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Effect of suction history on the small strain response of a dynamically compacted soil

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Abstract

The small strain behaviour is a key indicator for assessing the performance of compacted fills. Compaction conditions i.e. initial moisture content and applied energy, govern compaction effectiveness and, thus, the structure and matric suction of compacted soil. During their service life, most earth structures experience changes in hydraulic behaviour owing to climatic changes. While the results of previous research studies indicate that the effect of changes in suction on the dynamic response is significant, only limited research has been engaged in the assessment of the effect of post-compacted changes in suction induced by periods of intensive precipitation (i.e. wetting) and drought (i.e. drying). The seasonal fluctuations of moisture reflected in the soil's suction history have an important impact on the geomechanical performance of compacted soil. In this paper, the aspects related to the effect of suction history of a compacted silty sand soil subjected to cycles of wetting and drying are described. The results not only confirm the importance of the recent suction ratio (or CSR) in governing the mechanical response at small strain but also suggest that subsequent wetting-drying cycles further induce hysteretic changes, particularly when following the wetting paths.

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Effect of suction history on the small strain response of a dynamically compacted soil

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ABSTRACT

The small strain behaviour is a key indicator for assessing the performance of compacted fills. Compaction conditions i.e. initial moisture content and applied energy, govern compaction effectiveness and, thus, the structure and matric suction of compacted soil. During their service life, most earth structures experience changes in hydraulic behaviour owing to climatic changes. While the results of previous research studies indicate that the effect of changes in suction on the dynamic response is significant, only limited research has been engaged in the assessment of the effect of post-compacted changes in suction induced by periods of intensive precipitation (i.e. wetting) and drought (i.e. drying). The seasonal fluctuations of moisture reflected in the soil's suction history have an important impact on the geomechanical performance of compacted soil.
In this paper, the aspects related to the effect of suction history of a compacted silty sand soil subjected to cycles of wetting and drying are described. The results not only confirm the importance of the recent suction ratio (or CSR) in governing the mechanical response at small strain but also suggest that subsequent wetting-drying cycles further induce hysteretic changes, particularly when following the wetting paths.

Keywords: small strain stiffness, suction history, compacted soil

1 INTRODUCTION

The dynamic properties of the soil are usually evaluated to characterize the engineering behavior of earth structures subjected to repeated loading (i.e. vibrations caused by traffic of heavy and fast moving vehicles, heavy earthwork machinery, and earthquakes). Previous research studies report that the small strain shear modulus (G_0) is governed by the initial compaction state, the level of stress and post-compaction suction variation (Claria and Rinaldi, 2004; Sawangsuriya et al., 2008, Heitor et al., 2012). For instance, while the small strain shear modulus increases with the increase of suction there is a noted inflexion at the air entry value (AEV) and two distinct ranges can be distinguished, a bulk water regulated zone and a menisci water regulated zone (e.g. Mancuso et al., 2002). Before AEV the shear modulus increases linearly with suction, thereafter its increase is predominantly non-linear. Similar observations were also reported for a range of different soils by Marinho et al. (1996); Vinale et al. (2001), Inci et al. (2003), and Sawangsuriya et al. (2008). Mancuso et al. (2002) and more recently Heitor et al. (2013) also revealed that the small strain shear modulus is affected by the soil fabric derived from the compaction process (i.e. double porosity structure). Although, the soil behaviour at small strain is relatively well understood for different levels of suction, limited studies have evaluated the impact of cyclic wetting and drying on the small strain shear modulus. This evaluation is important as during their service life most earth structures experience the cyclic changes in hydraulic behaviour owing to the climatic changes (i.e. rainfall or extended periods of drought). These seasonal hydraulic fluctuations have in turn substantial effects on the soil geomechanical performance, particularly in relation to its dynamic response.
Ng et al. (2009) and Ng and Xu (2012) investigated the effect of a drying-wetting cycle on the small strain stiffness on compacted decomposed tuff. The most striking aspect was that alike the soil water retention curve (SWRC), the G_0 also showed hysteresis between the drying and wetting paths. Furthermore, for any given suction level, the shear modulus of the wetting path was higher than the

corresponding on the drying path. Similar observations were also reported for sand mixes (George, 2009), silt (Khosravi, 2012) and silty sand (Heitor et al. 2014a). In addition, Heitor et al. (2014b) studied the impact of the initial compaction state (i.e. energy level) in the drying-wetting hysteresis loops and showed that the extent of the variation of G_0 observed were associated with the initial soil structure derived from the compaction process. While these studies focussed on the behaviour of G_0 when subjected to wetting and drying cycles, the effect of suction history on the modulus response was not investigated.
The effect of suction history on G_0 (Ng et al., 2012 and Heitor et al., 2014a) can be quantified considering:

(a) hydraulic cycles,
(b) the current suction ratio or CSR and
(c) recent suction history.

The CSR (Eq.1) is defined as the maximum historical suction of a soil experienced divided by the current suction. The recent suction history refers to the influence of the penultimate suction path on soil behaviour along the current stress path. The magnitude of the recent suction path is quantified by the amount of suction change of the penultimate suction path, denoted by *l*. The hydraulic cycles refers to the number of times the soil has achieved a certain suction level upon drying and wetting.

$$CSR = \frac{s_{\max}}{s_{current}} \qquad (1)$$

where s= $(u_a - u_w)$, u_a is the pore air pressure and u_w is the pore water pressure. This paper aims to offer further evidence on the dynamic response in terms of small strain shear modulus (G_0) of a compacted soil subjected to wetting-drying and offers novel insights into effect of suction history on the small strain behaviour in cycles of wetting and drying, particularly in terms of CSR and hydraulic cycles.

2 EXPERIMENTAL WORK

2.1 Soil type and compaction characteristics

The soil used in this study was a silty sand classified as SP-SC (Unified Soil Classification System, USCS). The soil is a by-product of cobble quarrying activities that has been widely used to fill low-lying areas at the Penrith Lakes (NSW, Australia). While the soils are quite variable, for this study only a single grading was used. The particle size distribution was composed of 89% sand and 11% fines, of which 7% is silt and the remaining 4% is clay size particles. It has a liquid limit of 25.5%, a plasticity index of 10 and specific gravity of 2.7.
The compacted specimens used in the wetting and drying tests were obtained by using a ∅50×100mm mould. The compaction energy was adjusted so that the dry unit weight would correspond to the Proctor compaction (AS1289.5.1.1-2003). For illustration of the compaction behaviour of the material, the results obtained for three additional energy levels are plotted together with equivalent standard compaction effort corresponding to E_3=529.5 kJ/m^3 in Fig. 1.

2.2 Wetting and drying

For the wetting and drying tests specimens prepared at water content of 12% and energy level corresponding to 529.5 kJ/m^3 were selected (Fig. 1). The soil water retention curve is shown in Fig. 2. The specimens were tested using bender elements under isotropic confined conditions for different levels of suction. An isotropic confining pressure of 50kPa (equivalent to approximately 2.5m depth) was adopted because it is considered to be a conservative lower bound of the depth where soil is likely to be subjected to wetting and drying cycles (H_s) from climatic changes in Penrith. The adoption of this value was largely based on the Thornthwaite moisture index (TMI) distribution in Australian territories (Austroads, 2004; Fityus and Buzzi, 2008).
Suction was imposed to the specimens by applying axis translation technique to attain the desired pressure differential or suction. The air and water pressures (u_a and u_w respectively), applied to the specimen in a load frame triaxial cell, were controlled with pressure controllers designed by GDS Instruments (accuracy of 1mm^3) and the high air entry value (AEV) ceramic disk embedded on the bottom pedestal had an AEV of 15 bar. The water pressure controller was able to measure the volume

of water flowing in or out of the specimens when the suction was changed. The criterion for equilibrium was based on the change in the volume of water. In these tests, the increments in each stage were 50kPa and the water pressure was changed at a rate of 0.16kPa/min and kept constant until the end of the equilibration period. Typically, periods of 48h were sufficient for the specimens to reach equilibrium. The axial displacement was also monitored at every stage using an LVDT (Linear Variable Differential Transducer) with an accuracy of 0.001mm. Any changes in the axial strain associated with drying and wetting of the specimens were very small, typically less than 0.01%.

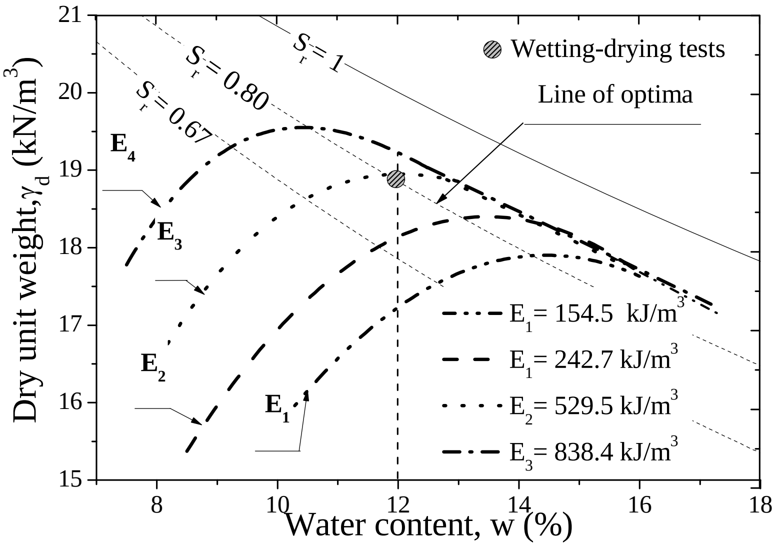

Figure 1. Compaction data for the silty sand soil (a) compaction curves (modified after Heitor et al. 2013).

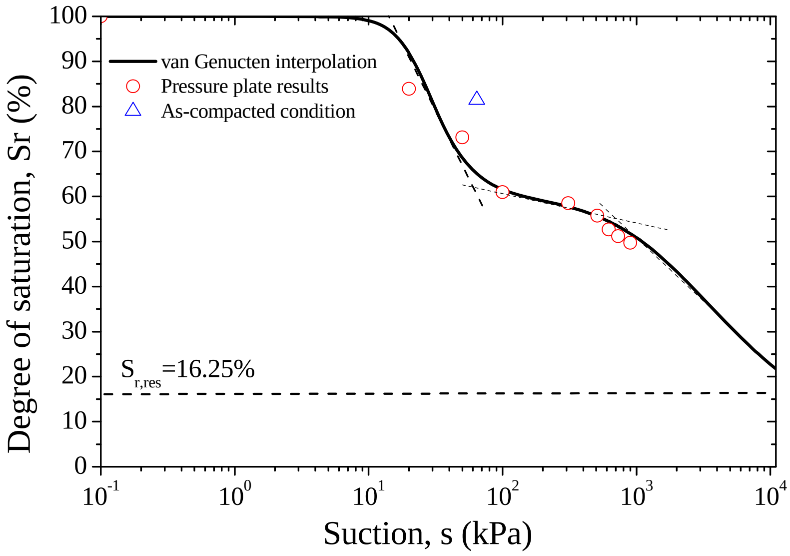

Figure 2. Soil water retention curve (Heitor, 2013).

2.3 Small-strain shear modulus

A pair of bender elements assembled in a bottom pedestal and top cap was used to monitor the shear waves transmitted through the specimens (Fig. 3). The bender elements signal generation was controlled by GDSBES v2.0 software (GDS Instruments) while the data acquisition system had two input channels with 16-bit resolution each.

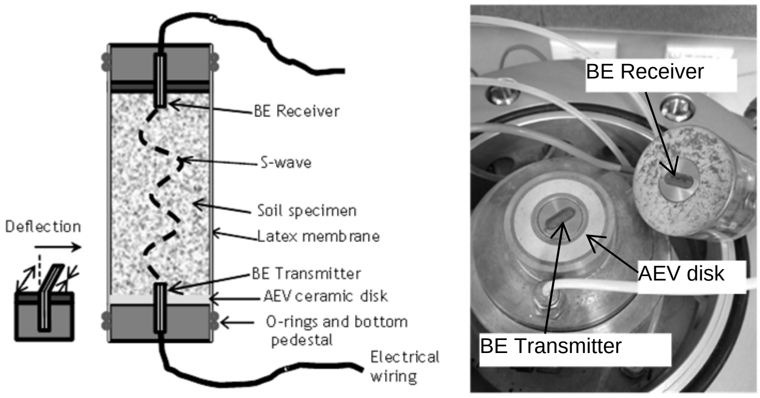

Figure 3. Illustration of a pair of BE (left) and detail of the bender elements cantilevered in the AEV ceramic bottom pedestal and top cap (right) modified after Heitor et al. (2014).

A sampling rate of 300 kHz was used to ensure an adequate resolution of the time and voltage of input and output signals (Clayton, 2011). In order to minimize background noise and improve the signal to noise ratio (SNR), a series of twenty sampled signals were stacked. In this study, it was found that testing frequencies (varying from 1.4 to 50kHz) having a ratio between wave path length (L_{tt}) and wavelength (λ) exceeding 2 (e.g. Leong et al., 2005) were adequate to minimize the effect of the near-field component effect and warrant the strength of the received signal (Fig. 4). The shear wave velocity (V_s) and small strain shear modulus (G_0) were computed based on the wave path length (L_{tt}), the travel time (Δt) and bulk unit weight (γ), as follows:

$$V_s = \frac{L_{tt}}{\Delta t} \tag{2}$$

$$G_0 = \frac{\gamma}{g} V_s^2 \tag{3}$$

where g = gravity constant.

The travel time (Δt) was taken as the time interval to the first bump maximum, as described by Lee and Santamarina (2005) or to the first deflection if the first bump was not visible.

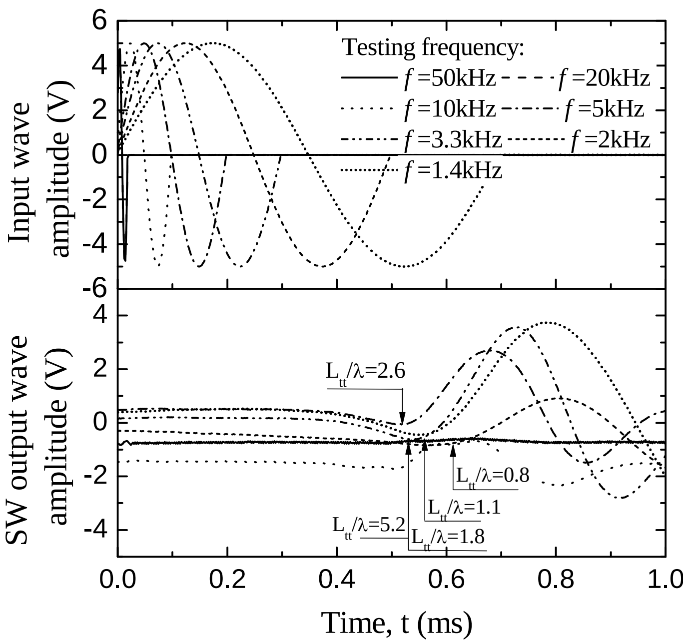

Figure 4. Typical shear wave velocity traces for different testing frequencies varying from 1.4 to 50kHz (Heitor et al, 2014b).

3 RESULTS AND DISCUSSION

3.1 Small strain shear modulus

The variation of G_0 with increasing (drying) and decreasing (wetting) suction is depicted in Fig. 5. The most striking aspect is that G_0 exhibits higher values when following the wetting paths. This might not correspond to the expected intuitive behaviour at first glance, but it can be associated with the soil-water exchange in soil pores. The amount of water in the soil, as reflected by the degree of saturation (S_r), represents the cumulative number of air-water menisci affecting inter-particle connections for a given suction level. Thus, despite having the same suction, upon drying and wetting, the different amounts of water in the soil lead to different mechanical behaviour. In addition, this behaviour can also be linked to the hysteretic response observed in the SWRC (i.e. the ink-bottle effect) and in turn with the fabric (i.e. macroporosity and microporosity range) during drying and wetting processes (e.g. Cuisinier and Laloui, 2004, Monroy et al., 2010). Fig. 5 also shows that hysteretic response in drying and wetting processes is different for values of s_{max} (i.e. the largest suction the specimen have been exposed to) and also differs for subsequent drying-wetting cycles. For instance, the hysteresis amplitude for s_{max} of 150kPa is 28MPa whereas for s_{max} of 300kPa is 56 MPa. This difference is likely associated with the amount of water in the soil, as reflected by the degree of saturation (S_r) and fabric changes that the specimens undergo during drying and wetting (e.g. Monroy et al., 2010). To illustrate the influence of degree of saturation on the G_0 response, the data is replotted in Fig. 6 with degree of saturation and water content. While the hysteretic response is still evident the small strain shear modulus seems to decrease nearly linearly with the increase of the degree of saturation.

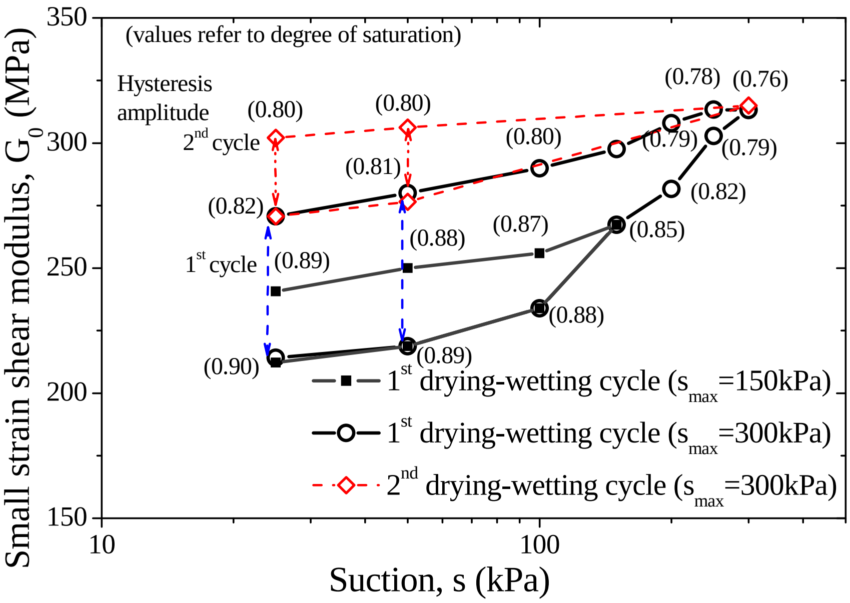

Figure 5. G_0 variation with suction during wetting and drying for specimens compacted at energy level of 529.5kJ/m^3 and different s_{max} values.

3.2 Hydraulic cycles

The hydraulic cycles refers to the number of times the soil has achieved a certain suction level upon drying and wetting. One of the tested specimens was subjected to two drying and wetting cycles for the same s_{max} of 300kPa. Fig. 5 shows that for the same suction, the G_0 response is influenced by the number of cycles of wetting-drying. For instance, at a suction 25kPa, the G_0 differed by 25.4 MPa, between the first and second cycle. Furthermore, the results in Fig. 5 seems to indicate that when compacted specimens experience multiple cycles of drying and wetting to the same suction level the soil skeleton is strengthened which may be attributed to some extent to hydraulic ageing albeit more testing with a large number of hydraulic cycles would be recommended to verify whether this is the case.

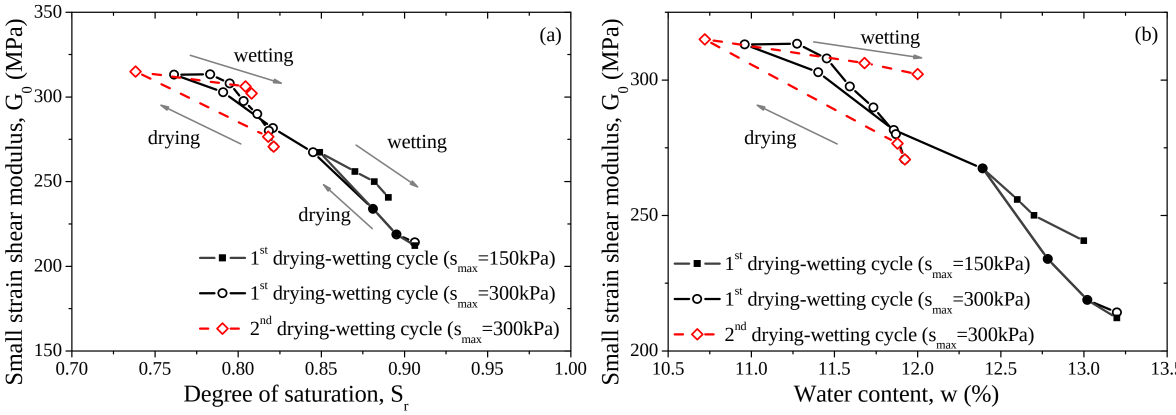

Figure 6. G_0 variation with (a) degree of saturation and (b) water content during wetting and drying for specimens compacted at energy level of 529.5kJ/m^3 and different s_{max} values.

3.3 Current suction ratio (CSR)

In Fig. 7a the G_0 values are plotted against the CSR values computed for the wetting paths. Only the the CSR values for the wetting paths are represented because in the first drying the highest suction the specimens experienced corresponded to the testing suction and thus CSR was 1 along the drying paths. The specimen subjected to a larger variation of suction (s_{max}=300kPa) and multiple drying-wetting cycles is also included. As expected for a given CSR, the G_0 for the specimen subjected to a larger interval of suction (s_{max} =300kPa) is higher than those obtained from that subjected to a suction of 150kPa. This is because the current suction was higher (i.e. for CSR=3, the current suction was 150kPa and 50kPa for the specimens subjected to a maximum suction of 300 and 150kPa, respectively). Nonetheless, even at the same current suction (i.e. 25kPa) the specimens' modulus increased significantly for a higher CSR. To better illustrate the influence of the suction stress history at different current suction ratios on G_0, the data normalised by the current stress state (p') is replotted in Fig. 6b. The current stress state can be represented by a function of the isotropic net confining pressure $(p-u_a)$, suction (u_a-u_w) and degree of saturation (S_r), as follows:

$$p' = \left[(p-u_a)+(u_a-u_w)S_r\right] \quad (4)$$

The above relationship allows for the current suction and degree of saturation and the current net confining stress to be incorporated in the moduli response. Fig 7b shows that the normalised G_0 increased with the CSR and the modulus response is strongly dependent on the current stress state (*p'*), as the normalised modulus values are smaller for larger s_{max}.

4 CONCLUSION

From a number of Bender element tests conducted in specimens compacted at an energy level equivalent to standard Proctor and then subjected to a post-compaction cycle of wetting and drying, it was observed that the effect of suction variation on small strain stiffness is significant. Larger values of G_0 were observed on the wetting paths and this difference was associated with the water retention properties and fabric. The maximum value of suction (s_{max}) attained during and drying-wetting cycle has a strong influence on the amplitude of the hysteretic response observed in a cycle of wetting and drying. Larger hysteresis amplitudes were observed for specimens subjected to larger s_{max} (i.e. 300kPa). This indicates that severe wetting and drying conditions (i.e. extreme climatic episodes) may result in relatively large changes in the post-compacted mechanical response of the compacted materials. The results also show that the suction history as reflected by the CSR and current stress state appear to control the response of G_0 during drying and wetting paths. However, subsequent drying and wetting cycles induce further changes in the G_0, which clearly shows that not only CSR is important but so too are the number of hydraulic cycles, albeit more testing would be beneficial to determine the extent of those changes for more than two hydraulic cycles. Finally, this study shows that the geomechanical behaviour of earth structures exposed to changes in hydraulic regimes (i.e. periods of precipitation and drought) is dynamic and should be considered when evaluating long term

performance particularly for locations where the depth of influence is large and where the fills are likely be exposed to larger in site moisture variations.

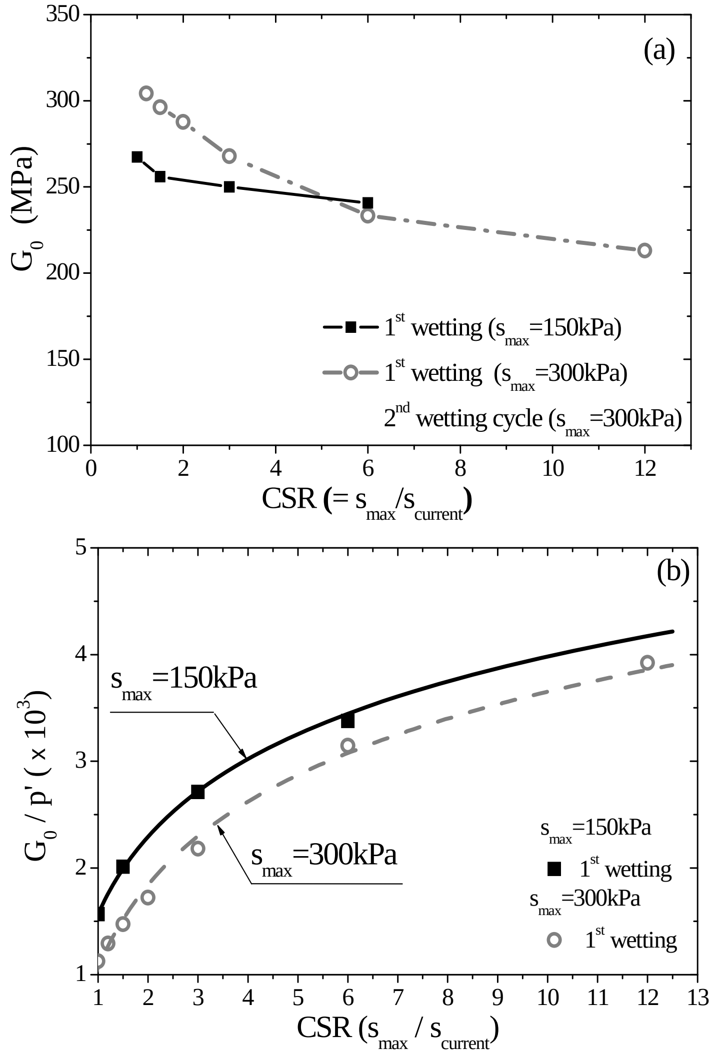

Figure 7. Variation of (a) G_0 and (b) normalised G_0 with current suction ratio (CSR) for the wetting paths of specimens with s_{max} of 150kPa and 300kPa.

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