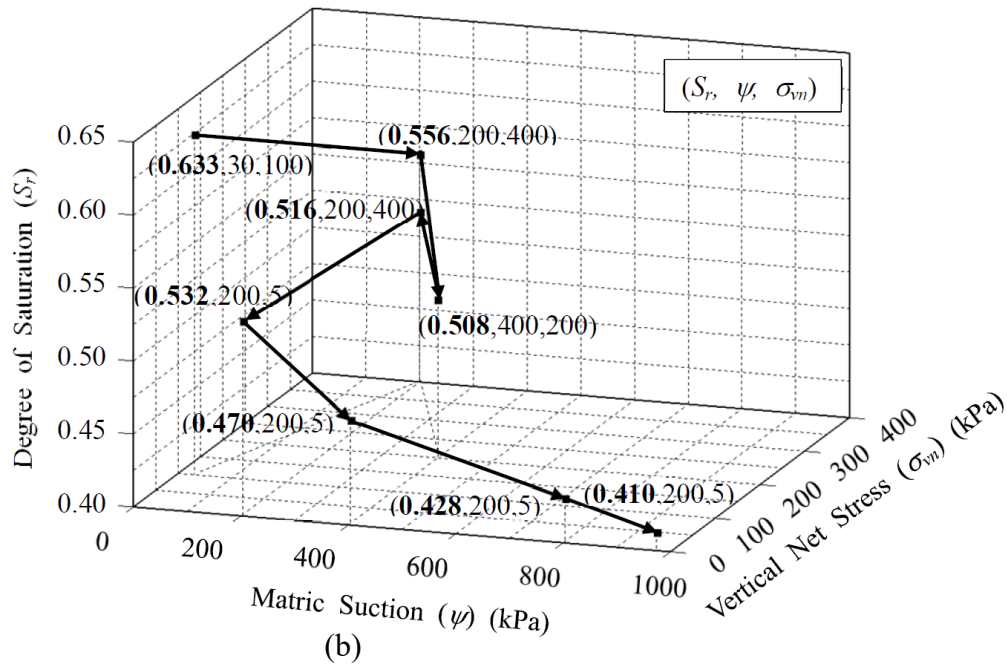


Fig. 3. 19 Variations of (a) void ratio and (b) degree of saturation during the model test stages

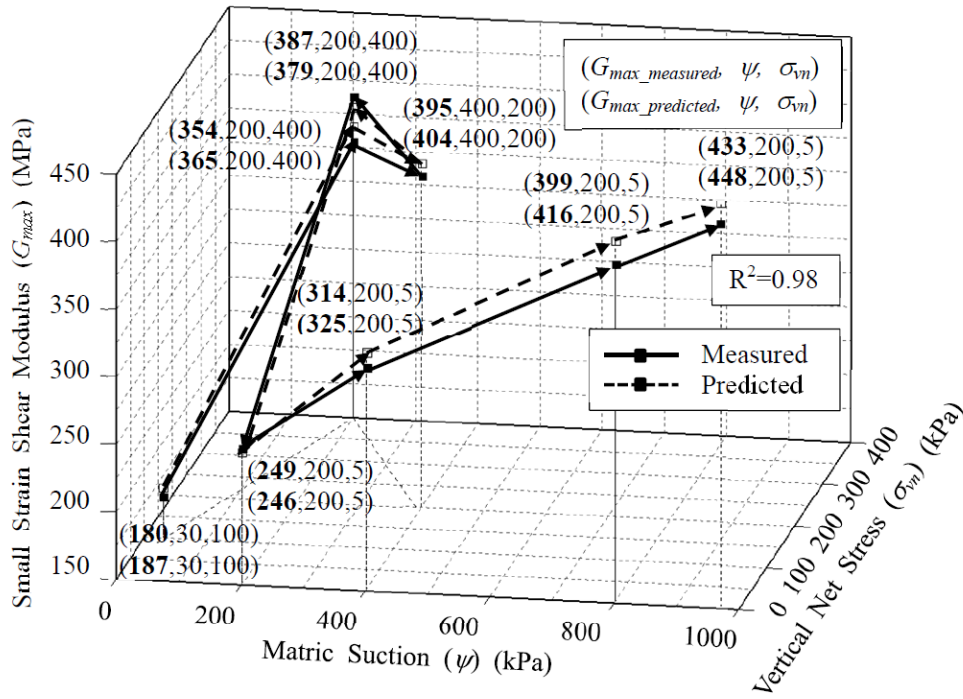


Fig. 3. 20 Measured and predicted G_{max} values during model variation test stages

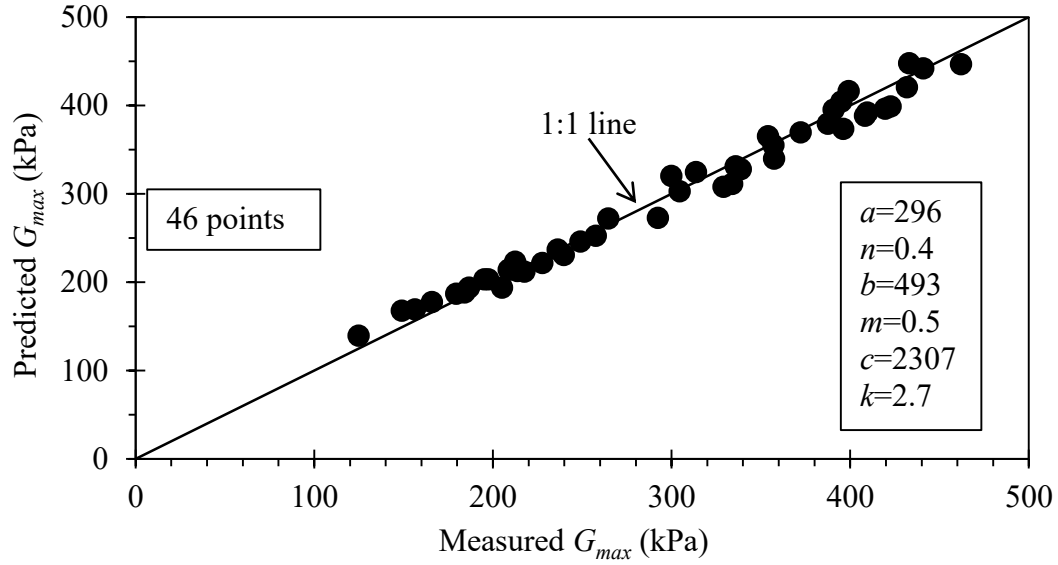


Fig. 3. 21 The entire set of measured and predicted G_{max} values in this study

As a result, G_{max} was observed to vary in accordance with variations in matric suction instead of vertical net stress (see Fig. 3.20). The observation confirms the finding of Leong and Cheng (2016) that matric suction can induce greater influence on shear wave velocity in comparison with an equal-magnitude isotropic effective stress, and can be explained by the dominant effect of the degree of saturation over the void ratio. During the drying process, the void ratio, the degree of saturation and G_{max} varied similarly to what observed in the other drying processes for the soil investigated. By adopting the calibrated model parameters reported in Table 3.3, good agreements between the measured data and the predicted results were obtained, as can clearly be observed in Fig. 3.20. The measured and predicted values of G_{max} for the soil sample, investigated in this study, are shown in Fig. 3.21.

Further verification using available data in the literature

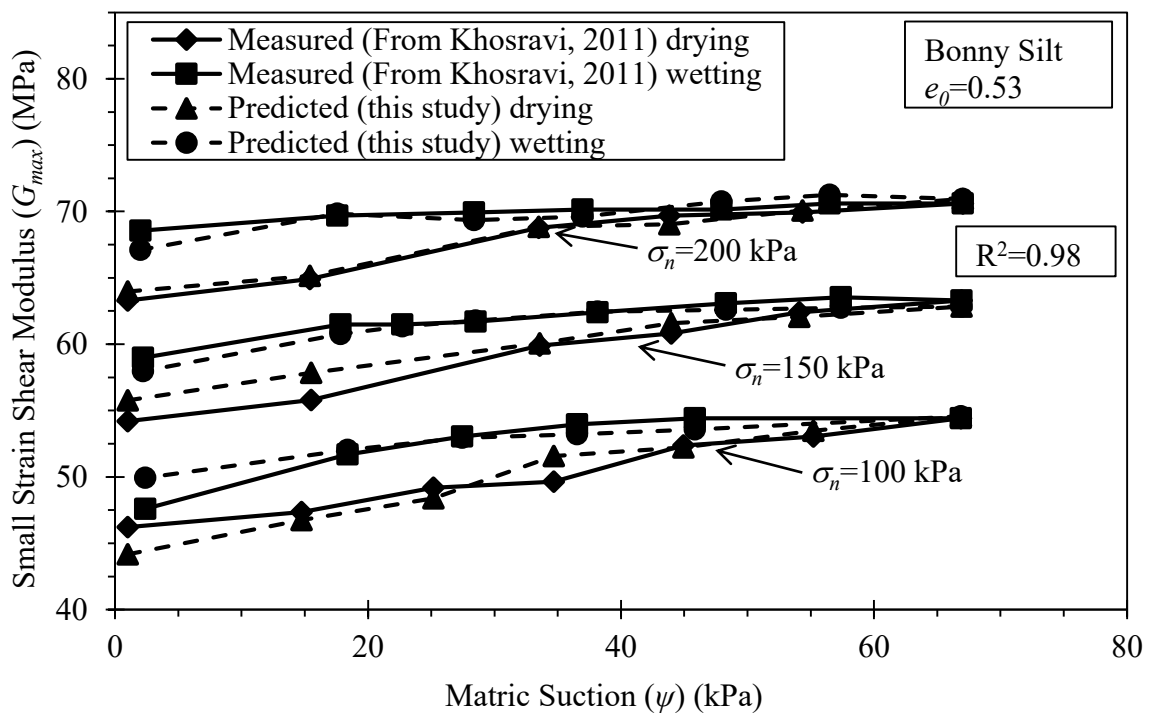
The proposed equation was then validated based on data available in the literature reported by Biglari et al. (2012), Khosravi (2011) and Ng et al. (2009) for three types of soils, including Zenoz clay, statically compacted Bonny silt, and recompacted completely decomposed granite,

respectively. Variations of the void ratio and degree of saturation under different stages of stress were reported for these soils in the above-mentioned references.

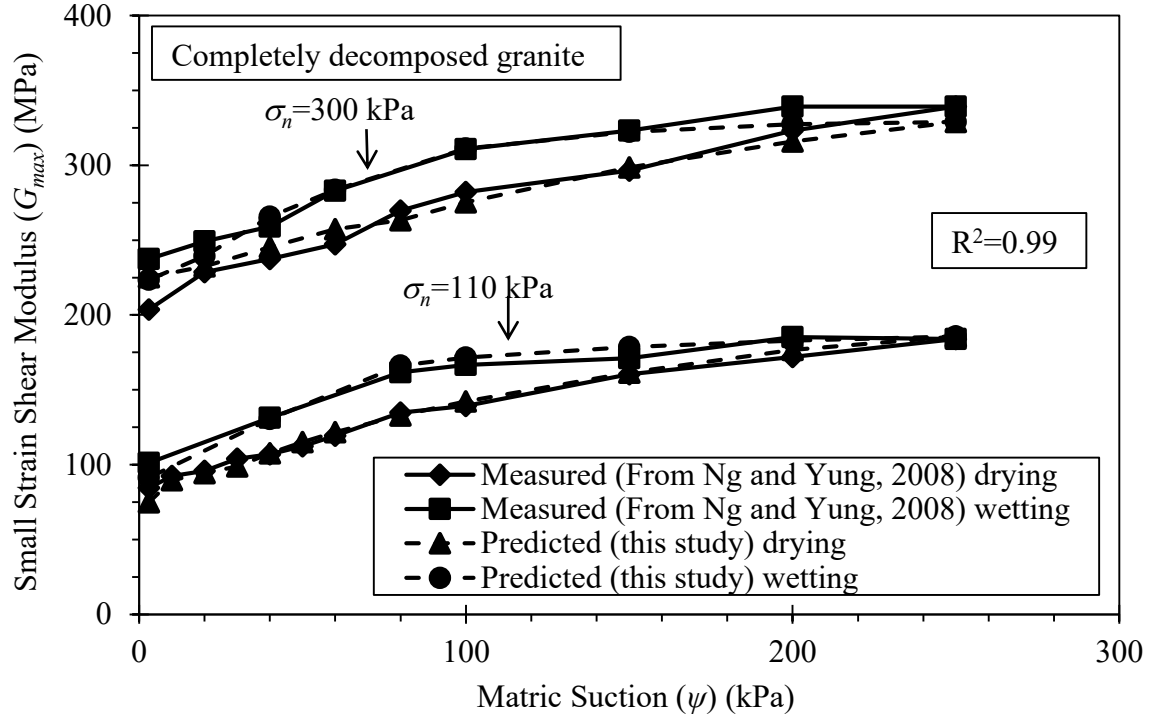
Table 3. 4 Values of model parameters for data available in the literature

Model parameter →	a	n	b	m	c	k
Bonny silt	131	0.5	57	0.03	22	0.7
Completely decomposed granite	308	1.08	42	0.14	695	0.59
Zenoz kaolin	381	0.57	26	61	802	4

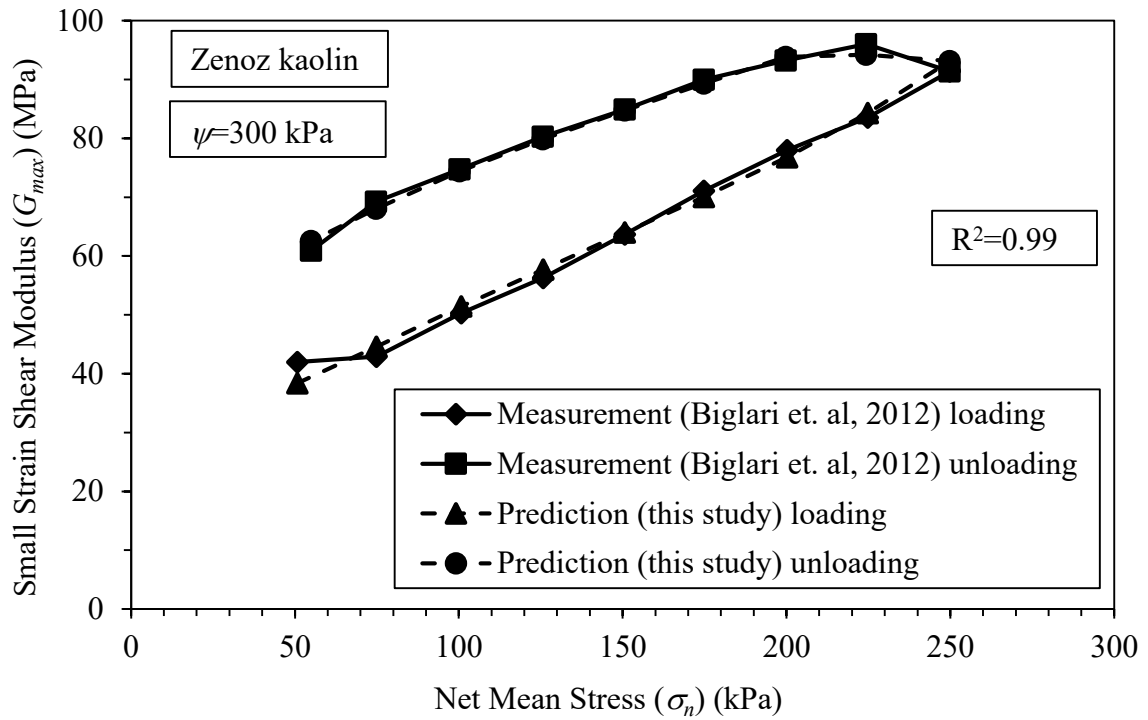
Table 3.4 summarises the optimised model parameters following the procedure reported in the previous section. Fig. 3.22 shows the measured and predicted values of G_{max} for these reported studies. There were good agreements between the measurements and predictions of G_{max} for different types of soil during drying-wetting cycles and loading-unloading stages of net stress, confirming the ability of the proposed model to capture the response of G_{max} while incorporating hydraulic hysteresis.



(a)



(b)



(c)

Fig. 3. 22 Prediction of G_{max} for (a) Bonny Silt, (b) Completely decomposed granite and (c) Zenoz kaolin

3.5 Summary

A suction-control Rowe cell apparatus with two built-in bender elements at the top and bottom of the sample was developed to measure the shear wave velocities and corresponding small strain shear modulus (G_{max}) of an unsaturated soil. In this study, the soil sample was subjected to different types of stress loops in a multi-stage test including three drying-wetting cycles and a loading-unloading cycle of vertical net stress, allowing the investigation of effects of matric suction and degree of saturation on G_{max} simultaneously.

To avoid overestimation of G_{max} determination from shear wave velocity, the effective dynamic mass density (ρ_{eff}) was used instead of the total mass density. It was assumed that during drying processes, the thin viscous layers of pore water moving together with particle surfaces during shear wave propagation reduces only when all the external water has been removed, while the reverse procedure occurs during wetting processes. Therefore, the effective dynamic mass density was determined as the minimum of the total mass density and the maximum effective dynamic mass density, which corresponds to the full thickness of the viscous boundary layer. Investigation of the relationship between $\rho_{eff}(1+e)$ and degree of saturation during the three drying-wetting cycles shows a threshold of degree of saturation that separates the low range corresponding to partial mass coupling and the high range corresponding to full mass coupling. At a given void ratio, ρ_{eff} is proportional to the degree of saturation only at the low range while at the high range degree of saturation has no or minor effect on ρ_{eff} .

G_{max} was observed to reflect the irreversible changes of void ratio and degree of saturation that occurred in all the stress loops investigated, especially during the drying-wetting cycles where these changes accumulated with increasing number of cycles. It is noted that the

hydraulic hysteresis had a huge effect on the measured G_{max} . The growth of $G_{max}/f(e)$ resulting from decreases of degree of saturation at a given stress state, during cycles of drying-wetting and loading-unloading of net stress, is clear evidence for the impact of van der Waals attractions and electric double layer repulsions on G_{max} of unsaturated soils. Thus, when hydraulic hysteresis presents, a decrease in the degree of saturation leads to a decrease in the contribution of matric suction and an increase in the combined contribution of van der Waals attractions and electric double layer repulsions to G_{max} . Indeed, as these two contributions follow different patterns with variations of degree of saturation, they need to be evaluated separately to capture effect of hydraulic hysteresis on G_{max} ,

An equation has been proposed for predicting G_{max} of unsaturated soils incorporating the effects of the void ratio, net stress, matric suction and degree of saturation. This equation was verified for the investigated soil in further experiments including a stress loop with mixed variations of matric suction and net stress, and a drying process. Apart from a good agreement between measurements and predictions for the entire data set, the proposed equation successfully captures the greater effect induced by matric suction compared to an equal-magnitude net stress during the stress loop. Verifications for measurements available in the literature were also conducted for different soils in different testing conditions during cycles of drying-wetting and loading-unloading. The proposed equation provided good predictions proving its ability to capture the effect of hydraulic hysteresis on G_{max} of unsaturated soils. For practical issues, this equation allows the determination of G_{max} of unsaturated soils based on the stress state, void ratio, and degree of saturation regardless of the stress and drying-wetting history, thus improving the accuracy of capturing the response of G_{max} in complex loading-unloading and drying-wetting cycles.

Chapter 4

Impacts of Matric Suction Equalisation on Small Strain Shear Modulus of Soils during Air-Drying

4.1 Introduction

In unsaturated experiments using axis-translation technique, time to reach suction equalisation is determined through monitoring volume change of water flowing in or out the sample with time (Delage et al. 2008; Romero et al. 2003). This method is used for a sample in a closed system where the sample is separated from the surrounding environment. However, during an air-drying process, the sample is often allowed to freely contact and exchange water vapour with a controlled environment. For example, samples in experiments conducted by Cho and Santamarina (2001) were placed into an incubator at a constant temperature of 50°C to speed up the drying process while the weight of the sample was monitored with an external scale. In experiments by Dong and Lu (2016), the soil samples were placed into an environmental chamber with adjustable openings on the top plate to accelerate or reduce the degree of natural evaporation. Indeed, in the above-mentioned studies, matric suction equalisation was not considered during testing (i.e. steady state condition not established), which could lead to misrepresentation of material response.

In this study, an experimental set up was developed by modifying the conventional bender element test to investigate the response of G_{max} during an air-drying process considering the effect of matric suction equalisation. The modified bender element test allowed the exchange of water vapour between the samples and the surrounding environment for the air-drying process and also could form a closed system allowing matric suction equalisation. Herein,

measured values of G_{max} was used to determine the state of matric suction equalisation with the assumption that matric suction equalisation was reached when G_{max} remained unchanged for at least 24 hours. In order to obtain the relationship between G_{max} and water content, the bender element system was attached to a digital scale enabling the determination of the sample water content continuously during an air-drying process.

The second objective of this experimental study has been to investigate factors controlling the matric suction equalisation time t_{se} . Thus, weight-controlled bender element tests were conducted on samples with different diameters (i.e. 50 mm, 76 mm, and 100 mm) which experienced the same drying procedure. A saturated hydraulic conductivity test was also conducted to provide the variation of the saturated hydraulic conductivity with varying void ratio. These test results together with the soil water characteristic curve derived from the shrinkage and filter paper tests, unveil the effect of unsaturated coefficient hydraulic conductivity on t_{se} . The experimental data was then analysed to establish and verify correlations to predict t_{se} and G_{max} of soil samples subjected to air-drying.

4.2 Laboratory Experiments

4.2.1 Sample Preparation

The basic properties of the soil mixture are summarised in Table 3.1. Statically compacted samples having the same post-compaction void ratio were prepared for different types of tests including weight-controlled bender element, contact filter paper, shrinkage, and hydraulic conductivity. The size and number of samples for each test were summarized in Table 4.1.

Table 4. 1 Number and size of samples for tests in the study

Test	Sample size		Number of samples
	Diameter (mm)	Height (mm)	
Weight-controlled bender element	50	20	2
	76	20	1
	100	20	1
Shrinkage	50	20	1
Contact filter paper	50	20	21
Permeability	100	20	1

Initially, predetermined amounts of dry kaolin and fine sand were mixed with a spatula until a homogeneous mix was obtained. The resulting soil mixture was then statically compacted in sample rings in three layers using a 50 kN load frame to have the same post-compaction void ratio of 0.37. For the sample saturation, similar to the process adopted by previous researchers (e.g. Tinjum et al. 1997; Vanapalli et al. 1999), filter papers and porous stones were placed on the top and bottom of samples, and placed into an empty bath. Then seating weights equivalent to a pressure of 15 kPa were placed on top of samples to minimise any possible swelling induced by the wetting process so as the void ratio whose initial value has significant effect on the mechanical and hydraulic behaviours of unsaturated soils (Gallipoli et al. 2015; Gallipoli et al. 2003; Sheng et al. 2004; Zhou et al. 2012) remained unchanged. The bath was then filled with de-aired water gradually until the water level just reached the top level of the sample. Indeed, the upward water flow in the sample, induced by the hydraulic capillary phenomenon and hydraulic head difference, could eventually push all air out and replace it with water in an attempt to saturate the sample.

A number of trial tests were primarily conducted to determine the time required to saturate samples. The weight of the sample was measured with time during the saturation process, and since the weight of dry soil was predetermined, while the initial void ratio of the sample was also known, the degree of saturation (S_r) could be determined during the saturation process from three known quantities, including the specific gravity, the void ratio, and the water content. Experimental results indicated that samples adopted in this study were deemed saturated after 48 hrs with a degree of saturation greater than 98%.

Following the saturation process, the soil samples were extruded from the moulds for the weight-controlled bender element, shrinkage, filter paper, and saturated hydraulic conductivity tests.

4.2.2 Developed weight-controlled bender element test

Inspired by previous research studies by Cho and Santamarina (2001) and Dong and Lu (2016), a weight-controlled bender element test was developed which used a digital scale to continuously monitor the weight of the soil sample while conducting the bender element tests during an air-drying process. The experimental setup was placed in a controlled temperature and humidity room where the temperature and relative humidity were set at $21\pm0.5^\circ\text{C}$ and $55\pm5\%$, respectively.

The samples were located between the lower and upper bender elements. To ensure good contact was established between bender elements and the soil sample, a seating load through a dead weight equivalent to 1 kPa pressure was placed on the top of the upper bender element. The entire system was then attached to a digital scale, while thin plastic sheets (cling wrap) were used to tightly wrap and seal the sample to create a closed space, isolating pore water vapour from the surrounding environment, as illustrated in Fig. 4.1.

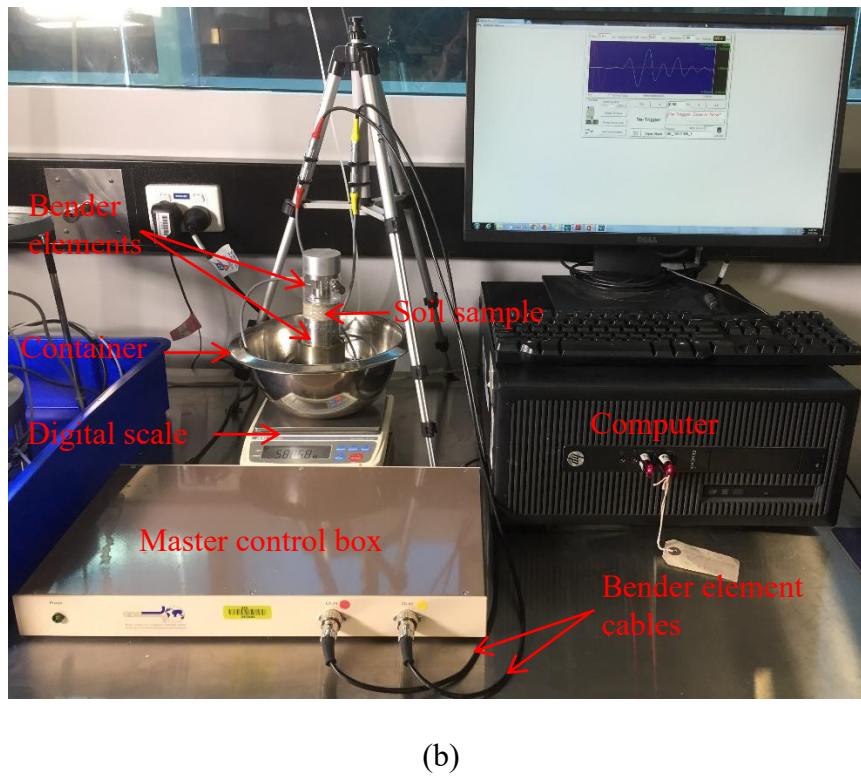
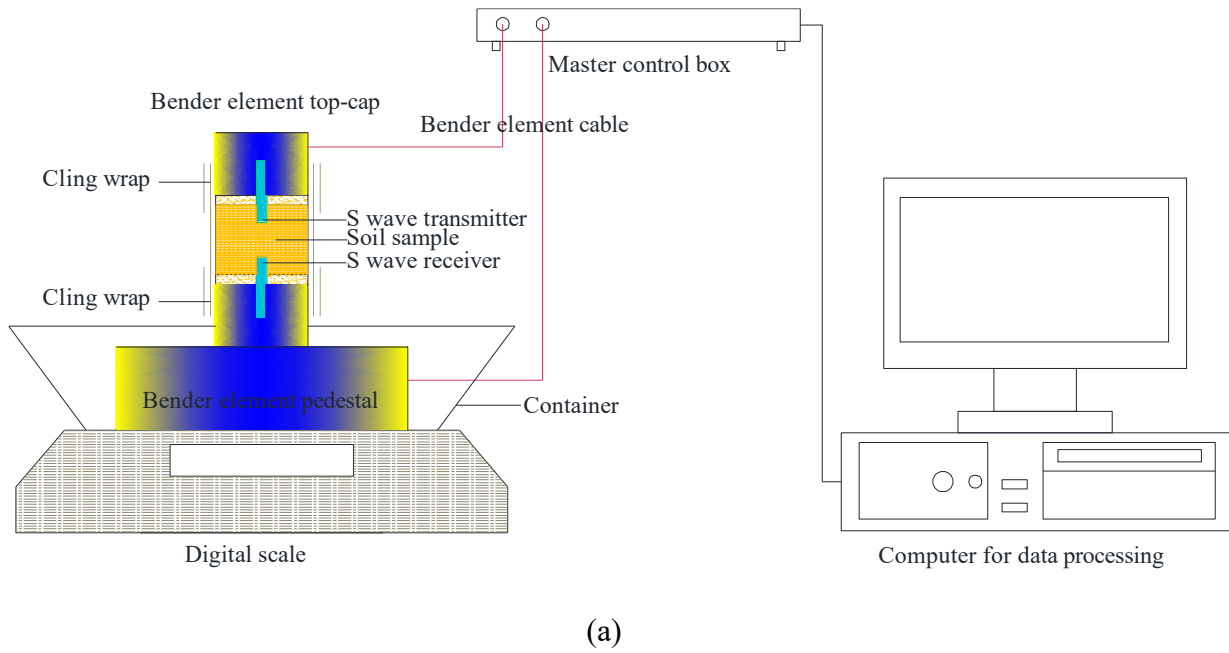


Fig. 4. 1 Weight-controlled bender element test (a) schematic diagram of the entire setup and (b) photograph of the sample in a matric suction equalisation stage

Following the recommendation by Bartel and Yaniv (1997) and Mohamed et al. (2009), since the weight on the scale would be sustained for very long time for the continuous

measurement of soil water content, the digital scale was calibrated to capture the deformation of the scale cantilever load cell subjected to long-term loads. The calibration factors, capturing the relationship between scale reading and time, were then established for the precise determination of the changes of the water content during the experiments.

As reported by Malhotra et al. (2015), cling wrap can act as a barrier against oxygen, chemical, and moisture exchange due to its tightly bound and coiled chains of molecules that prevent the penetration of gases, liquids, and water vapour. The long molecule chains also exhibit a spring-like characteristic allowing the cling wrap to stick not only to itself but also to a variety of materials such as plastic, glass, and stainless steel. The above-mentioned characteristics of cling wrap have allowed its usage as a sealing material in experiments by various researchers (Chan et al. 2011; Garland et al. 1989; Liu et al. 2003b) to protect devices or create a closed environment with constant relative humidity. In this study, by covering the sample with cling wrap tightly, only exchange of water vapour within the soil sample volume was allowed, thus, enabling the matric suction equalisation.

Shear wave velocity (V_s) was determined continuously to monitor the evolution of G_{max} during matric suction equalisation process. Once there was no change in the measured shear wave velocity of the soil sample sealed with the cling wrap for a sustained period of 24 hours, suction equalisation was considered to be reached and the following stages could be conducted. The used cling wrap was then placed into a desiccator followed by measuring its dry weight allowing the determination of the moisture content of the soil sample at the end of the matric such equalisation stage.

During the air-drying phase, the cling wrap was removed, the sample was left to air-dry freely until the weight of the sample shown on the weighing scale reached a predetermined

value, corresponding to a target moisture content. In this free-evaporation stage, the evolution of shear wave velocity and the reduction of sample density were also measured to capture the response of G_{max} under condition in which the pore water was allowed to evaporate freely. Subsequently, the sample was tightly wrapped again to assess the shear wave velocity evolution during the next matric suction equalisation, obviously at lower degree of saturation. The procedure of air drying followed by matric such equalisation was repeated until the sample was air-dried completely. At the end of the test, the residual water content of the sample was determined and used to confirm the calculation of the water content in all previous stages.

In an attempt to capture the response of G_{max} under the free-evaporation condition through the whole air-drying process excluding the matric such equalisation, another identical bender element test was setup and conducted in which variations of shear wave velocity and water content of the sample were measured continuously without covering the sample with cling wrap.

4.2.3 Contact filter paper test to obtain soil water characteristic curve

Complying with the ASTM D5298-16 (2016), the main aim for conducting filter paper tests was to determine the relationship between water content and matric suction (i.e. the soil water characteristic curve, SWCC) from low to extremely high matric suctions experienced during an air-drying process where the axis-translation based tests such as pressure plate test were not suitable. For the measurement of matric suction, pairs of soil sample were left to air-dry to different predetermined water contents and then stored in a small resealable air-tight plastic bag in a controlled room temperature of 21°C for 24 hours for moisture equalisation. For each test, three stacked standard filter papers, graded as Whatman No. 42, were placed between surfaces of two identical samples. The inner filter paper, which was used for matric suction

determination, was approximate 4 mm smaller in diameter than the two outer filter papers to avoid any possible soil contamination. Electrical tape was used to wrap the contact between the two soil samples, isolating filter papers from outside moisture vapour, thus allowing only fluid to transfer from soil samples to the filter papers. Then, glass containers with a capacity of 4 oz (118.3 mL) were used to store the wrapped samples. Once the lid was sealed with electrical tape, the sample container was stored in an insulated chest and placed in a controlled temperature chamber of 21°C for 7 days for suction equilibration. After 7 days, water contents of the two soil samples and the inner filter paper were measured. Due to lightweight of filter paper, a digital scale with 0.0001g readability was used to assure the accuracy. Once the water content of the filter paper was measured, corresponding matric suction was determined by adopting the calibration curve proposed in ASTM D5298–16 (2016). Thus the soil water characteristic curve (SWCC) of the soil during the drying process could be established.

It should be noted that the established SWCC (matric suction vs water content) in combination with weight-controlled bender element test results (G_{max} vs. water content) allows obtaining the relationship between G_{max} and matric suction.

4.2.4 *Shrinkage test to obtain the shrinkage characteristic curve*

Adopting the method proposed by Fredlund and Houston (2013), shrinkage tests were conducted to obtain the soil shrinkage characteristic curve (SSCC) that presents the relationship between water content and a pore volume related variable (e.g. void ratio) during an air-drying process (Cornelis et al. 2006a). In this study, the test was essential to determine the variations of density and height of the soil sample in the weight-controlled bender element tests as well as the calculation of correct degree of saturation to be used in SWCC established through the filter paper test.

Initially, the weight of the soil sample was determined using a digital scale with 0.001g accuracy, while its height and diameter were measured using a calliper. For each measurement of sample height and diameter, the average value was computed from three measured results. As the weight of the solid phase (i.e. soil particle) remained unchanged and the weight of the air phase (i.e. pore air) was negligible, the weight of the liquid phase (i.e. pore water) and the corresponding gravimetric water content could be estimated based on the total weight of the soil sample measured. From known values of the gravimetric water content, specific gravity, and unit weight of the sample, the corresponding void ratio could be calculated.

Then the sample was air-dried in a controlled temperature and humidity room at $21\pm0.5^{\circ}\text{C}$ and $55\pm5\%$ RH to different predetermined water contents in stages. It should be noted that after the air-drying process, the sample was resealed in an air-tight plastic bag for moisture equalisation for 4 to 9 days before taking the measurements. The time for moisture equalisation was determined to be equal to the time required for matric suction equalisation at the investigated water content obtained from the weight-controlled bender element test. The above procedure was repeated until the end of the air-drying process when the sample weight remained unchanged for 24 hours. At the end of the tests, the sample was placed into an oven at 105°C for 24 hours to determine the residual water content and the weight of solid particles which were used to check the determined water content and void ratio in the previous stages.

4.2.5 Saturated hydraulic conductivity measurements

Complying with AS 1289.6.7.3 (2016), the saturated hydraulic conductivity test was conducted to obtain the relationship between the saturated hydraulic conductivity and void ratio. The soil sample of 100 mm in diameter and 20 mm in height was placed in a permeability chamber. Latex membrane was used to cover the side boundaries of the sample, enabling the application

of desired confining pressures. Three water controllers were used simultaneously to (i) apply confining pressure and measure volume change of the sample; (ii) set hydraulic head at the top of the sample and measure volume of water-out flow; and (iii) apply water pressure at the bottom of the sample and measure volume of water-in flow. Initially, back pressure technique was used to ensure sample saturation at an effective mean stress of 10 kPa. A hydraulic conductivity test stage was then carried out by keeping the confining pressure constant while reducing the water pressure at the top and increasing the water pressure at the bottom of the sample by 5 kPa, resulting in the hydraulic head difference equivalent to 10 kPa between the top and bottom of the sample that resulted in an upward water flow. When the rates of in and out flows were the same and remained constant for at least 24 hours, it was deemed that steady state flow was established and the corresponding saturated coefficient of hydraulic conductivity was measured. In addition, soil hydraulic conductivity corresponding to different void ratios analogous to mean effective stresses of 20, 40, 80, 160, and 320 kPa were measured in stages.

4.3 Results and Discussion

4.3.1 Variations of Void ratio against water content/degree of saturation during free shrinkage

The soil shrinkage characteristic curves (SSCC) in terms of gravimetric water content and degree of saturation were presented in Fig. 4.2, while the degree of saturation was obtained using Eq. (4.1):

$$S_r = \frac{W G_s}{e} \quad (4.1)$$

where W is gravimetric water content, and G_s is specific gravity of soil particles.

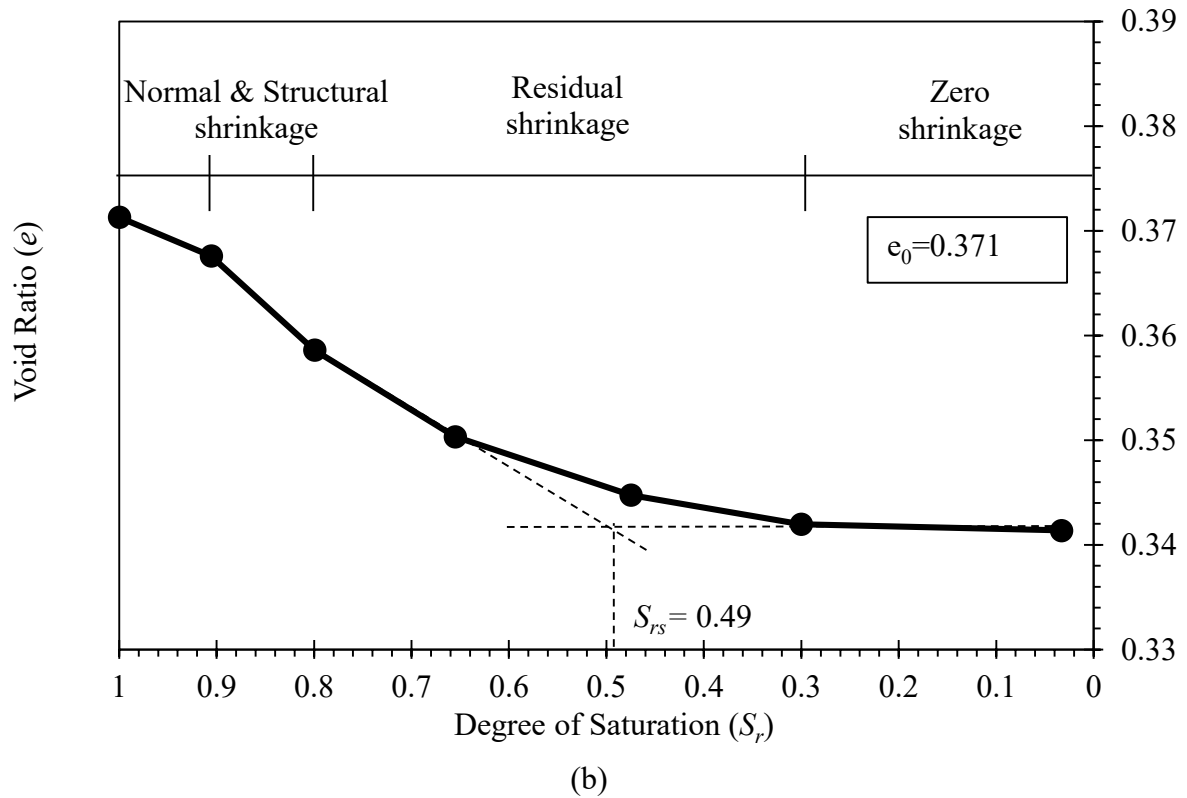
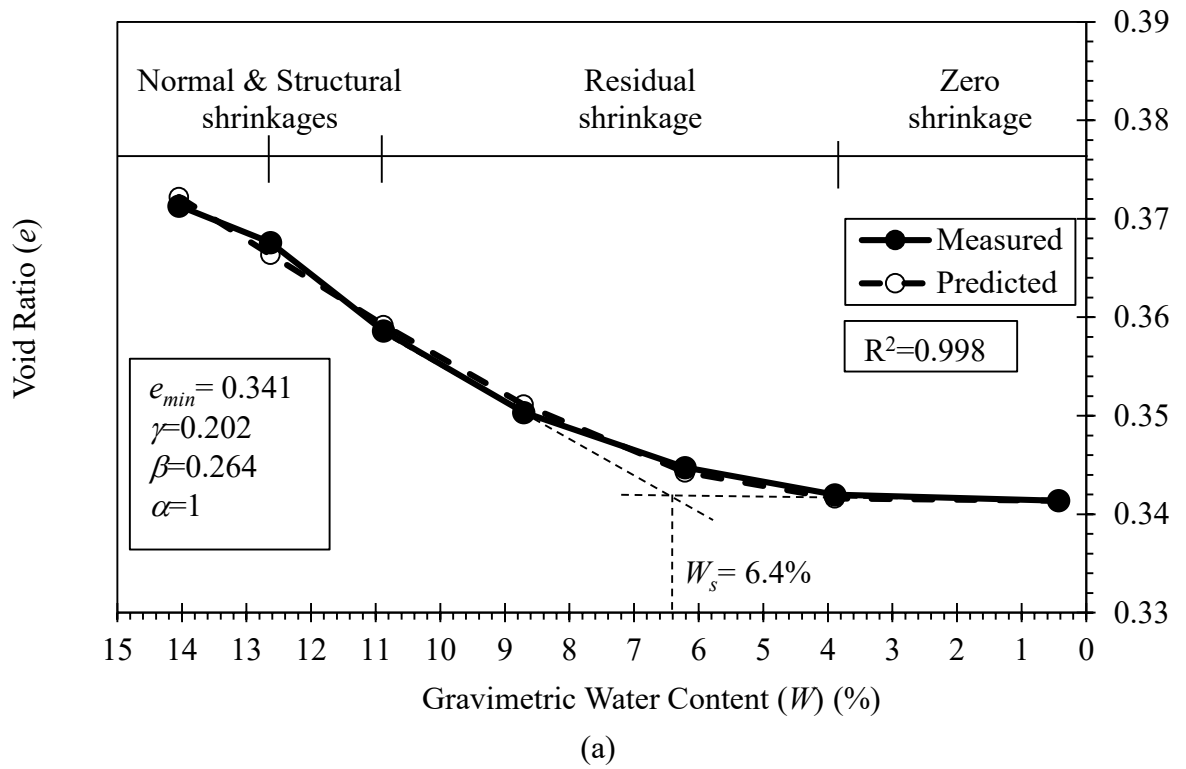


Fig. 4. 2 Soil shrinkage characteristic curves in term of (a) gravimetric water content, and (b) degree of saturation

It was observed that the soil sample experienced four shrinkage stages including structural shrinkage, normal shrinkage, residual shrinkage, and zero shrinkage, as shown in Fig. 4.2. A similar observation was also reported by a number of researchers (e.g. Bronswijk 1991; Cornelis et al. 2006a; Haines 1923; Stirk 1954). The differences in the shrinkage rate corresponding to various shrinkage stages can be explained via the process of water evaporation from the large inter-aggregate pores (i.e. macropores) and intra-aggregate pores (i.e. micropores). In the structural shrinkage phase observed in Fig. 4.2, the shrinkage was driven by water evaporation from the macropores, while the amount of water in the micropores remained unchanged (Al-Dakheeli and Bulut 2019; Chertkov 2008; Cornelis et al. 2006a). As the soil matrix was well compacted, the loss of water in the macropores did not directly result in contraction, evident through insignificant volume change in this stage.

Once water in the macropores was fully evaporated, the normal shrinkage commenced and water in the micropores started to evaporate. In this stage, the volume of water lost corresponded to the volume change of the micropores, and thus, directly caused the contraction of the soil matrix. The micropores were still saturated and the sample experienced a linear shrinkage with higher rate compared to the rate in the structural shrinkage (Cornelis et al. 2006a) as demonstrated in Fig. 4.2. The normal shrinkage ceased and was supplanted by the residual shrinkage when air started to invade the micropores at water content and degree of saturation of around 11% and 0.8, respectively. As the drying proceeded, the shrinkage rate decreased persistently until approaching zero corresponding to the zero shrinkage zone.

The invasion of air into macropores during the structural shrinkage as reported by a number of researchers (e.g. Al-Dakheeli and Bulut 2019; Cornelis et al. 2006a; Haines 1923; Tripathy et al. 2002) and shown in Fig. 4.2 indicates the early start of unsaturated states of compacted soils, whereas reconstituted soils were reported not to exhibit structural shrinkage and be

essentially saturated at water contents less than the shrinkage limit. For compacted soils, the term shrinkage limit was also used for the water content at the onset of the zero shrinkage stage (Haines 1923; Peng et al. 2005; Tripathy et al. 2002) even though at that water content, the compacted soils were actually desaturated. Adopting this definition in this study, a shrinkage limit W_s of 6.4% and a corresponding degree of saturation S_{rs} of 0.49 were determined as shown in Fig. 4.2.

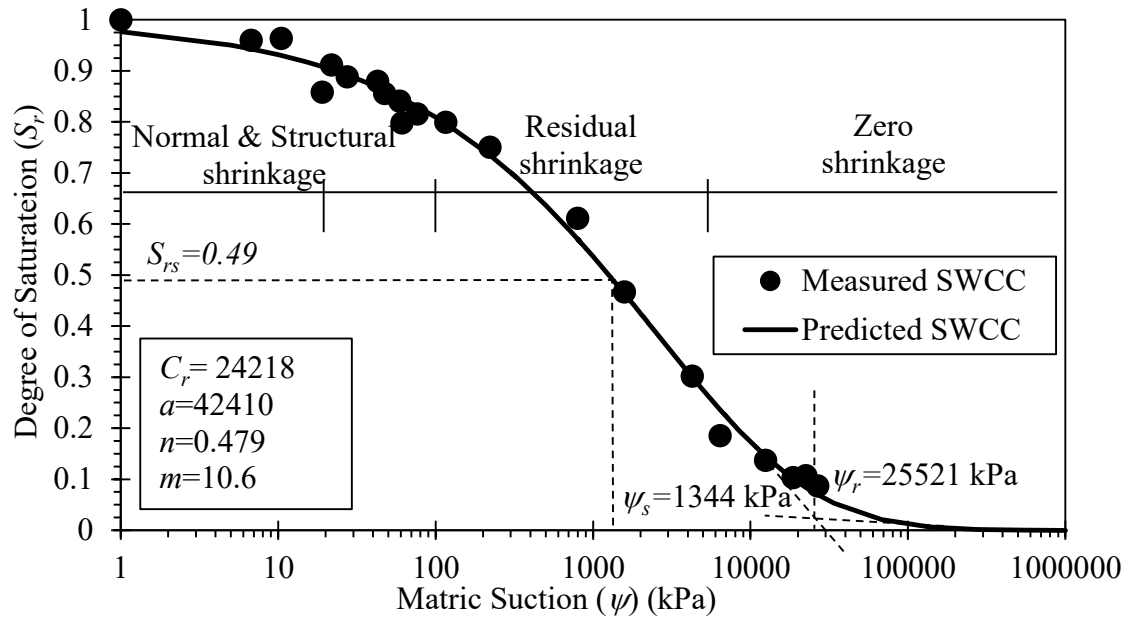
It should be noted that the results of shrinkage tests reported in Fig. 4.2 were used to determine the void ratio of the soil sample (e) as a result of decreasing water content (W) in the weight-controlled bender element and filter paper tests used in this study; thus Eq. (4.2), recommended by Cornelis et al. (2006b), were calibrated against the laboratory measurements and the comparison is shown in Fig. 4.2.

$$e = e_{min} + \gamma \exp\left(\frac{-\beta}{W^\alpha}\right) \quad (4.2)$$

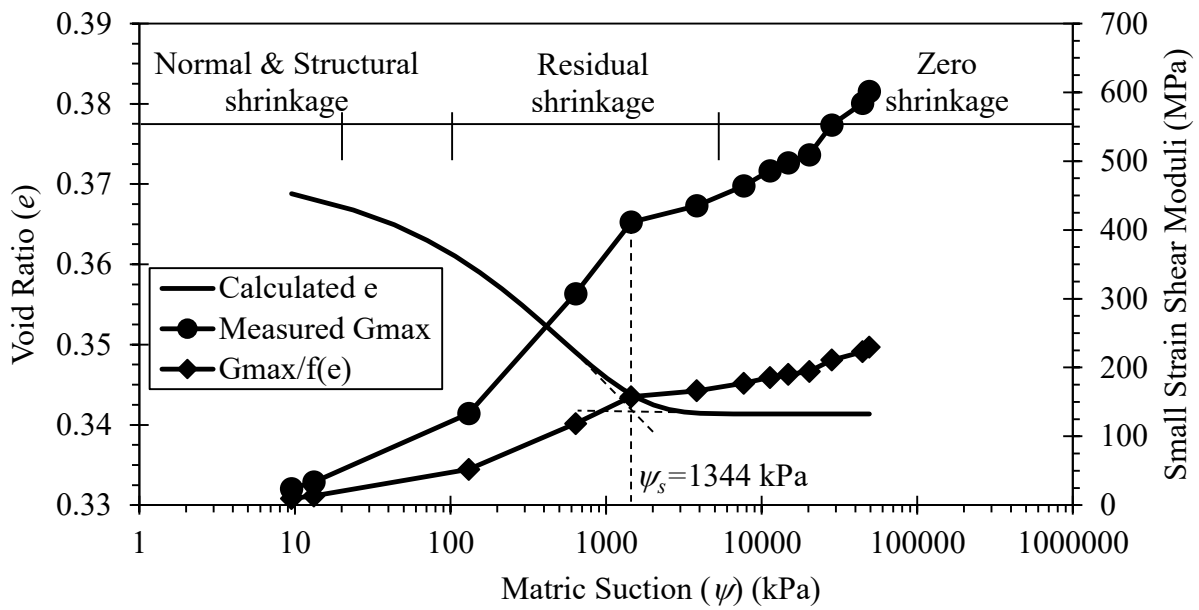
where e_{min} (=0.341 in this study) is the minimum void ratio at the end of the zero shrinkage stage; γ, β , and α (= 0.202, 0.264 and 1 in this study, respectively) are fitting parameters.

4.3.2 Soil water characteristic curve during air drying

Integrating the results of shrinkage test reported above with contact filter paper test results, the soil water characteristic curve (SWCC) representing the relationship between degree of saturation and matric suction (Fig. 4.3a), and the variations of void ratio with increasing matric suction (Fig. 4.3b) during an air-drying process were obtained.



(a)



(b)

Fig. 4. 3 Variations of (a) S_r ; (b) e , G_{max} , and $G_{max}/f(e)$ with increasing ψ during a drying process

Herein, the relationship recommended by Fredlund and Xing (1994) and reported in Eq. (4.3) was fitted to the laboratory measurements allowing continuous correlations between the magnitude of matric suction and the degree of saturation. It should be noted that the non-linear

least squares regression method was adopted to obtain the model parameters for the soil adopted in this study.

$$S_r(\Psi, a, n, m) = C(\Psi) * \frac{S_{r0}}{\left\{ \ln \left[\exp + \left(\frac{\Psi}{a} \right)^n \right] \right\}^m} \quad (4.3)$$

where a , m , and n are fitting parameters (estimated to be 42410, 0.479 and 10.6 in this study respectively); S_{r0} (= 0.98 in this study) is degree of saturation at saturated state; Ψ is matric suction; $C(\Psi)$ is a correction function defined as:

$$C(\Psi) = 1 - \frac{\ln \left(1 + \frac{\Psi}{\Psi_r} \right)}{\ln \left[1 + \left(\frac{10^6}{\Psi_r} \right) \right]} \quad (4.4)$$

where Ψ_r is the residual matric suction determined to be 25521 kPa for the soil adopted in this study as evident in Fig. 4.3.

4.3.3 Evolution of G_{max} during an air-drying process

Fig. 4.3b presents the variation of G_{max} measured at the end of matric suction equalisation stages in the first weight-controlled bender element test after an air-drying process. Two distinct responses of G_{max} have been captured at low and high ranges of matric suction. As soon as the air-drying of saturated soil started, G_{max} followed an exponential growth in the semi-log plot until matric suction reached a threshold (i.e. Ψ_s), beyond which the growth rate of G_{max} experienced a noticeable decrease followed by another exponential growth. The significant reduction in the growth rate of G_{max} when matric suction entered the high range (i.e. $\Psi > \Psi_s$) can be a result of change in the microscopic structure of the soil. Referring to variations of void

ratio and G_{max} with matric suction (see Fig. 4.3b), it is evident that the matric suction threshold ψ_s corresponded to the shrinkage limit W_s .

In order to investigate the responses of normalised small strain shear modulus nullifying the effect of void ratio, which is an important influencing factor (Jamiołkowski et al. 1994; Santagata et al. 2005; Shibuya et al. 1992), the variation of $G_{max}/f(e)$ during the air-drying process was plotted in Fig. 4.3b where $f(e)=1/(0.3+0.7e^2)$ is the void ratio function proposed by Hardin (1978). Similar responses of $G_{max}/f(e)$ to matric suction variations reported in Fig. 4.3b revealed that the variations of the void ratio could not justify the double exponential curves observed. Indeed, apart from the void ratio, the stresses in the soil skeleton can impact the magnitude of G_{max} (Hardin 1978; Rampello et al. 1997; Thomann and Hryciw 1990). For unsaturated soils, the soil stress state represents the inter-particle forces generated by the net stress, matric suction, van der Waals attractions, and electric double layer repulsions (Khalili and Khabbaz 1998; Lu and Likos 2006; Oh et al. 2011). The net stress is the difference between the total stress and the pore air pressure; matric suction is the difference between pore air pressure and pore water pressure; van der Waals attractions are the intermolecular forces between atoms of adjacent particles; and electric double layer repulsions are the repulsive forces existing among the cations in the electric double layers at the soil-water interface.

Among these four factors, only net stress remained unchanged across the weight-controlled bender element test adopted in this study, while the other three factors persistently changed during the air drying process. Due to the higher attractive intermolecular forces in air media than in water media (Visser 1995), the van der Waals attraction-induced inter-particle stresses evolved during the air drying process when the pore water was gradually replaced by air phase. On the contrary, the electric double layer repulsion-induced inter-particle stresses persistently reduced with the reduction in the thickness of the electric double layer. Since there was no

sudden change or kink in the degree of saturation when matric suction shifted over ψ_s as shown in Fig. 4.3a, the contributions of inter-particle stresses induced by the van der Waals attractions and electric double layer repulsions to G_{max} were not expected to induce evident changes or kink as observed in Fig. 4.3b. Thus, the only remaining factor that could explain the observed variations of G_{max} in Fig. 3b is the matric suction.

The inter-particle stress generated by a matric suction is proportional to the total contact area between pore water and soil particles (Alonso et al. 2010; Duriez and Wan 2017; Han and Vanapalli 2016; Likos and Lu 2004; Liu et al. 2003a; Öberg and Sällfors 1997; Vanapalli et al. 1996). As demonstrated in Fig. 4.4, the matric suction induced inter-particle force F_ψ , present between two identical spherical particles, is proportional to the pore water -particle contact area, matric suction ($\psi = u_a - u_w$), and the surface tension T of the meniscus water. During an air-drying process, with a reduction of degree of saturation, evolution of the matric suction induced inter-particle stress is determined by the increase of matric suction and the decrease of the total pore water-particle contact area. While minor changes in the growth rate of matric suction were observed in Fig. 4.3a due to decreasing degree of saturation around S_{rs} (i.e. the degree of saturation corresponds to the shrinkage limit), Fig. 4.4 indicates significant changes in the pore water-particle contact area. Specifically, when degree of saturation approaches the S_{rs} , a reduction in the pore water volume might only cause a minor reduction in the pore water-particle contact area as the water volume change was mostly compensated by the volume change of the soil sample, as a result of the distance between soil particles being shortened (Fig. 4.4a and b). However, when degree of saturation is less than S_{rs} , a reduction in the pore water volume directly resulted in a reduction in the pore water volume at the contacts between particles (refer to Figs. 4c, d, and e). Obviously, the relationship between degree of saturation

and the pore water-particle contact area during an air-drying process followed two distinct trends as illustrated in Fig. 4.5.

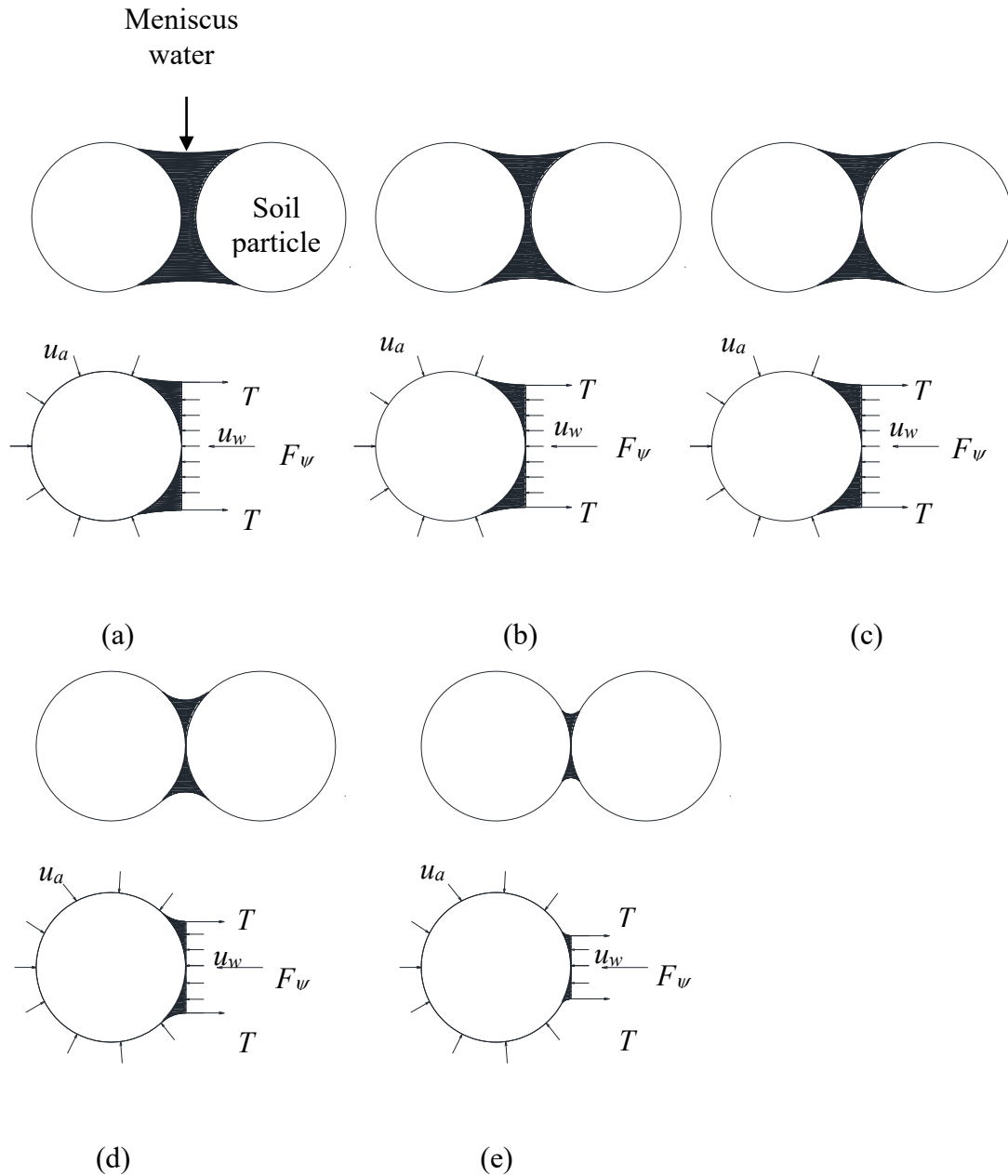


Fig. 4. 4 Matric suction induced inter-particle force at water contents (a) well above shrinkage limit, (b) approaching shrinkage limit, (c) at shrinkage limit, (d) smaller than shrinkage limit, (e) well below shrinkage limit

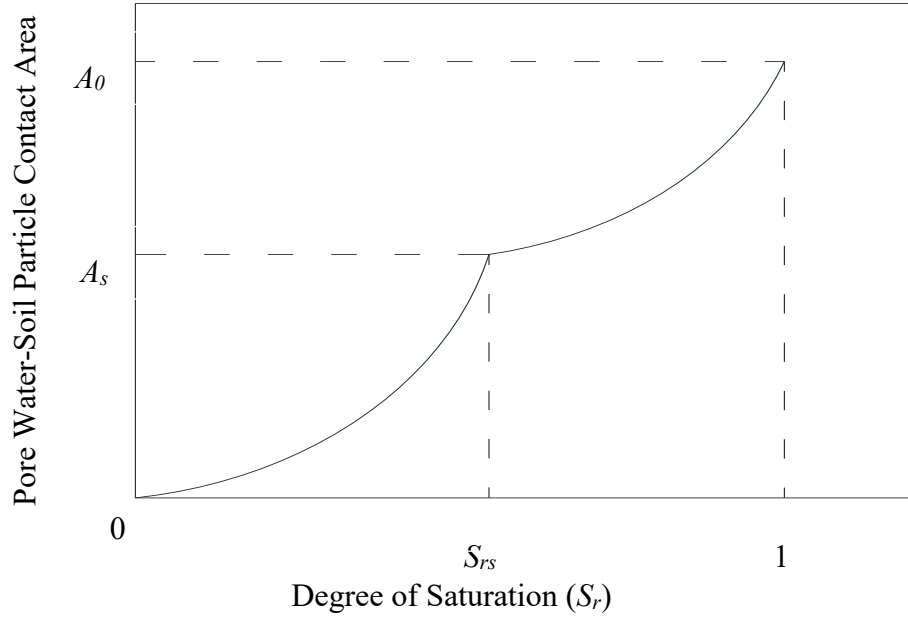


Fig. 4. 5 Conceptual variations of water-soil particle contact area with decreasing degree of saturation during an air-drying process (A_0 and A_s are the initial contact area and the contact area corresponding to the shrinkage limit, respectively)

Therefore, the contribution of matric suction to G_{max} also followed two distinct trends at degrees of saturation higher and lower than S_{rs} , leading to two different responses of G_{max} at matric suctions lower and higher than ψ_s as observed in Fig. 4.3b.

4.3.4 Impacts of matric suction equalisation on the measurement of G_{max}

Fig. 4.6 presents the measurements of G_{max} in the first series of weight-controlled bender element tests allowing matric suction equalisation, where the cling wrap was used to create a closed system enabling matric suction equalisation, following the air drying process in which sample was allowed to exchange water vapour freely with the surrounding environment. Two quite distinct responses of G_{max} to matric suction variations were observed depending on the level of matric suction. Specifically, in the shrinkage zone (i.e. matric suction lower than $\psi_s = 950$ kPa), the measurements of G_{max} in free-evaporation stages prior to matric suction

equalisation stage were slightly less than the corresponding values after matric suction equalisation.

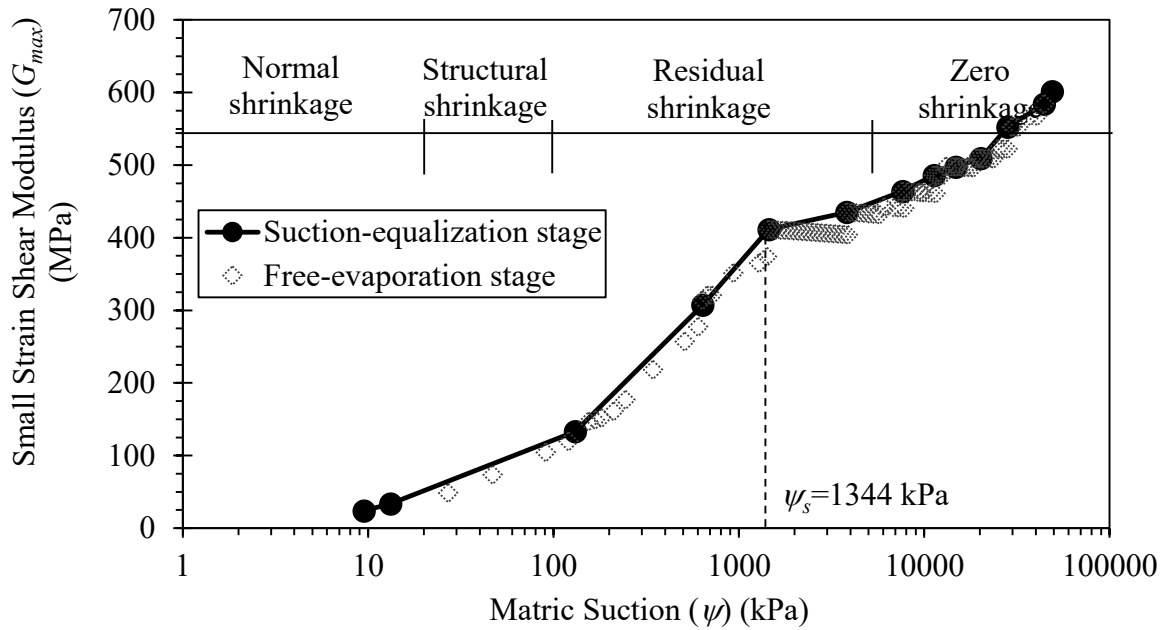


Fig. 4. 6 Measurements of G_{max} in the first weight-controlled Bender element test

Referring to Fig 4.1, the two vertical bender elements were placed at the centres of the top and bottom of the sample, thus measurements of G_{max} represented the small strain shear stiffness of soil within the central axis region only. Indeed, the measured G_{max} could represent the small strain shear stiffness of the entire sample cross section when uniform distributions of void ratio and stress level across the cross section of the sample would be established, which is achieved after matric suction equalisation. In free-evaporation stages, water evaporation and condensation took place simultaneously at the pore water-air interface (Flowers et al. 2015; Penman 1948; Silberberg 2006). Indeed, as reported by Headrick (1967), the evaporation rate well exceeds the condensation rate in an attempt to increase the partial water vapour pressure in the atmosphere to come into equilibrium with the partial water pressure at the pore water-air interface. The persistent loss of water at the sample boundaries during free-evaporation stages induced hydraulic gradient between the centre and boundaries of the sample, resulting in

outward radial flows of pore water. Obviously, the non-uniform distribution of sample water content during the free-evaporation stages resulted in non-uniform distribution of matric suction, with the lowest matric suction present at the centre of the sample and the highest on the outside boundaries. Clearly, in the free-evaporation stages, the measurements of G_{max} represented only the small strain shear modulus corresponding to the centre of the sample with the lowest suction (i.e. the lowest stresses in the soil skeleton) and certainly not reflecting the average conditions of the soil sample. For matric suctions greater than around 950 kPa, corresponding to the secondary desaturation zone (Fredlund et al. 2001; Vanapalli et al. 1996), the outward flow rate of pore water (i.e. from the centre of the sample toward the outside boundaries) was significantly reduced due to the development of the local discontinuity of pore water since more air volume invaded the soil pores. Consequently, this resulted in a more significant difference between the matric suction in the centre and boundaries of the sample, highlighting the importance of matric suction equalisation on the measurements of G_{max} .

Fig. 4.7 presents comparisons between G_{max} measured after matric suction equalisation (i.e. the first weight-controlled bender element test) and the second weight-controlled bender element test subjected to continuous air drying in which pore water was allowed to evaporate freely through the entire test without any matric suction equalisation. As evident in Fig. 4.7, matric suction equalisation had minor effects on measurements of G_{max} for matric suctions less than around 950 kPa. At higher matric suctions, the matric suction equalisation played a significant role in G_{max} measurements. As elaborated earlier, the discontinuity of water phase reduced the hydraulic conductivity at higher matric suctions resulting in reductions in the effect of the hydraulic flow in diminishing the non-uniform distribution of water phase across the cross-sectional area of the sample. It means that during the air-drying process, if matric suction equalisation was not allowed, soon after discontinuation of pore water at high matric suctions, the main portion of the water phase would gather around the central axis of the sample,

resulting in lower readings of G_{max} in comparison with the measurements after matric suction equalisation. It should be noted that the water available near the centre of the sample evaporated last during the air drying process, explaining why the measurements of G_{max} during the air drying process increased sharply toward the end of the experiment as shown in Fig. 4.7.

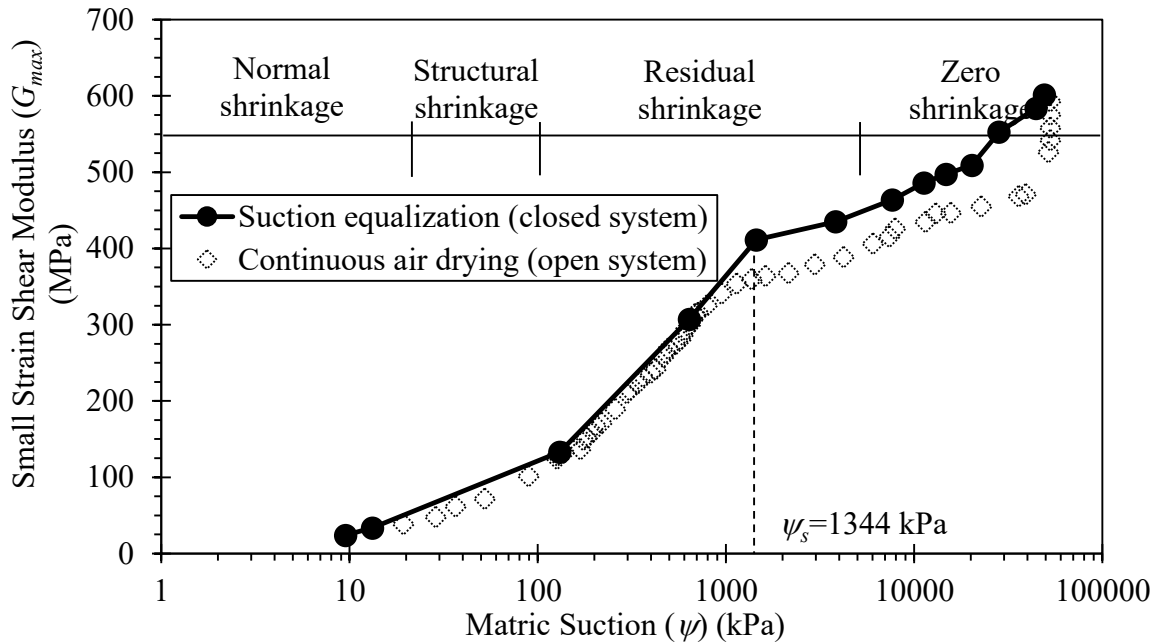


Fig. 4. 7 Comparison in the evolution of G_{max} in open and closed systems across an air-drying process

4.3.5 Elements impacting time required for matric suction equalisation (t_{se})

A number of studies have been conducted to determine the state at which matric suction equalisation is reached (e.g. Delage et al. 2008; Mancuso et al. 2002; Rampino et al. 1999; Romero et al. 2003; Sivakumar 1993; Wheeler and Sivakumar 1995) in experiments utilising suction-control devices adopting the axis-translation technique. In those experiments, predetermined pore air and pore water pressures were applied at the top of the sample and at the base of the High Air Entry Porous Disk (HAEPD), respectively. During a test stage, due to the difference between pore water pressure inside the sample and water pressure at the base of the HAEPD, an inward or outward flow of pore water through the HAEPD was generated

tending to diminish the differential water pressure. Sivakumar (1993), Rampino et al. (1999), and Mancuso et al. (2002) adopted the assumption that matric suction equalisation was reached after the water content change rate reduced to less than 0.04%/day, while Wheeler and Sivakumar (1995) proposed the state of matric suction equalisation corresponding to the specific water volume change rate below 0.001/day. In addition, based on the water-volume change, Delage et al. (2008) established an equation predicting the time required for 95% completion of the matric suction equalisation based on the analytical solution proposed by Kunze and Kirkham (1962). Excluding the effect of the HAEPD, the time required for matric suction equalisation was reported to be proportional to the sample height (i.e. the length of the pore water flow) and the slope of the soil water characteristic curve, while inversely proportional to the soil hydraulic conductivity. Since the measurement of water volume is affected by temperature fluctuation, Romero et al. (2003) proposed to determine the state of matric suction equalisation based on the measurement of vertical displacement, when the strain rate reduces to less than 0.025%/day. In brief, current criteria for the determination of matric suction equalisation were proposed for experiments using suction-control devices. Those criteria were based on the rate of the hydraulic flow or the rate of vertical strain, however, results from this study show that those criteria could not be applied at the high range of matric suctions during an air-drying process. While the criterion based on the rate of vertical strain has no use in the zero shrinkage stage, the criterion based on the rate of the hydraulic flow predicts consistent increase of the time require for matric suction equalisation with decreasing water content that was opposite to the experimental observations. Thus, apart from the effect of hydraulic flow, the effect of the water vapour flow needs also to be considered.

4.3.6 Effect of hydraulic flow and water vapour flow on t_{se}

Hydraulic conductivity is one of the main items impacting the rate at which water flows in unsaturated soils thus influencing the time duration at which the matric suction equalisation is established. For saturated soils with considerable clay content, Taylor (1948) recommended Eq. (4.5) for the variations of saturated hydraulic conductivity (k_s) with the void ratio (e):

$$k_s = k_{ref} 10^{-(e_{ref}-e)/c_k} \quad (4.5)$$

where, k_{ref} and e_{ref} are saturated hydraulic conductivity and void ratio at a reference point, respectively and c_k is the permeability change index.

Fig. 4.8 presents the results of hydraulic conductivity test conducted on the saturated soil used in this study following the AS 1289.6.7.3 (2016). Obviously, the soil hydraulic conductivity varies with the degree of saturation and Eq. (4.6) proposed by Averjanov (1950) and used by many other researchers (e.g. Assouline 2001; Fredlund 2006; Mertens et al. 2005; Ng and Menzies 2014) has been used in this study to predict the hydraulic conductivity at an unsaturated state (k_w):

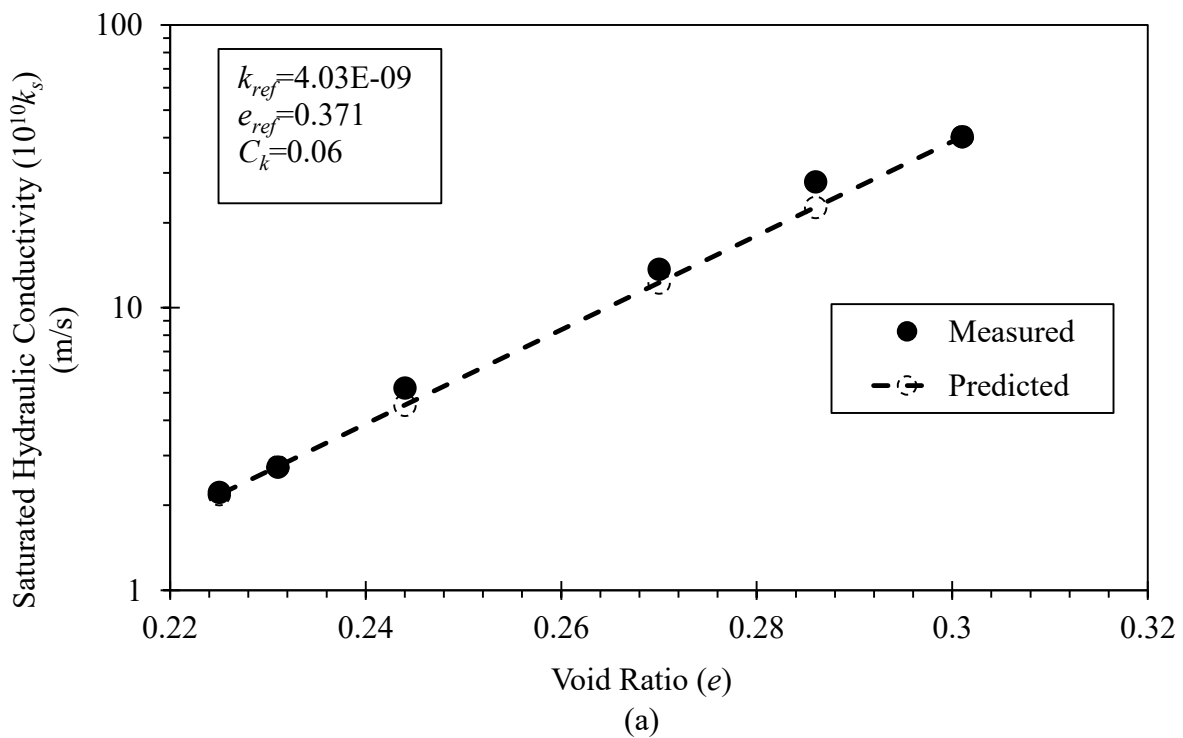
$$k_w = k_s S_e^\alpha \quad (4.6)$$

where, α is a model parameter and can be taken as 3.5 as recommended by Averjanov (1950), Brooks and Corey (1964), and Mualem (1976); S_e is the effective degree of saturation defined using Eq. (4.7) for a given degree of saturation S_r , where $S_{r,res}$ is the residual degree of saturation ($S_{r,res}=0.09$ from the soil water characteristic curve reported in Fig. 4.3a).

$$S_e = \frac{S_r - S_{r,res}}{1 - S_{r,res}} \quad (4.7)$$

Fig. 4.8b presents the variation of k_w during an air-drying process with degree of saturation. In the early stages of drying, k_w experienced rapid reductions until degree of saturation approached $S_{rs}=0.49$ (i.e. degree of saturation corresponding the shrinkage limit W_s). For degrees of saturation below S_{rs} , the magnitude of k_w became extremely small and the variations were insignificant. Comparing the variation of k_w with the responses of G_{max} observed in Figs. 4.6 and 4.7, it can be deduced that the local discontinuities in the water phase commenced when the degree of saturation approached S_{rs} .

Generally, it would be expected that the time required for matric suction equalisation for a specific sample should consistently increase due to substantial reduction in hydraulic conductivity as observed in Fig. 4.8b. However, the relationship between k_w and t_{se} presented in Fig. 4.9 reveals that while t_{se} increased with decreasing k_w in the early stages of the air-drying process (i.e. $S_r > 0.8$), t_{se} consistently decreased at lower values of k_w corresponding to $S_r < 0.8$, indicating that some other effects would also impact the time required for matric suction equalisation.



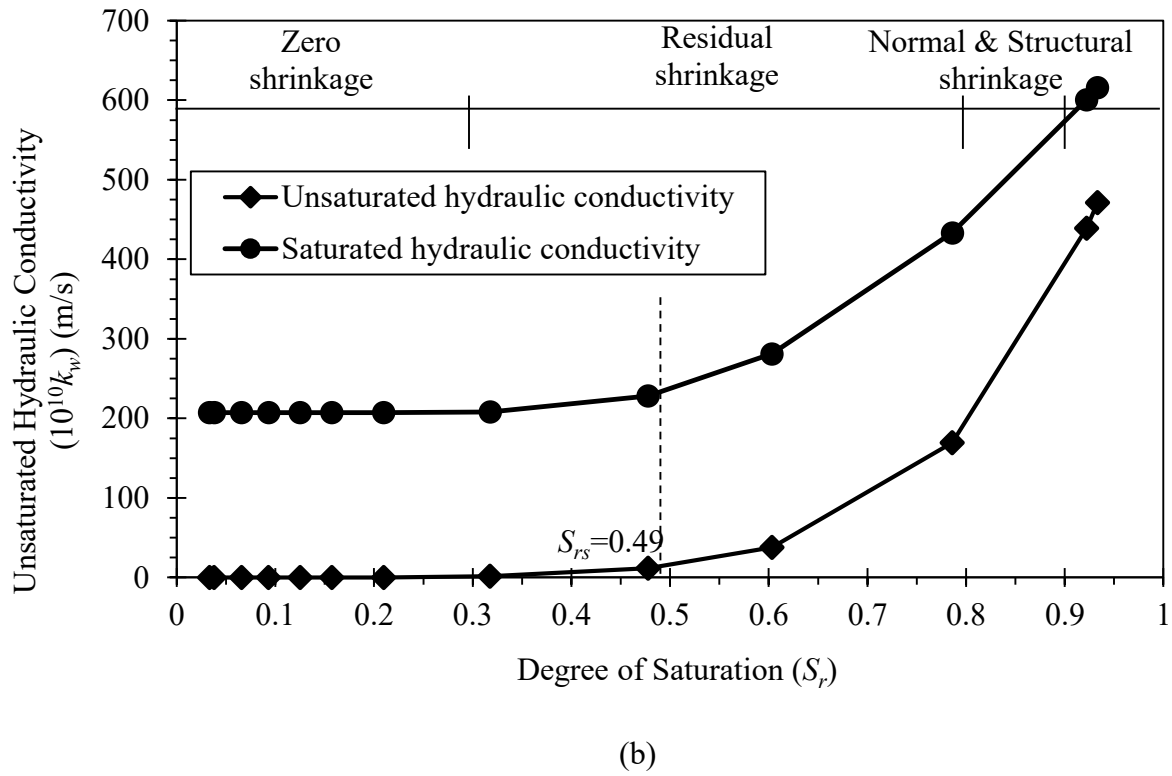


Fig. 4. 8 Variations of hydraulic conductivity (a) with void ratio (b) with degree of saturation during an air-drying process

It is noted that matric suction equalisation in this experiment involves the process of diminishing the non-uniform distribution of the water phase in a closed system, thus, driven by the hydraulic flow as well as the water vapour flow. While effect of the former is proportional to the hydraulic conductivity, effect of the latter is proportional to the total contact area between pore water and pore air as reported by Monteith (1981) and Raupach (2001). At high degrees of saturation, i.e. in the structural and normal shrinkage zones, the total area of pore water-air interface was rather small as the air could only invade the macropores between aggregates. In this condition, the matric suction equalisation was driven mainly by the flow of liquid water through the network of saturated micropores, justifying the increase in t_{se} with decreasing hydraulic conductivity in the early stages of the air-drying process as demonstrated in Figs. 4.8 and 4.9.

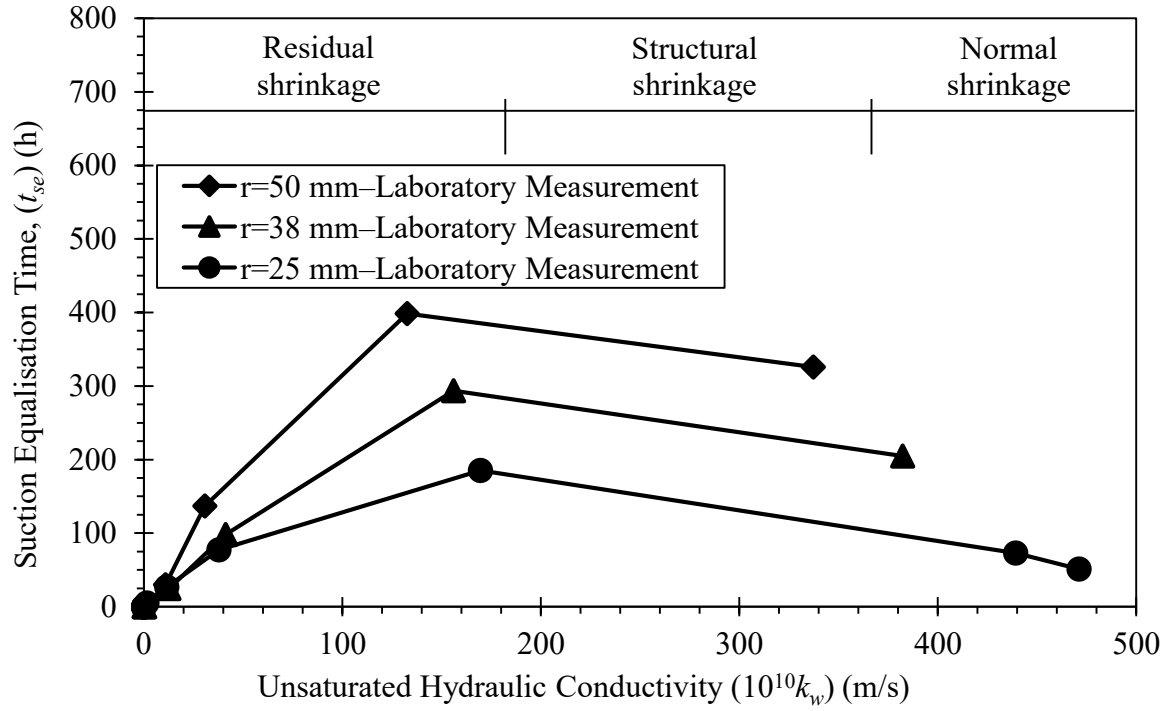


Fig. 4. 9 k_w - t_{se} relationship during an air-drying process

In the residual shrinkage zone, corresponding to $S_r < 0.8$, air commenced to displace water in the micropores resulting in significant increases in the total area of pore water-air interface. After sealing the sample using cling wrap, evaporation and condensation processes simultaneously progressed within the sample with the former playing the main role in establishing equilibrium between partial water vapour pressure at the pore-water interfaces and partial water vapour pressure available in the air phase. Although the evaporation rate for a unit of pore water-air interface remained unchanged at a constant temperature (Headrick 1967), the evolution of the partial water vapour pressure should vary across the cross-sectional area of the sample due to the initial non-uniform distribution of water phase. Indeed, the increase in the partial water vapour pressure at the centre of the sample was higher than that at the boundary due to the higher water content and corresponding area of water-air interface. Therefore, apart from the outward flow of liquid water, an outward flow of water vapour (water vapour diffusion) also occurred accelerating the matric suction equalisation. As the degree of

saturation decreased, the ratio of the area of pore water-air interface to the pore water volume increased leading to the reduction in the time required for matric suction equalisation, t_{se} , as shown in Figs. 4.9 and 4.10.

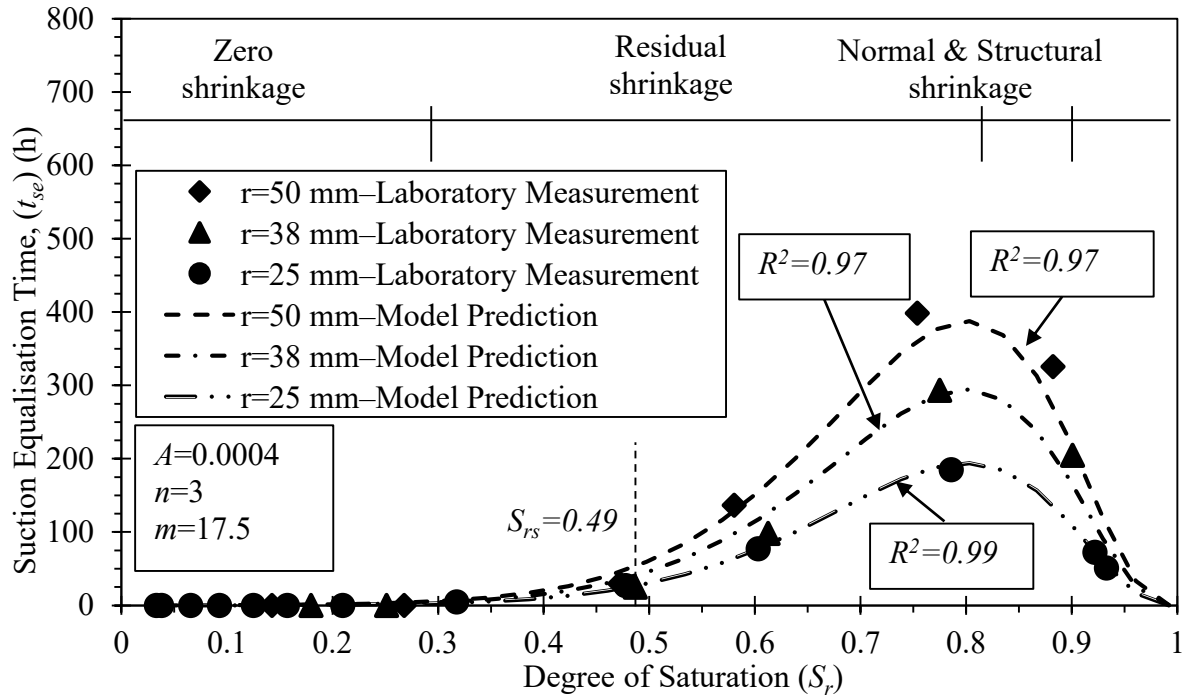


Fig. 4. 10 Measured and predicted t_{se} for different sample sizes

Once the air phase became continuous across the cross-sectional area of the sample, the non-uniform distribution of water phase during free-evaporation stages would be diminished due to the rapid flow of water vapour, leading to a shorter time required for matric suction equalisation. It should be noted that the effect of vapour flow would be more pronounced when the soil is drier. Indeed, referring to Fig. 4.10, it is observed that at degrees of saturation less than 0.49 (i.e. $S_r < S_{rs}$), the t_{se} was rather small and when $S_r < 0.3$, the matric suction equalisation was established almost immediately irrespective of the sample diameter. At degrees of saturation below the residual degree of saturation (i.e. $S_r < S_{r,res}=0.09$), water phase became discontinuous (Fredlund et al. 1993; Pande and Pietruszczak 2015; Vanapalli et al.

1996), thus the flow of liquid water stopped and the matric suction equalisation was driven by the flow of water vapour only and therefore, t_{se} approached zero as evident in Fig. 4.10.

4.3.7 Effect of sample size on t_{se}

Fig. 4.10 demonstrates effects of degree of saturation and sample diameter on the time required for matric suction equalisation t_{se} in the weight-controlled bender element tests. Since the sample was cylindrical with drainage boundaries at the vertical outer boundaries, the effective drainage path was equal to the radius of the sample representing the maximum length of the hydraulic flow and the water vapour flow. As expected and evident in Fig. 4.10, increases in the sample radius resulted in increases in t_{se} . It was also observed that the effect of sample size on t_{se} was significant in the structural shrinkage and normal shrinkage zones, while the effects diminished in the residual shrinkage zone. Referring to Fig. 4.10, the sample size effect was minor when $S_r < S_{rs}$. Indeed, the transition in the contributions of the hydraulic flow and the water vapour flow to the matric suction equalisation process can explain the above-mentioned observations. Specifically, the hydraulic flow dominated the response at high range of degree of saturation and became less significant with decreasing water content due to the substantial reductions in the hydraulic conductivity. On the contrary, the role of the water vapour flow was insignificant at high degrees of saturation, while the impacts grew swiftly when air commenced invading the micropores, which was more evident in the residual shrinkage zone and beyond.

4.3.8 Developing empirical relationships to predict t_{se}

Referring to the discussion in the previous sections, matric suction equalisation following an air-drying process is driven by the hydraulic flow and the water vapour flow. The former dominates at the early stage of the drying process within the structural and normal shrinkages, whereas the latter dominates the remainder toward the lower degrees of saturation (i.e. residual and zero shrinkages). The effects of both hydraulic and vapour flows on t_{se} depend on degree

of saturation, but with opposite trends as shown in Fig. 4.10. Other factors that directly influence the effects of hydraulic and water vapour flows on t_{se} are the drainage path (r) and effective cross section of the flows. Clearly, t_{se} is proportional to the ratio of the former to the latter. The determination of the cross section of the flows is challenging as it represents the pore size distribution, which alters during the air-drying process (Li and Zhang 2009). However, the alteration of the cross section of the flows can alter the hydraulic conductivity at saturated state, thus k_s can be used as a practical parameter capturing the pore sizes and their distribution. In this study, an equation for the prediction of t_{se} incorporating all the above-mentioned factors was proposed as follows:

$$t_{se} = A \frac{r}{k_s} (1 - S_r)^n \exp(-m(1 - S_r)) \quad (4.8)$$

where A , n , and m are fitting parameters, r is the drainage path (representing the maximum length of the hydraulic flow and the water vapour flow), k_s is the hydraulic conductivity at the corresponding saturated state for a given void ratio, $(1 - S_r)^m$ and $\exp(-m(1 - S_r))$ attempt to capture the way degree of saturation alters the contributions of the hydraulic flow and water vapour flow to t_{se} , respectively.

The nonlinear least-square data fitting method was used to determine the model parameters (i.e. $A = 0.0004$, $n = 3$ and $m = 17.5$) based on measurements obtained from the weight-controlled bender element test for the sample with diameter of 50 mm ($r = 25$ mm); measured and predicted values of t_{se} show a good agreement as presented in Fig. 4.10.

To further verify the proposed model for other sample sizes, the calibrated model parameters were then used for the prediction of t_{se} in the two remaining weight-controlled bender element tests for the soil samples with diameters of 76 mm and 100 mm. As shown in Fig. 4.10, a

reasonable agreement was achieved between predictions and the corresponding laboratory measurements, indicating the reliability of the proposed Eq. (4.8) in predicting the time required for matric suction equalisation following an air-drying process.

4.3.9 Empirical equation for the prediction of G_{max} during an air-drying process

In an attempt to formulate variations of the small strain shear modulus during an air drying process, a predictive equation for G_{max} capturing effects of matric suction, van der Waals attractions and electric double layer repulsions was developed. During an air-drying process, the combined contribution of van der Waals attractions and electric double layer repulsions grows consistently with reducing degree of saturation (Lu and Likos 2006), whereas the contribution of matric suction increases in the early stage due to rapid increases of matric suction before experiencing reductions at low degrees of saturation with the increasing effect of pore water loss and finally approaches zero at the end of the air drying (Alonso et al. 2010). The proposed empirical equations to estimate the small strain shear modulus during air drying process are:

$$G_{max} = p_r f(e) \left[b_1 \left(\frac{\psi S_r}{p_r} \right)^{m_1} + c(1 - S_r)^k \right] \text{ for } S_r \geq S_{rs} \quad (4.9a)$$

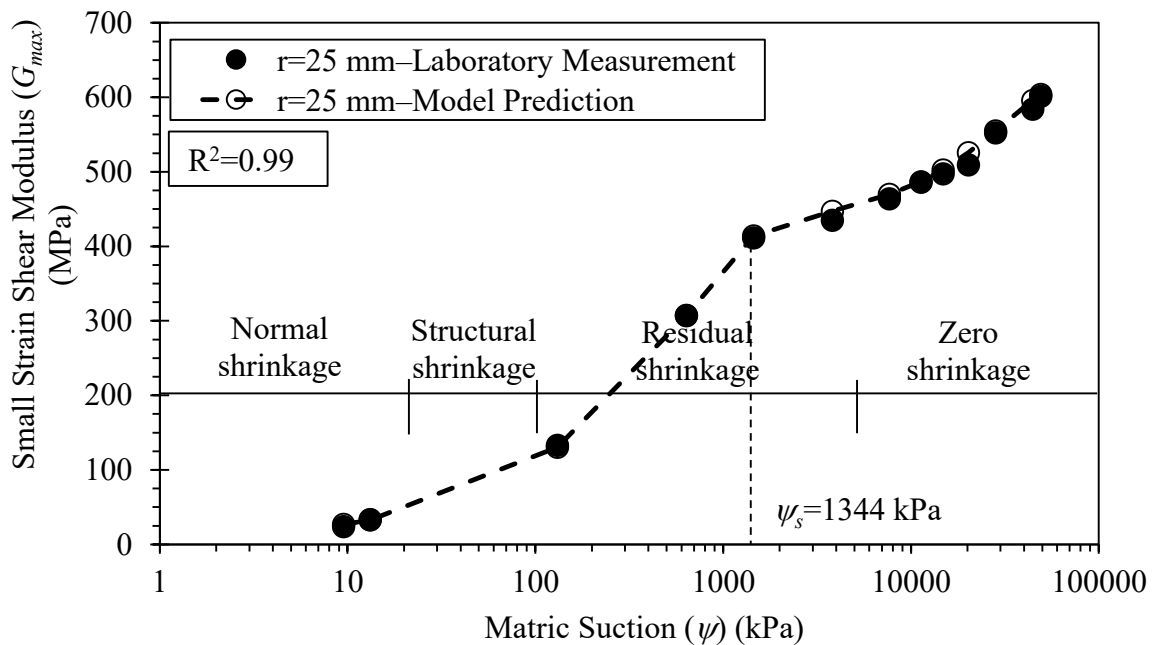
$$G_{max} = p_r f(e) \left[b_2 \left(\frac{\psi S_r}{p_r} \right)^{m_2} + c(1 - S_r)^k \right] \text{ for } S_r < S_{rs} \quad (4.9b)$$

where S_r is the degree of saturation, S_{rs} is the degree of saturation corresponding to the shrinkage limit and can be determined from the results of the shrinkage test, b_1 and m_1 are model parameters for evaluating the contribution of matric suction to G_{max} when $S_r \geq S_{rs}$, b_2 and m_2 are model parameters for evaluating the contribution of matric suction to G_{max} when $S_r < S_{rs}$, c and k are model parameters for evaluating the combined contribution of van der

Waals attractions and electric double layer repulsions, $p_r = 100$ kPa is the reference pressure, ψ is the matric suction, and $f(e) = 1/(0.3 + 0.7e^2)$ is the void ratio function proposed by Hardin (1978).

The model parameters for proposed Eq. (4.9) were determined based on data in the weight-controlled bender element test for the sample with a diameter of 50 mm (see Table 4.1) and were then adopted to predict G_{max} in the experiments for two other samples with diameters of 76 mm and 100 mm for further verification. Good agreements between measured and predicted values of G_{max} were observed as shown in Fig. 4.11 for all the three experiments.

In practice, Eq. (4.9) enables the prediction of G_{max} for compacted soils near the ground surface subjected to significant loss of water content, while Eq. (4.8) allows the determination of time required for sealing the sample for a matric suction equalisation prior to conducting experiments to measure parameters of unsaturated soils following air drying process.



(a)

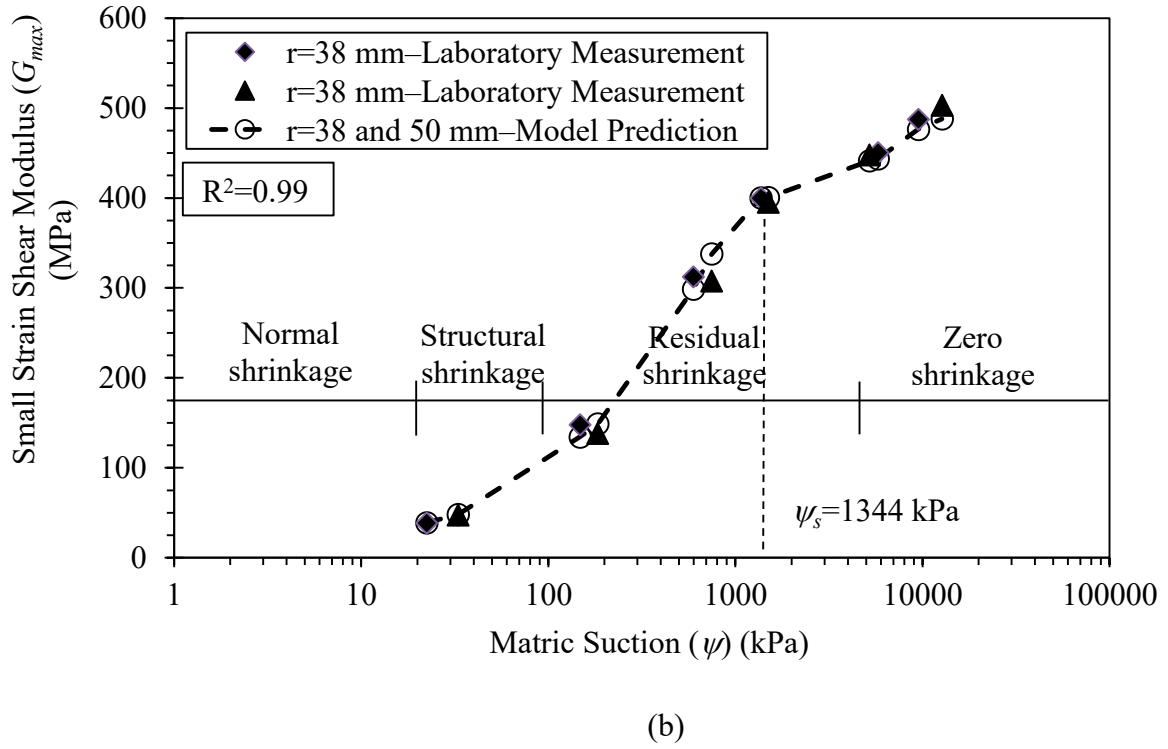


Fig. 4. 11 Measured and predicted G_{max} for samples (a) $r=25$ mm, and (b) $r=38$ and 50 mm

4.4 Summary

A weight-controlled bender element setup was developed to investigate variations of small strain shear modulus (G_{max}) of soils during an air-drying process. The comparison between measurements of G_{max} following the matric suction equalisation and the corresponding case skipping the matric suction equalisation revealed that the later underestimated the small strain shear modulus of partially saturated soils. This underestimation of G_{max} was believed to be due to the non-uniform distributions of the water phase and corresponding matric suction when matric suction equalisation was ignored. It was, however, observed that the underestimation was rather small in the early stages of the air-drying process, while the difference exacerbated when the degree of saturation approached S_{rs} (i.e. the degree of saturation corresponding to the shrinkage limit). It was argued that development of the water discontinuity enhanced the non-

uniform distribution of water phase and the underestimation of G_{max} when ignoring matric suction equalisation.

When matric suction equalisation was allowed, the response of G_{max} with increasing matric suction was heavily nonlinear. The reduction in the evolution rate of G_{max} , at the onset of the zero shrinkage zone, could be attributed to significant increases in the decreasing rate of the water–solid particle contact area as a result of the small degree of consolidation. That resulted in reduction in the contribution of matric suction on G_{max} which is proportional to the water-particle contact area.

During the matric suction equalisation, following the air drying process, the non-uniform distribution of water phase in the sample cross section resulted in differences in the partial water vapour pressure across the sample area, causing the formation of a water vapour flow to drive the system toward an equilibrium. Hence, matric suction equalisation was driven by not only the hydraulic flow but also the water vapour flow. Results from weight-controlled bender element tests with different sample diameters revealed that the hydraulic flow governed the time required for matric suction equalisation (t_{se}) at structural and normal shrinkage stages, whereas the effect of water vapour flow dominated as the soil became drier (i.e. $S_r < 0.8$). The effects of both hydraulic and vapour flows on t_{se} were found to be significantly affected by degree of saturation, but with opposite trends. A decrease of saturation led to a shorter matric suction equalisation time when the water vapour flow dominated the response, while a reduction in degree of saturation caused an increase in t_{se} when the hydraulic flow dominated the response (due to the reduction in the hydraulic conductivity).

An empirical equation was proposed for the estimation of t_{se} considering the effects of the degree of saturation, the flow path and the corresponding hydraulic conductivity. Another

empirical equation was also established in an attempt to capture variations of G_{max} during an air drying process as a function of matric suction and degree of saturation. The two proposed equations proved to be capable of providing reasonable predictions of the time required for matric suction equalisation and the magnitude of G_{max} for the investigated soil during an air-drying process. In practice, equations proposed in this study can be utilised to determine the time required for matric suction equalisation in experiments studying the behaviour of unsaturated soil after air drying and to predict G_{max} of compacted soil layers near the ground surface, which can experience significant evaporation when exposed to the open environment.

Chapter 5

Small Strain Shear Modulus of Unsaturated Lightly Cemented Soil Subjected to Drying-Wetting and Loading-Unloading Cycles

5.1 Introduction

Soil stabilization with cement has wide applications in earthworks including roads, embankments, and railway tracks. It was reported that cement stabilization could increase small strain shear modulus (G_{max}) of treated soils effectively (Acar and El-Tahir 1986; Chang and Woods 1987; Chiang and Chae 1972; Puppala et al. 2006; Saxena et al. 1988; Sharma and Fahey 2004; Yang 2008; Yang and Woods 2014). The study related to G_{max} of cemented soils is important in predicting the response of soil subjected to dynamic loadings and during earthquakes. Chiang and Chae (1972) investigated G_{max} of a uniform sand and a silty clay treated with 2% to 6% of Type I Portland cement using a resonant column apparatus. Test results showed that G_{max} of the cement treated soils was proportional to the confining pressure, especially for the treated uniform sand. A similar observation was reported in torsional resonant column tests on Monterey sand treated with 1% to 4% of Portland cement by Acar and El-Tahir (1986). It was reported that increases of confining pressure increased the number of inter-particle bonds, thus, resulting in enhancement of the resistance of the cement treated sand subjected to shear deformations.

On the contrary, Lovelady and Picornell (1990) and Baig et al. (1997) believed that G_{max} of cement treated soils was affected by the confining pressure only when confining pressure

was high enough to destroy the cementation bonds. They concluded that the notable effect of confining pressure on G_{max} of cemented soils, observed in previous resonant column tests, was due to the loose connections between the sample and the end platens. With the cement treated sand samples being glued to the end platens with epoxy, measurements of G_{max} in resonant column tests conducted by Lovelady and Picornell (1990) and Baig et al. (1997) showed negligible effects of confining pressure at the low range of stress. The independence of G_{max} on confining pressure at the low range of stress was confirmed in later experiments by Yang (2008) and Yang and Woods (2014) on kaolinite and bentonite treated with 2.5% to 7.5% of cement. Similar behaviours of G_{max} of kaolinite treated with 4% of cement were also reported by Trhlíková et al. (2012). Rinaldi and Santamarina (2008) classified the relationship between shear wave velocity and confining pressure into two regions: cementation-controlled region at low confining pressures and stress-controlled region at high confining pressures. Specifically, in the cementation-controlled region, the shear stiffness was determined by the degree of cementation, while confining pressure had no effect on the small strain soil stiffness, while in the stress-controlled region, the small strain soil stiffness increased with confining pressure similar to untreated soils.

In most experiments mentioned above, G_{max} responses were assessed for samples after the curing stage, while a large proportion of cement treated soils are subjected to drying and wetting cycles in real conditions. Results of durability tests conducted by Zhang and Tao (2008) on a clayey silt, stabilized with 2.5% to 12.5% of Type 1 Portland cement, showed that the volumetric swelling and mass loss induced by wetting - drying cycles exacerbated with the decrease in cement dosage, and failures of samples with low cement dosages were recorded after 12 cycles of wetting and drying. Increasing mass loss, cracking, and structural failure with increasing number of drying-wetting cycles were also reported in an experiment on cement solidified lead-contaminated silty clay conducted by Li et al. (2014). Liu et al. (2018) studied

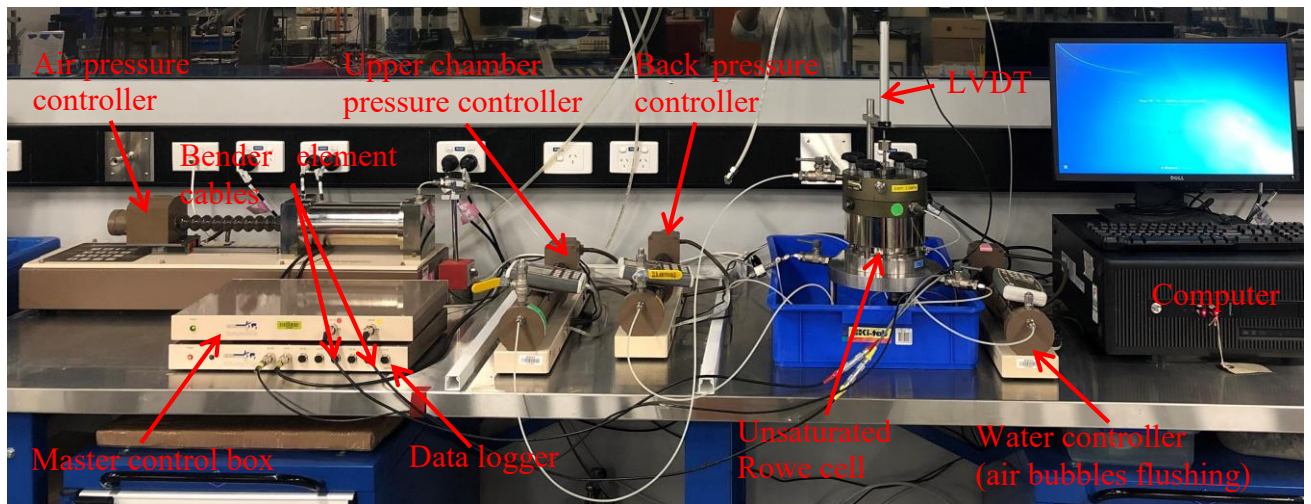
the development of cracks in Cd-contaminated lean clay samples treated with 2% to 10% of Portland cement during drying-wetting cycles. The observed variations of cracking intensity factor (i.e. the ratio of the cracked area to the total surface area) revealed that cracks induced by drying surpassed cracks induced by the subsequent wetting and that wetting not only caused further development of cracks due to non-uniform swelling but also healed some cracks owing to cement hydration. Obviously, drying and wetting have significant effects on mechanical properties of cement treated soils, including G_{max} , however, research on the response of G_{max} of cement treated soils subjected to cycles of drying-wetting is still very limited.

In this study, effects of drying-wetting cycles on G_{max} of a lightly cemented soil and subsequent impacts of loading-unloading cycles were investigated adopting a modified unsaturated Rowe and Barden consolidometer for controlled matric suction and net stress values.

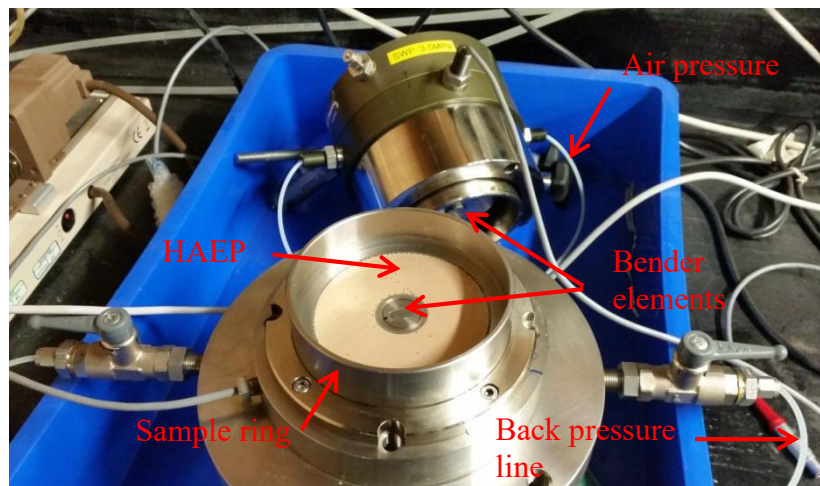
5.2 Laboratory Experiments

5.2.1 Unsaturated Rowe cell apparatus with bender elements

A Rowe and Barden type cell was modified to allow consolidation testing with shear wave velocity measurements on unsaturated soil samples subjected to controlled matric suctions and net stresses and on saturated soils with different consolidation pressures. With three pressure/volume controllers being connected directly to the cell, the device is capable of simultaneously applying vertical stress and back water pressure on the sample in saturated stages. In unsaturated stages, adopting the axis-translation technique proposed by Hilf (1956), vertical stress and air pressure can be applied on the top of the sample using the upper chamber pressure controller and the air pressure controller, respectively, while back water pressure is applied at the bottom of the sample using the back pressure controller (see Fig. 5.1).



(a)



(b)

Fig. 5. 1 Unsaturated Rowe cell setup: (a) the entire system assembled in the lab, (b) unsaturated Rowe cell with built-in bender elements

For accurate measurements of volume changes of the soil sample and pore water during the experiment, GDS advanced pressure/volume controllers (ADVDP) were used as the upper chamber pressure controller and the back pressure controller. The change in volume was measured to 1 mm^3 with the accuracy of measurement to be 0.1% of the measured value. Due to relative high initial stiffness, the cement treated soil in this study was expected to experience

small deformations during the experiments. To reduce the error of the volume measurement, prior to the first test, volumes of distilled water used in those controllers were set to 30% of the initial volume of pore water (i.e. 36400 mm³). In addition, the variation of void ratio in each test stage was compared to the variation of the vertical displacement to assure capturing the correct volume change.

To retain the difference between pore air pressure and pore water pressure (i.e. matric suction), the normal porous disk at the base pedestal of the Rowe cell was replaced by a high air entry porous disk (HAEPD). The presence of the HAEPD could isolate air from the base pedestal, however, a small amount of air could still go through the disk due to air diffusion as also observed by other researchers (Padilla et al. 2006). Thus, in this study, water containing diffused air, accumulated at the bottom of the HAEPD, was periodically flushed by using an additional water controller (see Fig. 5.1a) connected to the same line operating at 3 kPa lower pressure than the corresponding back pressure; this pressure difference was chosen so as the back pressure remained unchanged during the flushing.

The cell was also equipped with a linear variable differential transformer (LVDT) for the measurement of sample axial displacement (see Fig. 5.1a). To determine G_{max} of the sample at any stages during a long-term experiment, two bender elements were embedded on the top and bottom of the sample to measure the shear wave velocity propagating along the central axis of the cylindrical sample (see Fig. 5.1b)

5.2.2 Sample preparation and calculating the initial physical properties

The untreated soil mixture consisted of 45% of fine sand and 55% of kaolin clay by dry weight, and its particle size distribution curve was presented in Fig. 5.2. Laboratory tests also provided the specific gravity, plastic limit, and liquid limit of the soil as showed in Table 5.1. According

to the Unified Soil Classification System the soil is classified as sandy lean clay (CL). The chemical agent used for soil treatment was a High Early Strength Portland Cement (HE cement) with a specific gravity of 3.14. The typical values of the initial and final setting times of this HE cement are 1.5-3 hours and 2.5-4 hours, respectively. The evolution of the compressive strength of cement with curing time, presented in Table 5.2, showed that around 80% of the compressive strength at 28 days was obtained at 7 days of curing.

Table 5. 1 Basic properties of the untreated soil

Specific gravity	2.65
Plastic limit	16.6%
Liquid limit	38.2%

Table 5. 2 Typical compressive strength of the High Early Strength Portland Cement used in this study

Curing time (day)	Compressive strength (MPa)
1	26-29
3	38-45
7	51-58
28	62-70

The dry fine sand and kaolin were first mixed in a container using a spatula until a homogeneous mix was obtained. A predetermined amount of distilled water was then gradually

sprayed into the mixture during the ongoing mixing to form the final slurry. The final soil slurry along with the container was stored in an air-tight plastic bag at a room temperature of 21°C for moisture stabilization.

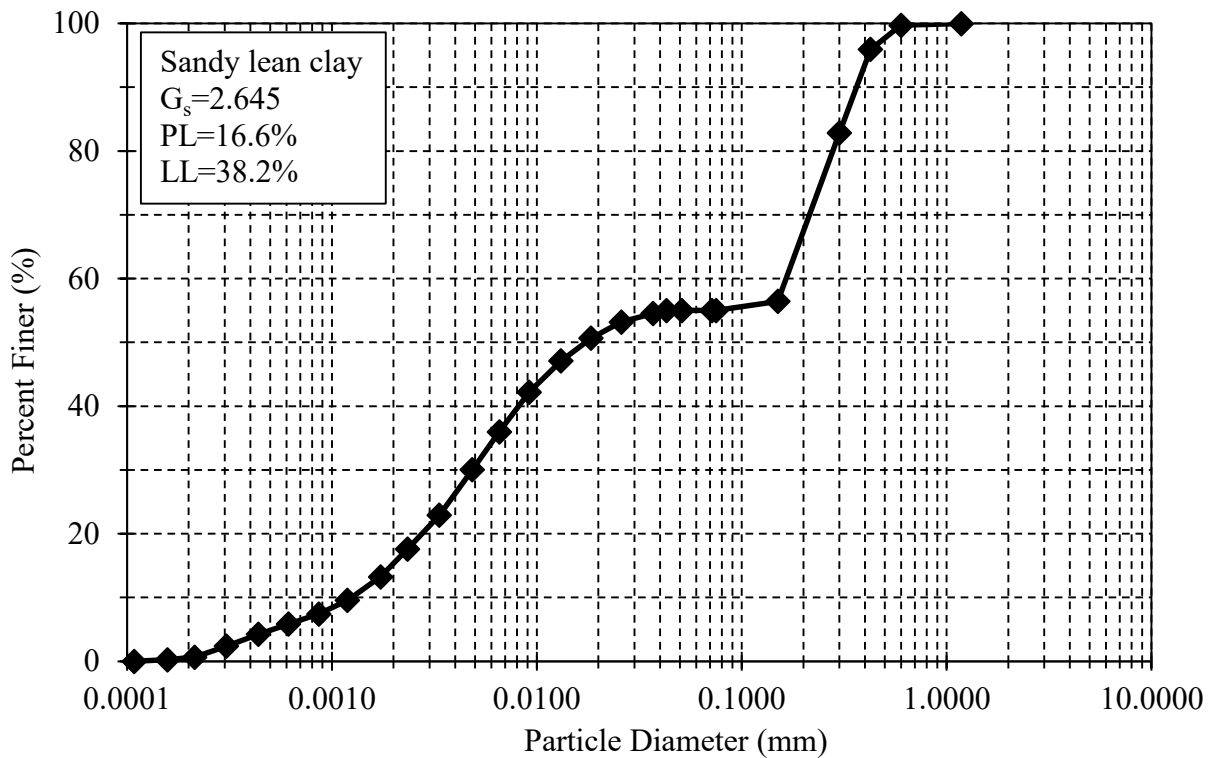


Fig. 5. 2 Particle size distribution curve for the sand-kaolin mixture

After 24 hours of curing for homogeneous moisture distribution, the soil slurry was mixed with a cement slurry which was formed by mixing 2% HE cement (by dry weight of soil) with distilled water with the water:cement ratio of 1:1. The mixing continued until forming a homogeneous soil-cement paste. Then, the soil-cement paste was placed into the sample ring of the unsaturated Rowe cell by using a spatula. Edges of the sample ring were filled first with care in an attempt to prevent the formation of air voids. It should be noted that prior to and during placing the soil-cement paste into the cell, the saturated condition of the HAEPD was maintained by using the Back pressure controller, filled with de-aired water, to persistently

apply a constant pressure of 30 kPa at the bottom of the porous disk. To avoid direct contact between the porous disk and the soil-cement paste, right before the placement of the paste, a wet filter paper was placed onto the top of the HAEPD. Another filter paper was also placed on the top of the paste prior to assembling the apparatus to avoid direct contact between the soil-cement paste and the upper part of the Rowe cell.

Weights of the material before and after placing it into the sample ring were measured to calculate the initial weight of the sample in the ring. Right after the completion of placing material into the sample ring, the leftover material was used to determine the initial water content of the cement treated soil. From the initial weight and initial water content, the weights of the solid phase (i.e. sand, kaolin, and cement) and water phase were determined.

The initial volume of the solid phase including sand, kaolin, and cement of the treated sample was then calculated from the weights and specific gravities of the sand-kaolin mixture and cement. Once all the weights and volumes of solid and water phases had been determined, every other physical property at the initial state, such as void ratio and degree of saturation were determined.

5.2.3 Procedure for unsaturated tests

Right after the filter paper was placed on the top of the soil-cement paste, the Rowe cell was assembled and a constant stress stage was applied on the sample with a vertical stress of 80 kPa and a back pressure of 30 kPa, corresponding to an effective stress of 50 kPa. This stress state remained in the first 7 days to allow initial soil-cement paste curing, before the vertical stress and back pressure were simultaneously and gradually increased to 900 kPa and 850 kPa, respectively, while the effective stress of 50 kPa was maintained for saturation purpose allowing further curing during saturation under a constant effective stress. Using the back

pressure technique adopted by many other researchers (e.g. Indraratna et al. 2009; Konrad and Pouliot 1997; Oh et al. 2008), the air bubbles, possibly introduced during mixing and placement of the paste in the ring, could be dissolved so the initial state of the soil in the Rowe cell was saturated. Shear wave velocity was measured continuously during these stages allowing investigation on variations of G_{max} during the curing and saturation periods.

After 16 days of soil-cement paste curing in the Rowe cell (7 days initial curing and 9 more days during the saturation process and ensuring evolution rate of G_{max} with time became minor), the first matric suction increment was applied. The back pressure of 850 kPa, applied at the bottom of the sample, remained unchanged while a vertical pressure of 950 kPa and an air pressure of 900 kPa were applied on the top surface of the sample. Thus a vertical net stress (i.e. the difference between the vertical stress and pore air pressure) of 50 kPa and a matric suction (i.e. the difference between pore air and pore water pressures) of 50 kPa were applied in the first drying stage. In the subsequent stages, the air pressure at the top of the sample was kept constant whereas the vertical stress and back pressure varied to apply target net stresses and matric suctions. Variations of net stress and matric suction in different stress states of the unsaturated Rowe cell test are summarized in Table 5.3.

As presented in Table 5.3, the maximum matric suction of 400 kPa was used during drying processes. This maximum matric suction was selected after failures of two previous experiments during the first drying stage at matric suctions of 700 kPa and 600 kPa, respectively. In the failed experiments, after 1 day from the application of the above-mentioned matric suctions, air was detected to flow through the HAEPD, leading to extreme increases in the volume of the back water controller. This should be attributed to the formation of cracks induced by the uneven shrinkage of the sample and developed through the sample height, allowing air pressure to apply directly on the HAEPD. The high air pressure accelerated the

evaporation process of water in the HAEPD. Due to extremely low hydraulic conductivity of the HAEPD with the air entry value of 1500 kPa, the amount of water lost by evaporation can surpass the amount of water the HAEPD received from the back water controller. Eventually, air could flow through the HAEPD when parts of it became dry.

Table 5. 3 Unsaturated stress states of cement treated sandy clay used in this study to investigate variations of the small strain shear modulus

Test stage	Net stress (kPa)	Matric suction (kPa)
1 st drying-wetting cycle	50	50, 100, 200, 400
	50	200, 100, 50
1 st loading-unloading cycle of net stress	50, 100, 200, 400, 800	50
	400, 200, 100, 50	50
2 nd and 3 rd loading-unloading cycles of net stress	400, 800	50
	400, 50	50
2 nd and 3 rd drying-wetting cycles	50	50, 100, 200, 400
	50	200, 100, 50

A trial test in which the Rowe cell was only filled with a thin layer of distilled water was conducted to simulate the failed tests. After 1 day from the applications of back and air pressures of 30 kPa and 630 kPa, respectively, air was also found to flow through the HAEPD when the HAEPD became dry. The trial test confirmed the assumption of the formation of cracks developed through the cemented soil sample at high matric suctions. In an attempt to limit the length of these cracks so as they could not develop through the soil sample, the highest matric suction of 400 kPa was selected for the cemented soil investigated. The observed

small changes in water content in the second and third drying-wetting cycles as shown in Fig. 5.5 indicates that the HAEPD functioned properly during the entire experiment.

In this study, changes in void ratio and degree of saturation of the sample at each stress state were computed from the variations of the sample pore volume and water volume, which were obtained from the variations of the upper chamber and back volumes, respectively. The termination condition for each stage during wetting and drying or loading and unloading cycles was when matric suction equalisation within the sample was achieved with the rate of water content change dropping below 0.04%/day as recommended by other researchers (Mancuso et al. 2002; Rampino et al. 1999; Sivakumar 1993), while stable values of the shear wave velocity also confirmed establishment of the matric suction equalisation.

5.2.4 Scanning Electron Microscopy (SEM) images

After the completion of the unsaturated Rowe cell test, SEM images of the soil sample was taken using a Zeiss EVO LS15 to investigate the formation of cracks induced by cycles of drying-wetting and loading-unloading. The surface of the SEM sample was scanned by an electron beam under a system vacuum of 4.63e-004 Pa.

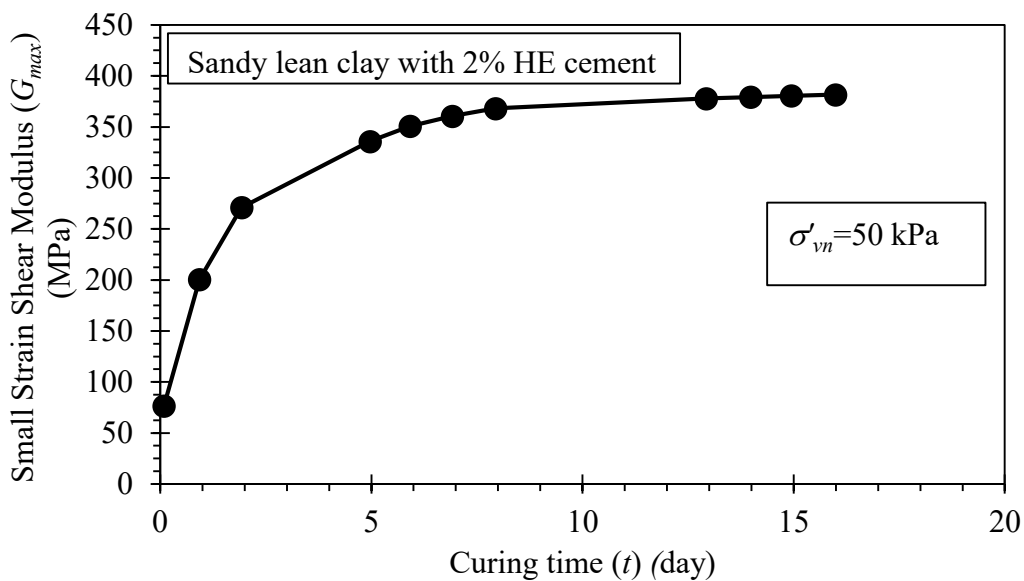
5.3 Results and Discussion

5.3.1 Evolution of G_{max} during curing time

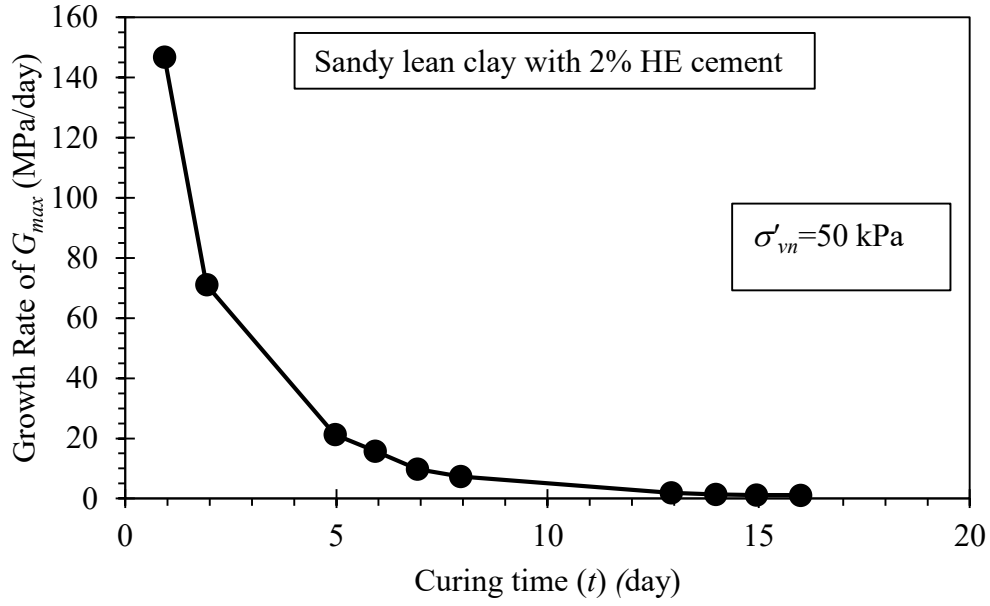
Fig. 5.3 represents the growth of G_{max} during 16 days of curing time under vertical effective stress of 50 kPa. At the beginning of the curing age, when cement and water were mixed, hydration reactions occurred producing hydrated products including hydrated calcium silicates, hydrated calcium aluminates, and hydrated lime (Neville 1995). Hydrated calcium silicates and hydrated calcium aluminates are primary cementitious products which are responsible for the

hardening of the soil-cement paste in the short term. In the long term, as the total content of silica (SiO_2) and alumina (Al_2O_3) in Kaolin is greater than 90% (Aroke and El-Nafaty 2014; Yahaya et al. 2017), hydrated lime reacts with silica and alumina from clay particles in the secondary pozzolanic reactions to produce extra hydrated calcium silicates and hydrated calcium aluminate (Chew et al. 2004; Read et al. 2001). The new generated hydrated calcium silicates and hydrated calcium aluminate then continue to react with available silica and alumina from clay particles allowing further pozzolanic reactions, contributing to the further evolution of soil strength and stiffness.

As observed in Fig. 5.3, the highest stiffness growth rate of 146.8 MPa/day was observed on the first day of the curing, beyond which a significantly reduced growth rate was observed; e.g. 71.1 MPa/day for the second day and 21.3 MPa/day for the fifth day. The rate of stiffness gain at 7 days curing was about 10 MPa/day, while the growth rate was less than 1 MPa/day on the final day of the curing stage (i.e. 16 days). It is evident that the use of the HE cement significantly reduced the required curing time for the cement treated soil.



(a)

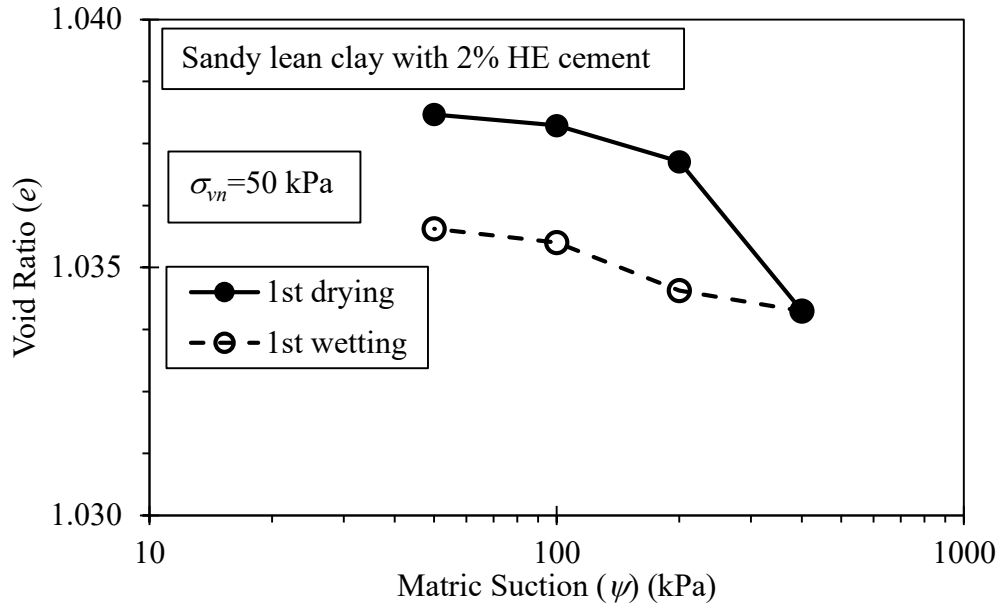


(b)

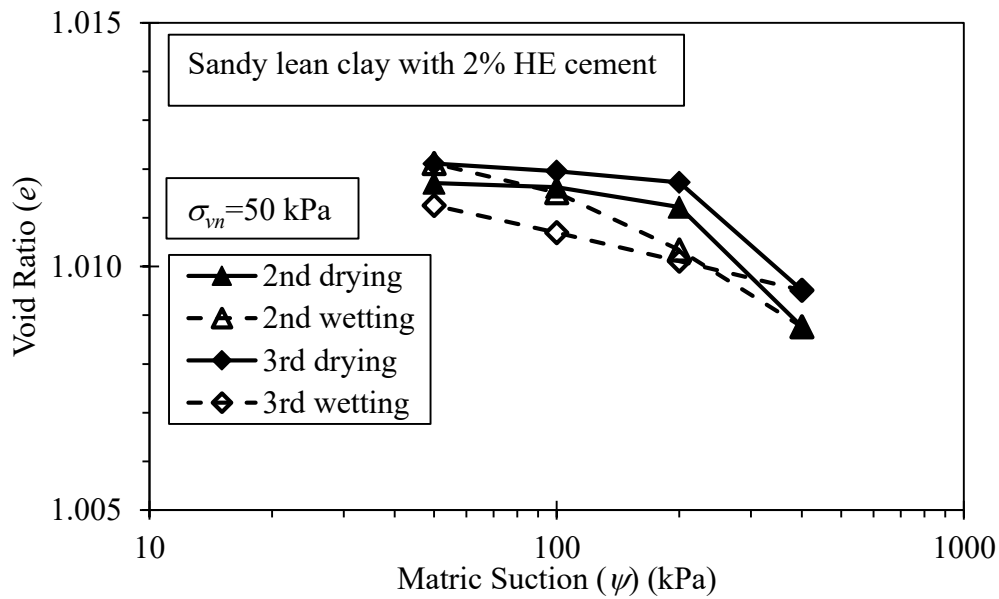
Fig. 5. 3 Evolution of G_{max} during curing time under vertical effective stress of 50 kPa (a)
variations of G_{max} and (b) growth rate of G_{max}

5.3.2 Variation of void ratio and SWCC during drying-wetting cycles

Variations of void ratio during the three drying-wetting cycles under constant net stress of 50 kPa were demonstrated in Fig. 5.4. It is noted that after the first drying-wetting cycle, the cement treated soil experienced three loading-unloading cycles of vertical net stress before being subjected to the second and third drying-wetting cycles as shown in Table 5.3, explaining the lack of continuity of the void ratio as shown in Fig. 5.4.



(a)



(b)

Fig. 5. 4 ψ - e relationship during the (a) first and (b) second and third drying-wetting cycles

Generally, variations of void ratio of cemented soil were insignificant, while maximum reduction and increase of void ratio corresponded to matric suction increase from 200 kPa to 400 kPa in the first drying, and matric suction decrease from 400 kPa to 200 kPa in the second wetting, respectively. Referring to Fig. 5.4, shrinkage dominated over swelling in the first drying-wetting cycle, indicating an irreversible reduction in void ratio, while swelling

surpassed shrinkage in the second drying-wetting cycle. The growing swelling in the second wetting process indicated the reduction in the effect of cementation on restricting swelling of clay particles during wetting as a result of the gradual degradation of cementation, accumulated during several drying-wetting cycles. This observation confirmed the fact that drying and wetting could cause degradation of cementation of cemented soils as reported in the experiments by Liu et al. (2018) and Li et al. (2014). The swelling and shrinkage seem to converge in the third drying-wetting cycle since the void ratio nearly fully recovered after the entire cycle.

Fig. 5.5 depicts the soil water characteristic curve in terms of degree of saturation (*SWCC-S_r*) for the lightly cemented soil adopted in this study considering three drying-wetting cycles. In all cycles, degree of saturations at a specific matric suction during wetting was observed to be persistently lower than the corresponding previous drying. The observation in Fig. 5.5 indicated that the lightly cemented soil also exhibited hydraulic hysteresis behaviour similar to untreated soils reported by other researchers (Khalili and Zargarbashi 2010; Khosravi 2011; Likos et al. 2013; Wheeler et al. 2003). Indeed, maximum reductions in degree of saturation of 3.6%, 0.46%, and 0.29% were observed in the first, second, and third drying-wetting cycles, respectively.

The hydraulic hysteresis in the lightly cemented soil might result from the ink-bottle effect with numerous pores connecting through smaller ones (throats) due to the nonhomogeneous pore size distribution. As known in the capillary phenomenon, pores with smaller diameters can hold higher matric suctions. Thus, during the drying process, the highest matric suction a pore can hold depends on the diameter of its throat, while to refill the pore, matric suction needs to reduce to a lower value corresponding to the largest diameter of the pore (Fredlund et al. 1993; Gallage et al. 2013; Hillel 2003; Moro and Böhni 2002; Taylor 1948). As a result, during

wetting, some pores will no longer be filled with water even though they had been filled at the same matric suction in the previous drying stage. Another cause of the hydraulic hysteresis for lightly cemented soil might be the unrecoverable alterations of the pore network induced by the irreversible volume change accumulated during the drying-wetting cycle, as shown in Fig. 5.4 for the first cycle. That explains the significant reduction of hydraulic hysteresis in the last two drying-wetting cycles compared to that in the first cycle (see Fig. 5.5). In addition, possible formation of micro-crack network, developed during drying and wetting processes as reported by Neramitkornburi et al. (2015) and Liu et al. (2018), could also influence the hydraulic hysteresis behaviour of the lightly cement treated soil investigated in this study.

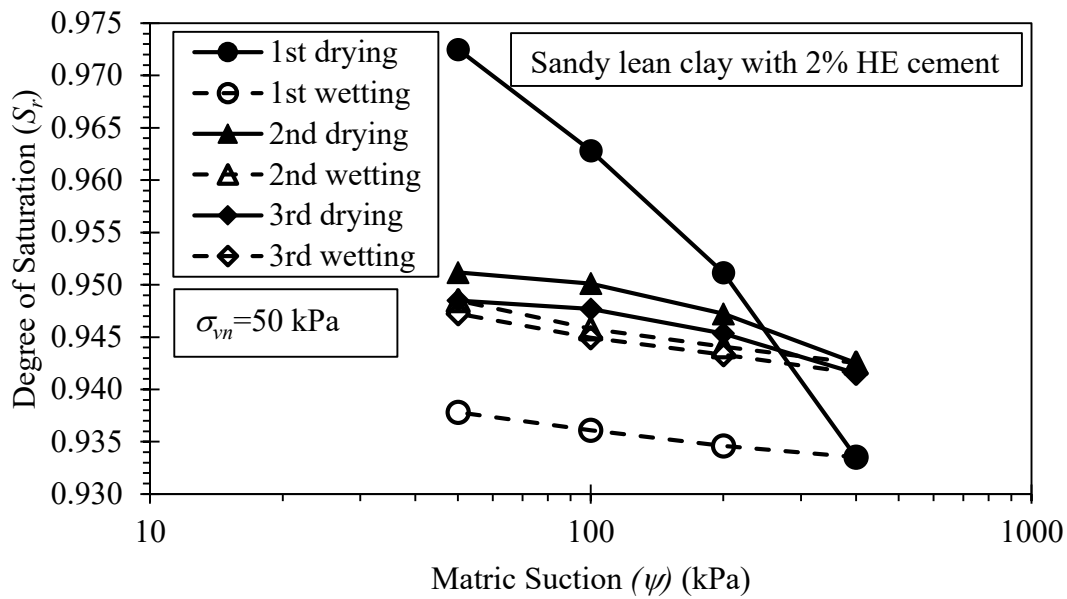


Fig. 5. 5 ψ - S_r relationship during drying-wetting cycles

5.3.3 Variation of G_{max} during drying-wetting cycles

Fig. 5.6 demonstrates variations of G_{max} during three drying-wetting cycles. In the first drying process, the modest growth rate of G_{max} with matric suction from 50 kPa to 200 kPa, was followed by a sharp increase corresponding to higher matric suctions. As observed,

measurements of G_{max} at the same stress state (i.e. the same net stress and matric suction) in the wetting curve were always higher than the corresponding values in the previous drying curve. Since G_{max} still obtained growths at the end of the curing stage (i.e. less than 1 MPa/day), residual cement hydration should partially contribute to the above observation. According to Read et al. (2001) and Kamruzzaman et al. (2009), the secondary pozzolanic reactions could also take several years. It was also reported by Ayeldeen et al. (2016) that Kaolin clay treated with 15% of Portland cement still exhibited a notable growth rate after 50 days of curing.

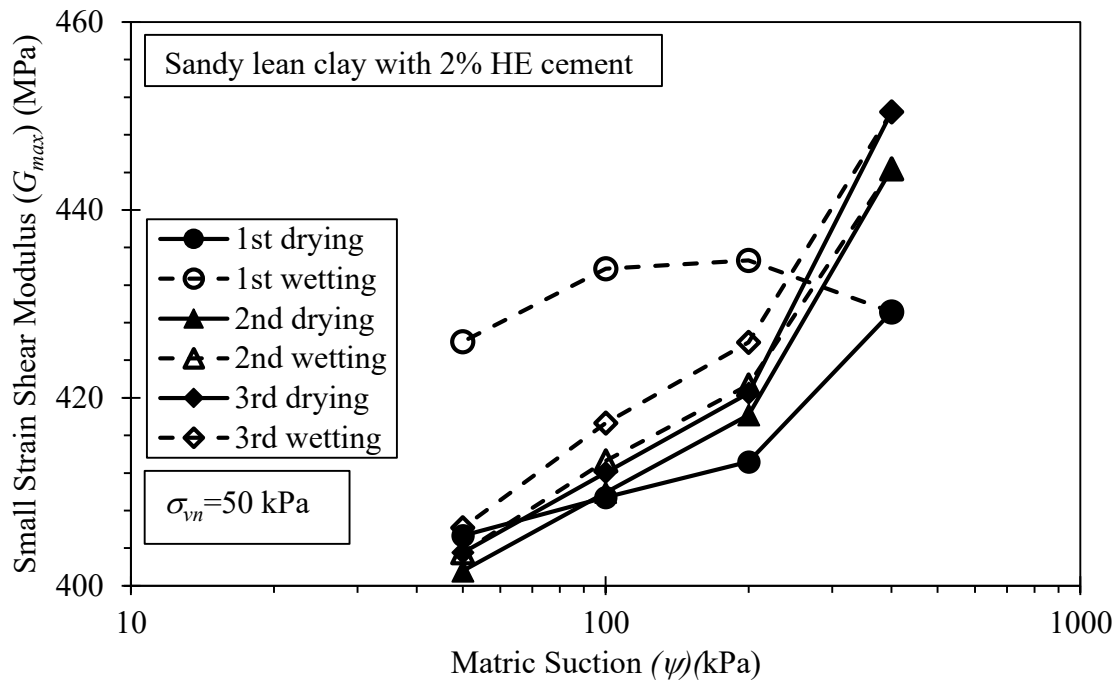


Fig. 5. 6 ψ - G_{max} relationship during drying-wetting cycles

Apart from the residual cement hydration and pozzolanic reaction, the growth of G_{max} during the first drying-wetting cycle should be induced by the reductions of void ratio accumulated during the cycle (refer to Fig. 5.4), and the increase in the combined contribution of the van der Waals attraction and electric double layer repulsion. Herein, the van der Waals attraction is the attractive intermolecular force while the electric double layer repulsion is the repulsive force that exists among the cations in the electric double layers at the soil-water interface. As

reported by Ingles (1962) and Lu and Likos (2006), the magnitudes of van der Waals attraction and electric double layer repulsion on the soil stress state are notable among clay particles. As reported in the multi-stage unsaturated Rowe cell test on the reconstituted clayey sand consisting of 25% of Kaolin and 75% of fine sand by dry weight (see Chapter 3), remarkable effects of van der Waals attraction and electric double layer repulsion on G_{max} of the soil sample were observed during drying-wetting cycles and a loading-unloading cycle of net stress. It was observed that a decrease in the degree of saturation led to an increase in the combined contribution of the van der Waals attraction and electric double layer repulsion, and vice versa. By considering the hydraulic hysteresis behaviour of the soil sample during the first drying-wetting cycle (Fig. 5.5), it is rational to believe that reductions in degree of saturation during wetting compared to that during drying at the same matric suction level enhanced the combined contribution of the van der Waals attraction and electric double layer repulsion to G_{max} .

The above-mentioned factors including the residual cement hydration, reduction in void ratio, and the increases in the combined contribution of the van der Waals attraction and electric double layer repulsion due to reductions in degree of saturation all contributed to the growing difference between the measured G_{max} during the drying and following wetting stages for a given matric suction. Referring to Fig. 5.6, the observed difference in measured G_{max} in the first drying-wetting cycle can confirm the possibility of formation of micro cracks induced by drying and wetting processes as also mentioned by Neramitkornburi et al. (2015) and Liu et al. (2018).

In this study and referring to Fig. 5.1, during a drying stage, the increase in matric suction by reducing pore water pressure at the bottom of the sample, while retaining the pore air pressure controlled from the sample surface, caused an outward flow of pore water towards the base pedestal. It is noted that a soil mass is intrinsically inhomogeneous (Harper et al. 1965;

Ledesma 2016; Vogel et al. 2005), thus, the drying-induced shrinkage is intrinsically uneven. In this study, the uneven sample shrinkage during a drying stage was even enhanced due to the uneven distribution of pore water across the sample height due to the transient flow prior to steady state condition. As cementing bonds restricted any differential deformation, internal tensile stresses could be developed. Micro cracks induced by tensile stresses in the transient state were very likely to be formed during and toward the end of the first drying stage, however, the resulting effect should have been rather minor since G_{max} still kept growing after the first stage of the subsequent wetting as shown in Fig. 5.6. On the contrary, an inward flow of pore water from the base pedestal during a wetting stage was observed, as a result of an increase in water pressure at the bottom of the sample induced by the reduction in matric suction. Uneven swellings of clay particles (induced by uneven increases of pore water during the wetting and the heterogeneity in the soil mass) were restricted by cementing bonds creating internal tensile stresses, possibly resulting in the formation of further cracks. The development of cracks during the drying-wetting cycle caused degradation of cementation bonds, degrading soil stiffness i.e. G_{max} and therefore compensating the growth of G_{max} as a result of the residual cement hydration and slow pozzolanic reaction, reduction in void ratio, and the increases in the combined contribution of the van der Waals attraction and electric double layer repulsion. The combination of all above-mentioned factors caused the observed variations of the G_{max} during drying and wetting cycles which were more evident in the first drying-wetting cycle as shown in Fig. 5.6.

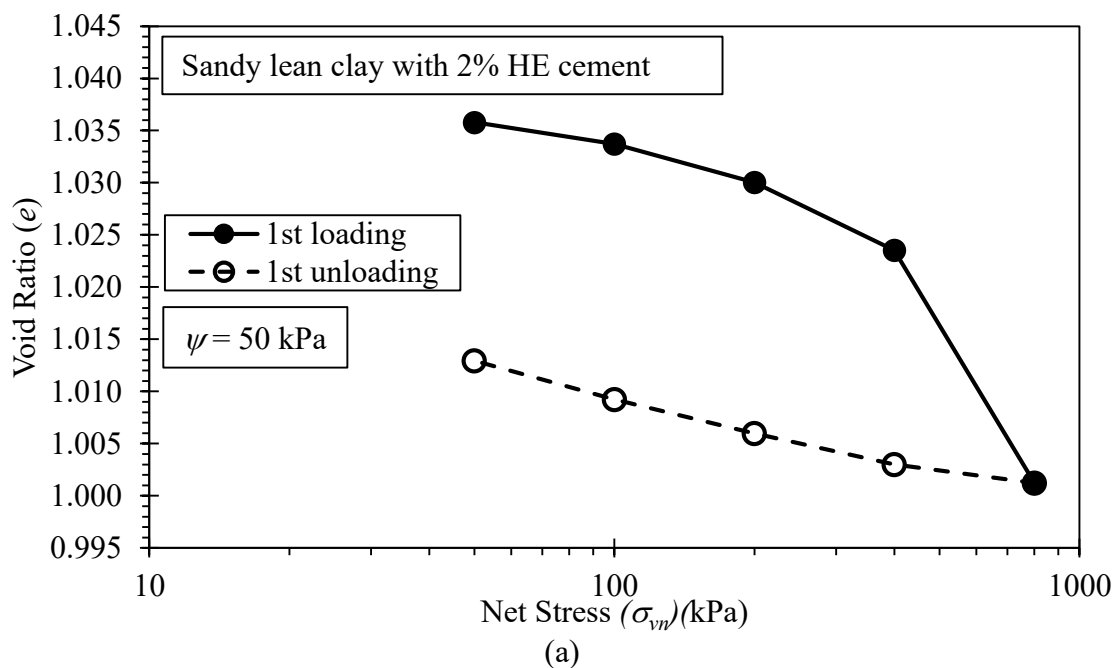
The second drying–wetting cycle commenced after the completion of three loading-unloading cycles of net stress that caused a reduction of 2.32% in void ratio, an increase of 1.42% in degree of saturation, and a reduction of 5.73% in G_{max} in comparison with the state at the end of the first drying-wetting cycle. The responses of G_{max} in the second and the third drying stages were similar to that in the first drying stage, but with higher average growth rates

under the same increments of matric suction, indicating more significant impacts of matric suction on G_{max} . Moreover, as observed in Fig. 5.6, the measurements of G_{max} in the wetting curves were always higher than the corresponding values in the drying curves for a given matric suction level; however, the differences were less significant compared to those in the first drying-wetting cycle. Considering the insignificant variations of void ratio and degree of saturation during the last two drying-wetting cycles (see Figs. 5.4 and 5.5), it is reasonable to believe that the pore size distribution and developed soil crack network were in rather stable states during the last two drying-wetting cycles and that the higher magnitudes of G_{max} in the wetting curves compared to that in the previous drying curve were induced mainly by the cementation effect. This indicates the occurrence of possible residual cement hydration and the secondary pozzolanic reactions in long term even for soils lightly treated with HE cement.

The increases and decreases of G_{max} with alterations of matric suction, observed during the three drying-wetting cycles as reported in Fig. 5.6 revealed that behaviour of G_{max} of lightly cemented soils, subjected to drying-wetting cycles, was controlled by not only cementation but also the stress state (i.e. net stresses and matric suctions). This was different to the observations in a number of previous studies (Baig et al. 1997; Lovelady and Picornell 1990; Yang 2008; Yang and Woods 2014) that the stress level had a negligible effect on G_{max} . Indeed, the degradation of cementation reduced the effect of cementation while enhancing the effect of stress state. As discussed earlier, drying and wetting processes not only caused changes of the combined contribution of the van der Waals attraction and electric double layer repulsion but also resulted in degradation of cementation due to formation of micro cracks.

5.3.4 Variation of void ratio and degree of saturation during loading-unloading cycles of net stress

After the completion of the first drying-wetting cycle, the soil sample was subjected to three loading-unloading cycles of net stress under constant matric suction of 50 kPa as shown in Table 5.3. Loading and unloading stages were applied by increasing and decreasing the upper chamber pressure (i.e. the vertical stress on the top of the sample), correspondingly, while retaining the magnitude of the back pressure (i.e. the pore water pressure at the bottom of the sample) and pore air pressure at the top of the sample. The observations of void ratio variations presented in Fig. 5.7, reveal the loading-induced contraction and unloading-induced swelling. In the first cycle, the loading-induced contraction far more surpassed the following unloading-induced swelling, presenting remarkable plastic volume change.



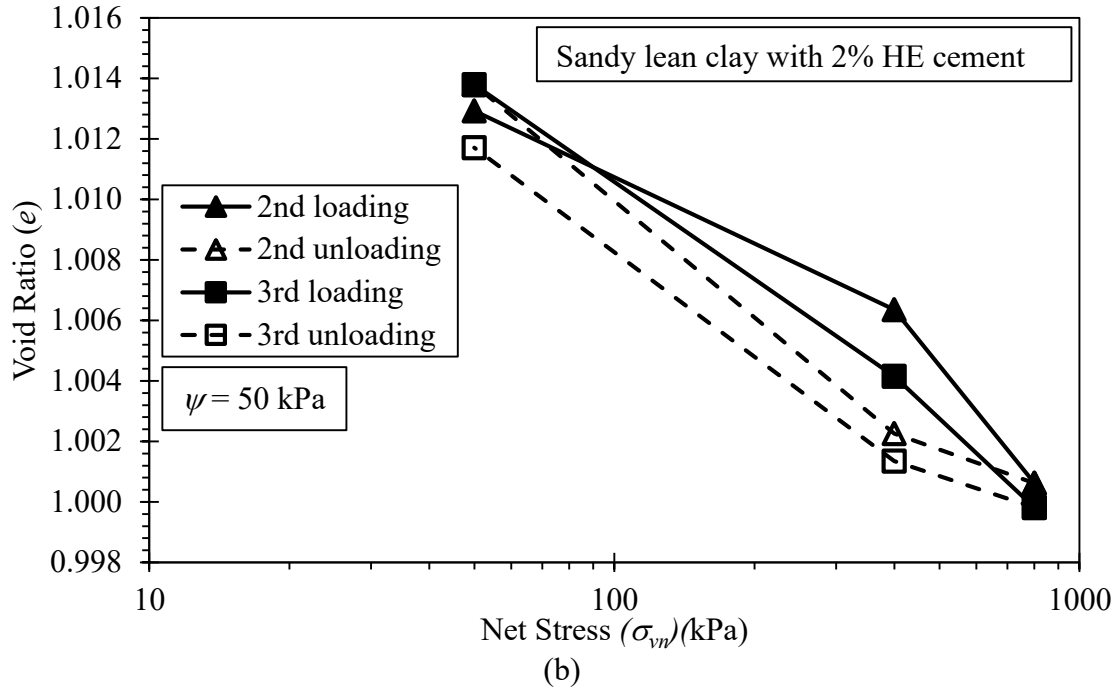


Fig. 5.7 σ_{vn} - e relationship during (a) first and (b) second and third loading-unloading cycles of net stress

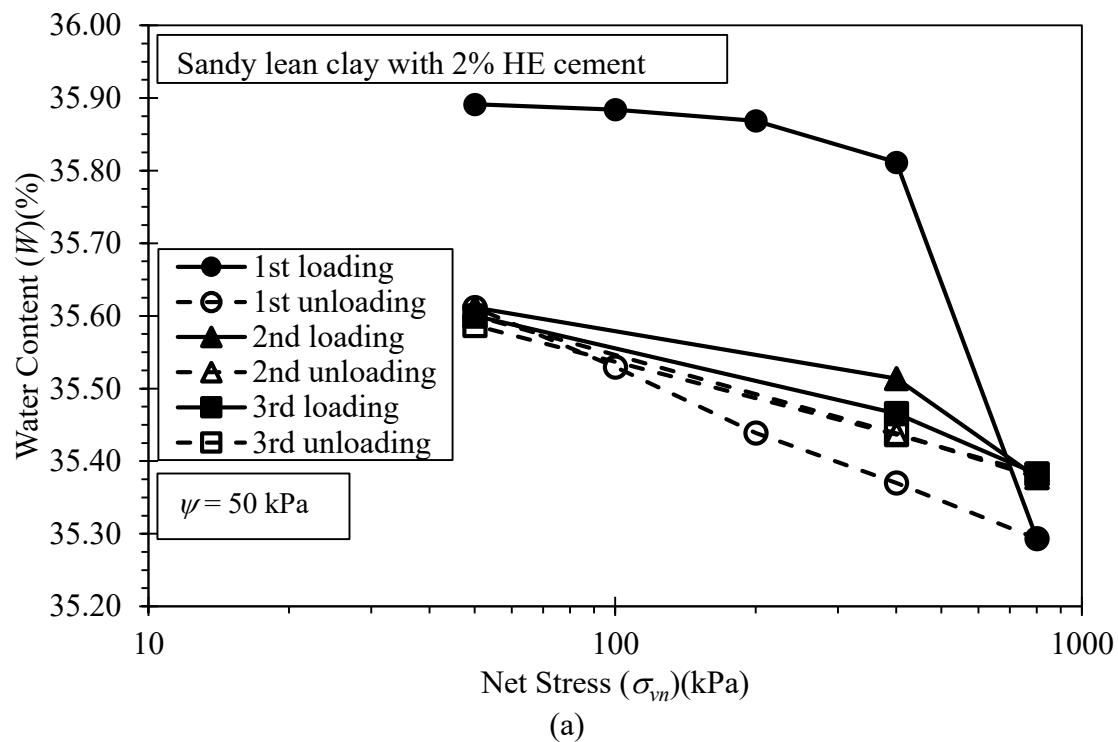
Indeed, lower void ratios were observed in the unloading curve compared to that in the loading curve for a given level of net stress. It is noted that a major portion of the void ratio reduction in the first loading stage occurred when net stress increased from 400 kPa to 800 kPa. This observed volume change indicates a significant plastic volumetric strain increment corresponding to the yield point of the soil (i.e. equivalent pre-consolidation pressure) (Liu and Carter 2002; Nguyen et al. 2014; Trhlíková et al. 2012) of cemented soil, beyond which a significant cementation breakage occurred when net stress exceeded 400 kPa,. Referring to Fig. 5.8, the wetting condition during unloading stages (i.e. net stress reduction) where sample absorbed water via HAED at the base, could be explained by the fact that during the unloading, the sample swelled resulting in reduction in degree of saturation and increase in the soils suction, so an inward flow of water from the base to the sample was observed, to maintain the constant suction condition. With the increase in the degree of cement degradation as a result of uneven swellings, the effect of cementation on restricting the swelling of clay matrix during

the wetting process (moisture absorption from the base) would be curtailed, presenting the domination of the unloading-induced swelling over the loading-induced contraction in the second loading-unloading cycle. In the third cycle, the effect of unloading-induced swelling was surpassed by the effect of loading-induced contraction. Therefore, the difference between void ratios in loading and unloading curves became minor as demonstrated in Fig. 5.7, indicating stable conditions of the volumetric contraction and swelling induced by the loading-unloading cycles.

Fig. 5.8 shows variations of water content and degree of saturation during the three loading-unloading cycles of net stress. In general, the responses of water content and degree of saturation to a variation of net stress had opposite trends. An increase of net stress in a loading stage resulted in a decrease of water content and an increase of degree of saturation, while a decrease of net stress in an unloading stage led to an increase of water content and a decrease of degree of saturation. Referring to Figs. 5.6 and 5.7, it is evident that the impact of water content variations on the observed variations of degree of saturation was veiled by the variations of void ratio in most stages, except for the first stage of the unloading in which minor variations of void ratio were observed. Indeed, a considerable reduction of water content was observed in the first loading stage when net stress increased from 400 kPa to 800 kPa (refer to Fig. 5.8a), while the corresponding impacts on the degree of saturation were minor (see Fig. 5.8b).

The observed sharp reduction in water content in Fig. 5.8a could be attributed to the corresponding sharp reduction in void ratio as shown in Fig. 5.7 inducing outward flow of pore water to the base pedestal in an attempt to maintain the matric suction of 50 kPa. Interestingly, Fig. 5.8a shows that the water contents at the end of the second and the third drying stages were even higher than that at the end of the first drying stage. This might be the result of partial

healing of drying induced micro cracks during the following wetting stages as also observed by (Liu et al. 2018), which could enhance the capability of these micro cracks in holding capillary water under the range of applied matric suction. It was also observed that the impact of loading and unloading cycles on the soil water content was significantly diminished as the number of cycles increased (see Fig. 5.8a). Fig. 5.8b shows that a similar response was observed for the variation of the degree of saturation during all loading-unloading cycles, with the most notable changes occurring in the first cycle. As observed in Fig. 5.8b, degree of saturation persistently increased during loading stages, and then showed a slight increase in the first unloading stage and persistently reducing with net stress reduction.



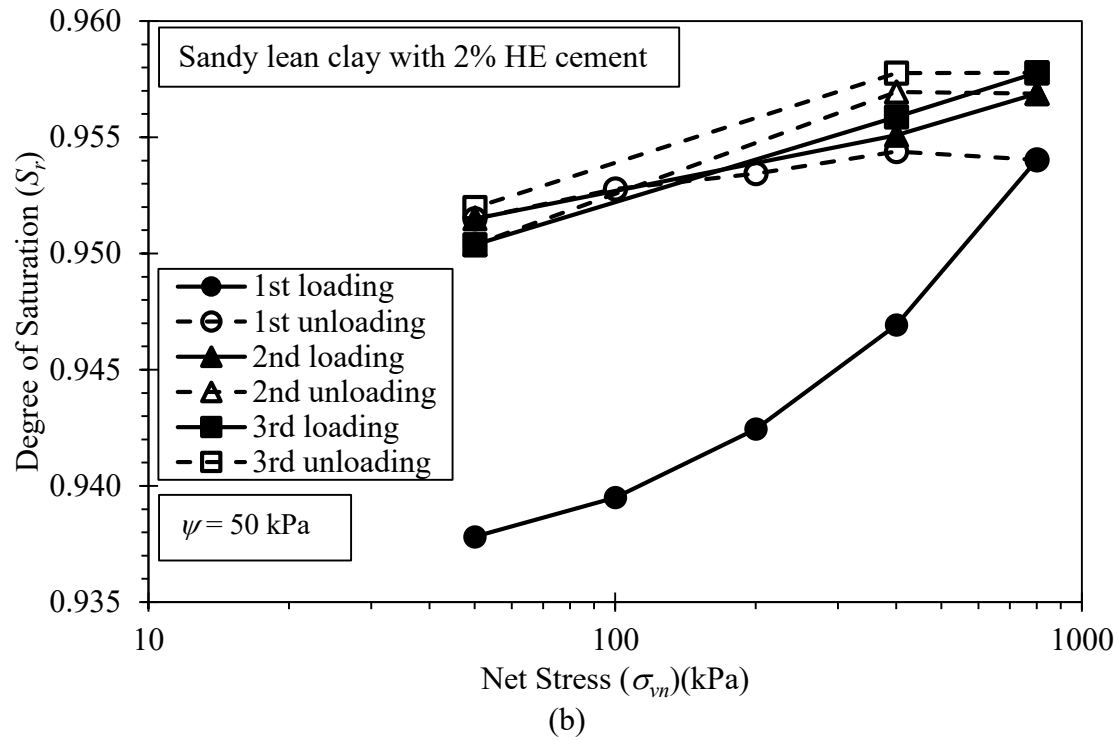


Fig. 5. 8 Relationships between (a) σ_{vn} and W_r , and (b) σ_{vn} and S_r during three loading-unloading cycles

5.3.5 Variation of G_{max} during loading-unloading cycles of net stress

As loading caused volume contraction and unloading caused swelling of the cement treated soil sample (see Fig. 5.7), pore water pressure experienced an increase and subsequent decrease during loading stage and unloading stages, respectively. Consequently, drying occurred during loading stages whereas wetting occurred during unloading stages (see Fig. 5.8) to maintain the matric suction of 50 kPa during the testing across all three cycles. Hence, during the three loading-unloading cycles of net stress, G_{max} of the treated soil sample was influenced by not only the variation of net stress, but also the presence of wetting and drying processes (i.e. water content variations). Variations of G_{max} during the three loading-unloading cycles are depicted in Fig. 5.9.

In the first loading stage, after obtaining growth of up to 5% corresponding to increases of net stress from 50 kPa to 200 kPa, G_{max} nearly remained unchanged when net stress increased from 200 kPa to 400 kPa, before slightly reducing when net stress increased to 800 kPa. This reduction of G_{max} , along with the sharp reductions of void ratio and water content shown in Figs. 5.7 and 5.8, confirmed significant degradation of cementation bonds and development of micro-crack network within the treated soil sample in this loading stage. As a result, as illustrated in Fig. 5.9, magnitudes of G_{max} at the same net stresses in the following unloading stages were consistently less than that in the first loading stage, confirming the formation of permanent cementation destruction in the soil.

In the second loading stage reported in Fig. 5.9, G_{max} obtained a small increase compared to the corresponding value in the first loading stage at a given net stress of 400 kPa. Indeed, G_{max} still followed a growing trend when net stress increased from 400 kPa to 800 kPa, instead of reducing as in the first loading stage. A similar trend with higher growth rates was observed in the third loading stage (Fig. 5.9) in which the magnitude of G_{max} almost recovered its value in the second loading stage and achieved the highest value at net stress of 800 kPa observed among all three loading-unloading cycles. Referring to Fig. 5.9, it can be observed that the magnitudes of G_{max} in the second unloading stage were consistently lower than the corresponding values in the previous loading stage, whereas, magnitudes of G_{max} in the third unloading curve were always higher than that in the third loading curve at the same net stress.

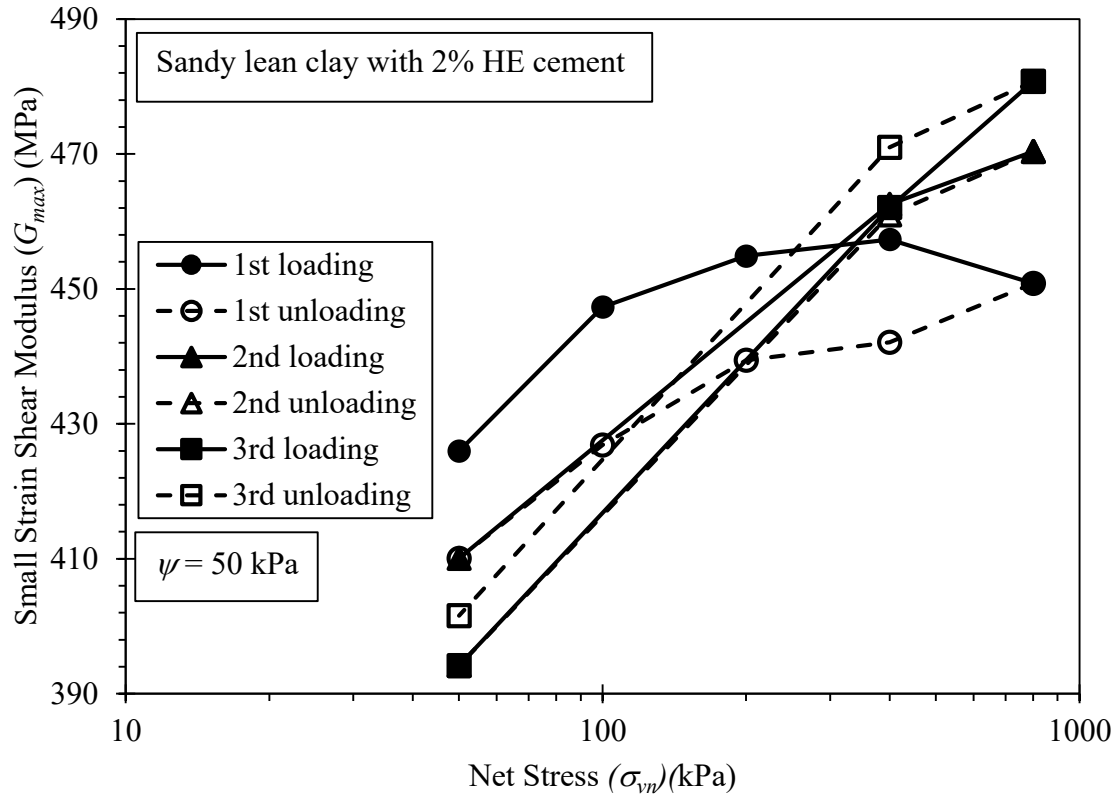


Fig. 5. 9 Variation of G_{max} during the three loading-unloading cycles of net stress

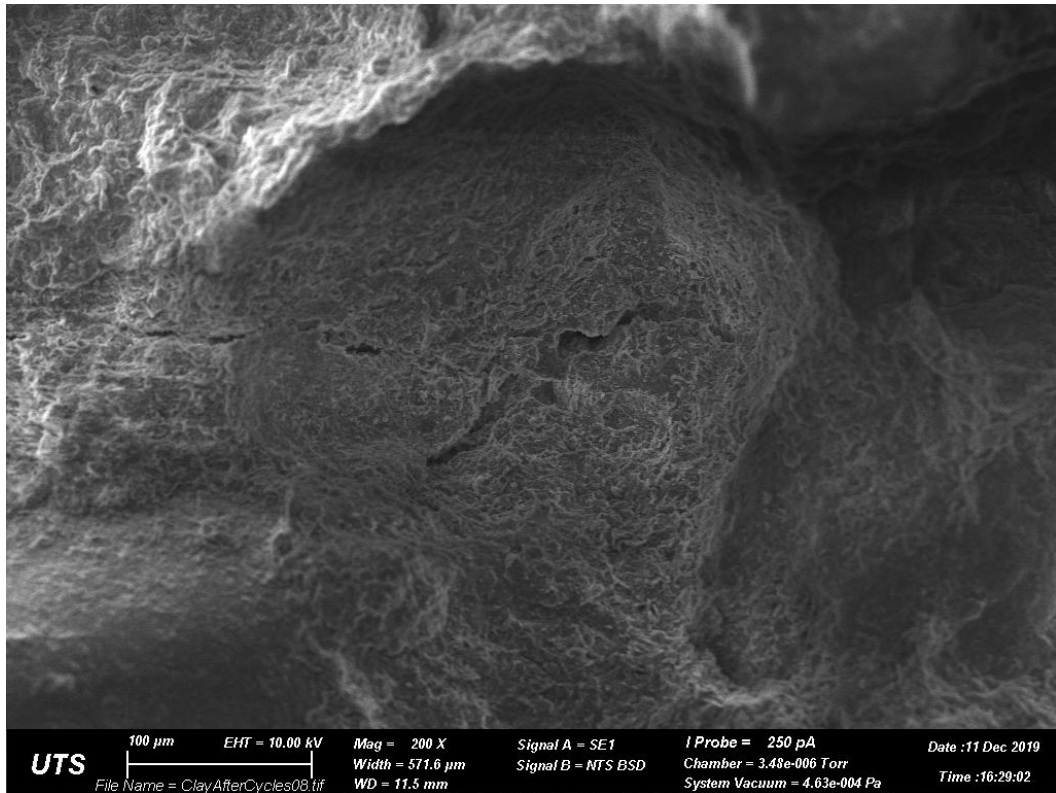
The rather complex responses of G_{max} in the second loading-unloading cycle in which G_{max} gained an increase at net stress of 800 kPa, while experiencing a decrease at net stress of 50 kPa in comparison with corresponding values in the first cycle, could be due to the reduction in the contribution of cementation and the growth in the contribution of inter-particle stresses to G_{max} . Specifically, the degree of cementation degradation kept increasing in the first unloading stage and the second loading-unloading cycle due to transient state before establishing constant matric suction, which induced uneven wetting-induced swelling during unloading and uneven drying-induced contraction during loading. The progressive breakage of cementation bonds reduced the contribution of cementation to G_{max} , while increasing the number of contacts whose relative movement was influenced by the stress level, thus, led to enhancements of the contribution of the stress level. Increases of G_{max} at net stress of 800 kPa with increasing number of loading-unloading cycles observed in Fig. 5.9 indicated the

domination of stress contribution over cementation effect at the high range of applied net stresses. On the contrary, the cementation contribution dominated G_{max} response at the low range of applied net stresses presenting in the observed reduction in G_{max} when the number of cycles increased. The growth of G_{max} at the end of the third unloading stage compared to that in the second unloading stage could be due to the compound effects of the reduction in the void ratio (see Fig. 5.7), healing of the micro cracks due to wetting, possible residual hydration, and the long-term pozzolanic reactions.

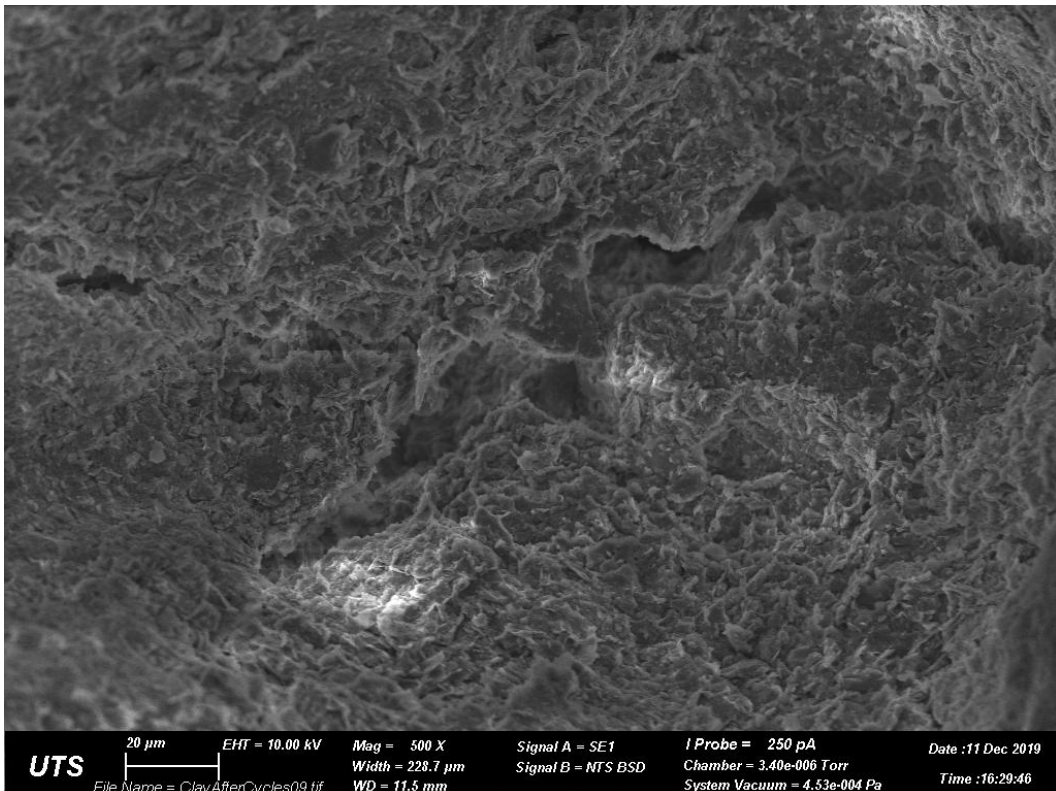
5.3.6 Scanning Electron Microscopy (SEM)

Fig. 5. 10 confirms the presence of micro cracks induced by cycles of drying-wetting and loading-unloading of net stress during the unsaturated Rowe cell experiment. The development of micro cracks caused degradation of cementation, resulting in reductions of the overall stiffness of the soil sample presenting in the sharp reductions of void ratio (see Figs. 5. 4 and 5. 7) and the enhancement in the effect of stress state on G_{max} (see Figs. 5. 6 and 5. 9).

The fact that only locally distributed cracks were observed on the SEM sample indicates that the local cracks formed during the three drying-wetting cycles and three loading-unloading cycles of net stress had not been merged into a connected network developing over the thickness of the Rowe cell sample. Thus, the desaturation of the HAEPD induced by direct application of air pressure on its surface as observed in the trial tests was avoided in the Rowe cell test. The good working condition of the HAEPD was revealed in the small changes in the water content during drying-wetting cycles and loading-unloading of net stress as shown in Figs. 5. 5 and 5. 8, respectively.



(a)



(b)

Fig. 5. 10 SEM images of the cemented soil at (a) 100 μm with the magnification of 200 and
(b) 20 μm with the magnification of 500

5.4 Summary

Small strain shear modulus of a sandy clay treated with 2% of high early strength cement was investigated during cycles of drying-wetting and loading-unloading of net stress using a modified unsaturated Rowe cell apparatus. The measurement of shear wave velocity was taken using two built-in bender elements at the top and bottom of the sample.

The results confirmed the cementation bond breakage of lightly cemented soil subjected to drying-wetting cycles. The cementation degradation reduced the contribution of cementation while enhancing the contribution of stress level to G_{max} , thus, resulting in the stress-dependent responses of G_{max} even at low stress levels during loading-unloading cycles as observed in this study. This observation is contrary to the cementation-dependant responses of G_{max} of saturated soil sample subjected to loading stages at low stress levels, reported in a number of previous studies.

It was also observed that under constant matric suction, loading-induced contraction caused drying with flows of water toward the high air entry value porous disk (HAEPD), while unloading-induced swelling caused wetting with flows of water from the HAEPD. Since drying during loading stage and wetting during unloading stage also caused cement degradation, the reduction in the contribution of cementation and enhancement in the contribution of inter-particle stresses to G_{max} was observed with increasing number of loading-unloading cycles. Hence, when the number of loading-unloading cycles increased, G_{max} experienced growths at the high range of net stress, the region at which the contribution of stress surpassed the contribution of cementation; whereas, at the low range of net stress, the cementation contribution dominated the G_{max} response.

In general, small strain shear modulus of lightly cemented soil was influenced by void ratio, cementation, degree of cementation degradation, and stress level. The effects of these influencing factors varied during drying-wetting cycles as well as loading-unloading cycles of net stress, thus, stress-strain history plays an important role in predicting the G_{max} of lightly cemented soils on site.

Chapter 6

Conclusions and Recommendations

6.1 Summary

The main objective of this study was to conduct experimental studies on the small strain shear modulus, G_{max} , of unsaturated soils subjected to various loading conditions. A modified Rowe cell, adopting the axis-translation technique, was adopted for the measurement of shear wave velocity and the corresponding G_{max} of reconstituted and lightly cemented soil samples subjected to cycles of drying-wetting and loading-unloading. A weight-controlled bender element setup was also developed. This setup could control the exchange of water vapour between the sample and surrounding environment, thus, enable the investigation of the effect of matric suction equalisation on the measurement of G_{max} of soil sample during an air-drying process. The main contributions of this study are as follows:

- To propose a method to determine the effective dynamic mass density of unsaturated soils (three-phase media) in evaluating G_{max} from shear wave velocity
- To confirm the importance of the contributions of van der Waals attractions and electric double layer repulsions to G_{max} of unsaturated soils subjected to cycles of drying-wetting and loading-unloading when hydraulic hysteresis is present
- To propose predictive models incorporating the combined contribution of the van der Waals attractions and electric double layer repulsions to G_{max} of unsaturated soils

- To prove that measuring G_{max} when matric suction equalisation would have not been reached would cause underestimations, especially at the high range of matric suction
- To provide explanations for different behaviours of G_{max} at low and high ranges of matric suction during an air-drying process by considering the change in the effect of degree of saturation on the inter-particle stress induced by matric suction before and after shrinkage limit
- To provide explanations for the change in the time required for matric suction equalisation, t_{se} , during an air-drying process and to propose an empirical equation to estimate t_{se}
- To confirm that drying-wetting cycles significantly affect G_{max} of cement treated soils subjected to different loading conditions
- To experimentally show that degradation of cementation induced by non-distribution contraction and swelling during drying and wetting could cause reductions in the contribution of cementation while enabling and increasing the contribution of stress state to G_{max} , and thus, affecting the behaviour of G_{max} . It was specifically found that by increasing number of drying-wetting cycle, the contribution of stress stage would dominate the behaviour of G_{max} at the high range of stresses, while the contribution of cementation would still dominate at the low range of stresses.

6.2 Conclusions

6.2.1 The impacts of drying-wetting and loading-unloading cycles on G_{max}

Based on the results of the unsaturated Rowe cell experiments on a reconstituted clayey sand, presented in Chapter 3, the following conclusions can be drawn:

- To avoid overestimation of G_{max} determination from shear wave velocity, the effective dynamic mass density (ρ_{eff}) should be used instead of the total mass density. By assuming that during drying processes the thin viscous layers of pore water moving together with particle surfaces during shear wave propagation reduces only when all the external water has been removed, while the reverse procedure occurs during wetting processes, the effective dynamic mass density was determined as the minimum of the total mass density and the maximum effective dynamic mass density, which corresponds to the full thickness of the viscous boundary layer.
- Investigation of the relationship between $\rho_{eff}(1+e)$ and degree of saturation during the three drying-wetting cycles shows a threshold of degree of saturation that separates the low range corresponding to partial mass coupling and the high range corresponding to full mass coupling. At a given void ratio, ρ_{eff} is proportional to the degree of saturation only at the low range while at the high range degree of saturation has no or minor effect on ρ_{eff} .
- Hydraulic hysteresis was evident in all the stress loops investigated in this study including cycles of drying-wetting and loading-unloading. It was found that hydraulic hysteresis had a significant effect on the measurements of G_{max} .
- The contributions of van der Waals attractions and electric double layer repulsions to G_{max} of unsaturated soils were evident as a result of a decrease of degree of saturation at a given stress state, during cycles of drying-wetting and loading-unloading of net stress, that caused a reduction in the contribution of the current matric suction to G_{max} , and a growth of $G_{max}/f(e)$ with degree of saturation was observed.
- When hydraulic hysteresis was present, a decrease of degree of saturation caused a reduction in the contribution of matric suction and an increase in the combined

contribution of van der Waals attractions and electric double layer repulsions to G_{max} .

- Since the contribution of matric suction and the combined contribution of van der Waals attractions and electric double layer repulsions followed different patterns with variations of degree of saturation, they need to be evaluated separately to capture effect of hydraulic hysteresis on G_{max} .
- An equation has been proposed for predicting G_{max} of unsaturated soils incorporating the effects of the void ratio, net stress, matric suction and degree of saturation. The proposed equation provided good predictions proving its ability to capture the effect of hydraulic hysteresis on G_{max} of unsaturated soils. For practical issues, this equation allows the determination of G_{max} of unsaturated soils based on the stress state, void ratio, and degree of saturation regardless of the stress and drying-wetting history, thus improving the accuracy of capturing response of G_{max} in complex loading-unloading and drying-wetting cycles.

6.2.2 The impacts of matric suction equalisation on the measurement of G_{max}

Based on the results of the weight-controlled bender element, shrinkage, filter paper, and permeability experiments on a statically compacted clayey sand, presented in Chapter 4, the following conclusions can be drawn:

- Measuring G_{max} of unsaturated soils when matric suction equalisation has not been reached resulted in underestimations. This underestimation could be due to the non-uniform distribution of the water content and the corresponding matric suction across the cross section of the soil sample (i.e. higher water content and lower matric suction at the centre of the sample compared to the rest).
- The impact of matric suction equalisation on the measurement of G_{max} was rather small in the early stages of the air-drying process but accelerated when degree of saturation

approached the threshold corresponding to the shrinkage limit. It was believed that water discontinuity, developed at water content smaller than the shrinkage limit, prevented the hydraulic flow from diminishing the non-uniform distribution of the water content, and thus, caused the underestimation of G_{max} .

- The plunge in the evolution rate of G_{max} , at the onset of the zero shrinkage zone, could be attributed to the reduction in the growth rate of the contribution of matric suction to G_{max} once the drying-induced reduction in the water–soil particle contact area accelerated.
- Matric suction equalisation was driven by not only the hydraulic flow but also the water vapour flow due to the differences in the partial water vapour pressure across the sample area. The hydraulic flow governed the time required for matric suction equalisation at structural and normal shrinkage stages, whereas effect of the water vapour flow dominated as soil becomes drier (i.e. residual and zero shrinkage stages).
- The effects of both hydraulic and vapour flows on t_{se} were found to be significantly affected by degree of saturation, but with opposite trends. A decrease of saturation led to shorter matric suction equalisation time when the water vapour flow dominated the response, while a reduction in degree of saturation caused an increase in t_{se} when the hydraulic flow dominated the response (due to the reduction in the hydraulic conductivity).
- An empirical equation was proposed for the estimation of t_{se} considering the effects of the degree of saturation, the flow path and the corresponding hydraulic conductivity. In addition, another empirical equation was established in an attempt to capture variations of G_{max} during air drying process as a function of matric suction and degree of saturation. The two proposed equations proved to be capable of providing reasonable

predictions of the time required for matric suction equalisation and the magnitude G_{max} for the investigated soil during an air-drying process. In practice, equations proposed in this study can be utilized to determine the time required for matric suction equalisation in experiments studying behaviours of unsaturated soil after air drying and to predict G_{max} of compacted soil layers near the ground surface which can experience significant evaporation when exposed to the open environment.

6.2.3 G_{max} of unsaturated lightly cemented soil subjected to drying-wetting and loading-unloading cycles

Based on the results of the unsaturated Rowe cell experiment on a lightly cemented sandy clay, presented in Chapter 5, the following conclusions can be drawn:

- Drying and wetting caused degradation of cementation (i.e. cementation bond breakage) of lightly cemented soil. The cementation degradation resulted in reductions in the contribution of cementation and increases in the contribution of the stress state to G_{max} . The contribution of stress state to G_{max} could not be observed in previous studies which were conducted for samples after the curing stage.
- It was observed that, under constant matric suction, drying and wetting also occurred during the loading and unloading stages, respectively, due to the changes of the pore water pressure with loading-induced contraction and unloading-induced swelling. Consequently, degradation of cementation increased with increasing number of drying-wetting cycles as well as loading-unloading cycles.
- With the development of degradation of cementation, the magnitude of G_{max} would be dominated by the stress state at the high range of stresses, while it would be still dominated by the cementation effects at the low range of stresses.
- With an increase in the number of drying-wetting and loading-unloading cycles, G_{max}

at the high stresses would intensify due to an increase in the contribution of the stress state, while G_{max} at the low stresses would decrease due to the reduction in the contribution of the cementation.

- In general, small strain shear modulus of lightly cemented soil was influenced by void ratio, cementation, degree of cementation degradation, and stress level. The effects of these influencing factors varied during drying-wetting cycles as well as loading-unloading cycles of net stress, thus, stress-strain history plays an important role in predicting the G_{max} of lightly cemented soils on site.

6.3 Recommendations for Future Studies

The research study on small strain shear modulus of unsaturated soils can be further expanded as follows:

- This study investigated the effect of matric suction equalisation on the measurement of G_{max} during the air-drying only. The study should continue with the subsequent wetting, for example, by placing the samples in a humidity chamber. As proposed in this study, matric suction equalisation at a given humidity can be determined by continuously monitoring the variation of G_{max} until it becomes stable. It should be noted that the key challenge would be that the experiment will be very time consuming.
- More experiments on the behaviour of lightly cemented soil subjected to cycles of drying-wetting and loading-unloading are required to evaluate the effects of uneven drying-induced contraction and wetting-induced swelling on G_{max} . There might be a relationship between the change of the water content and the resulting change of cementation degradation, depending on the current degree of cementation degradation.
- Further study should be conducted by comparing the variations of G_{max} obtained from isotropic loading and 1D settlement to assess the contribution of mean and shear

stresses, particularly when assessing the response of cemented soils.

- Expanding this research for different soils treated with different dosage of cement and different chemical agents such as lime and fly ash commonly used for soil stabilisation particularly for subbase and formation stabilisation.
- Investigating effects of cement content, moulding water content, initial density on the soil water characteristic, and small strain shear modulus of cemented soils.

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