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TECHNICAL NOTE

Small strain shear moduli of unsaturated natural and compacted loess

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Suction and microstructure play critical roles in the mechanical behaviour of loess, yet their effects on small strain (from 0·001 to 1%) shear moduli are not fully understood. In this study, shear moduli of loess with different microstructures and at different suctions are investigated and reported. Suction-controlled triaxial tests were carried out on two compacted and two intact loess specimens. Testing procedures include isotropic compression, wetting and shearing at constant mean net stress and constant suction. In addition, the soil microstructure was studied through scanning electron microscope images. At a given suction, the intact specimens have larger shear moduli than the compacted specimens at deviatoric strain below 0·025%, mainly because more clay aggregates accumulate at grain contacts in the intact loess. As suction decreases (i.e. wetting), contrary to the typical behaviour of compacted soils, the small strain shear moduli increase in the compacted loess. The increase is most probably because of significant wetting-induced contraction during the wetting process. In contrast, the shear moduli of the intact specimens remain unchanged, owing to slight swelling observed during wetting. The behaviour of the intact loess is likely to be dominated by the soil microstructure, and suction effects are relatively minor. With continued shearing, the differences resulting from the specific microstructures and wetting-induced volume changes (i.e. suction) diminished rapidly.

KEYWORDS: fabric/structure of soils; laboratory tests; stiffness; suction

INTRODUCTION

In arid and semi-arid regions (e.g. the Loess Plateau in China), the unsaturated loess layer can be up to 25 m thick. The behaviour of unsaturated soil is fundamentally associated with the soil microstructure (e.g. Gens & Alonso, 1992; Alonso *et al.*, 2013). Likewise, intact loess and compacted loess exhibit unique hydro-mechanical behaviour because of their different microstructures (Ng *et al.*, 2016b). The effects of soil structure on the shear behaviour of unsaturated loess at large strain are often reported (Wen & Yan, 2014; Haeri *et al.*, 2016). The highly non-linear behaviour (Atkinson & Sallfors, 1991) of intact and compacted loess at small strains (from 0·001 to 1%), however, has not yet been fully understood.

Many studies have shown that the small strain shear moduli increase with increasing suction (e.g. Vassallo *et al.*, 2007; Ng & Xu, 2012) and decrease with decreasing suction when wetting-induced swelling takes place (Ng *et al.*, 2009; Khosravi & McCartney, 2011). If volumetric contraction is observed during wetting, the initial shear modulus may remain unchanged (Biglari *et al.*, 2012), owing to the competing effects of hardening due to wetting-induced contraction and softening due to suction reduction. These studies were conducted in compacted soils and often reported only the initial shear modulus. Although wetting-induced collapse has often been reported in loess (Li, 1995; Muñoz-Castelblanco *et al.*, 2011; Ng *et al.*, 2016b), the effects of suction during wetting on the small strain shear moduli of intact and compacted loess are unclear.

The aim of the present study is to investigate the small strain shear moduli of unsaturated compacted and intact loess. To this end, variation in shear moduli with strain was deduced from a series of suction-controlled triaxial tests. The shear moduli of intact and compacted loess, which have different structures, were compared at a given suction and the effects of suction were determined. Additionally, the soil microstructure was investigated through scanning electron microscope (SEM) images.

TESTING PROGRAMME, APPARATUS AND PROCEDURES

To investigate the effects of structure and suction on variation in shear moduli in the small strain range, four suction-controlled triaxial tests were conducted. Two compacted and two intact loess specimens were sheared at constant mean net stress of 50 kPa and constant suction of 1 or 50 kPa. Table 1 contains details of the test programme.

A suction-controlled triaxial system (Ng & Yung, 2008) was utilised in the current study and its schematic diagram is shown in Fig. 1. The matric suction $u_a - u_w$ of the specimen was controlled through the axis translation technique (Hilf, 1956), by controlling pore air pressure u_a and pore water pressure u_w independently. Bender elements were fixed at both end platens of the cell to measure the initial shear modulus of a soil specimen. Hall-effect sensors were set up as local axial and radial displacement transducers for small strain measurement.

Figure 2 shows the stress paths employed in this study. Each test involved three stages. In the first stage, after a specimen was set up and instrumented in the triaxial system,

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Table 1. Testing programme and soil states

Specimen identity	Specimen type	Suction: kPa	Before suction equalisation		After suction equalisation	
			Void ratio, *e*	Degree of saturation, S_r: %	Void ratio, *e*	Degree of saturation, S_r: %
CS1	Compacted	1	1·142	13·85	0·973	71·50
CS50	Compacted	50	1·131	13·98	1·036	37·45
IS1	Intact	1	0·986	14·47	0·992	82·99
IS50	Intact	50	1·042	15·98	1·047	32·37

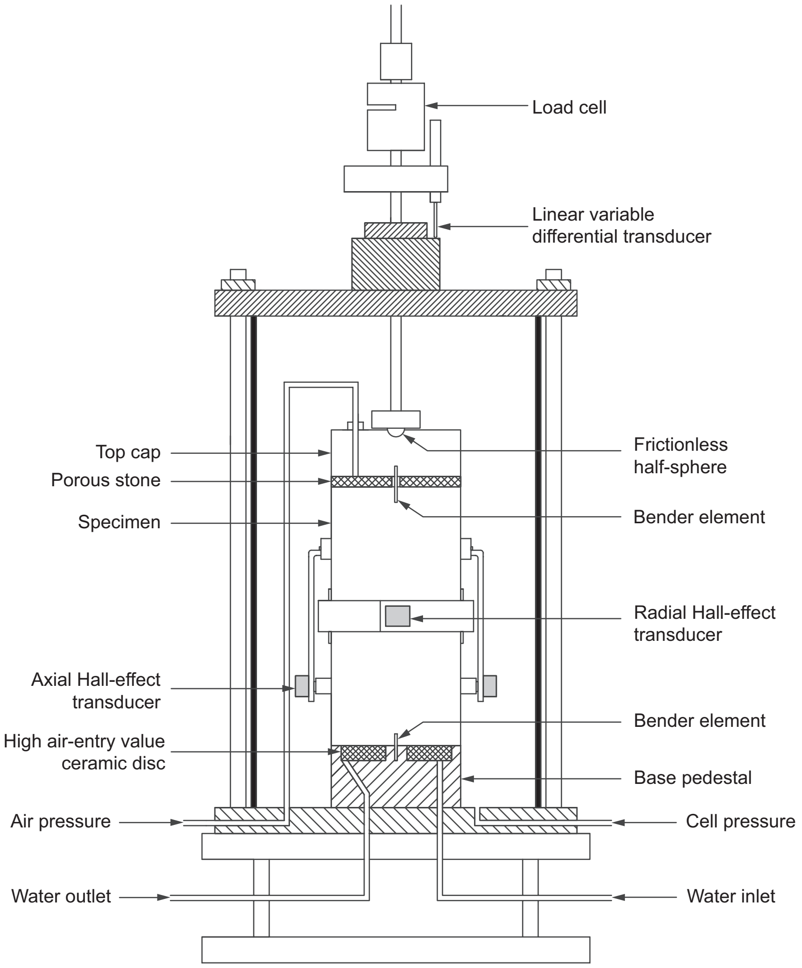

Fig. 1. Schematic diagram of the suction-controlled triaxial apparatus (modified from Ng & Yung, 2008)

mean net stress $p - u_a$, where p is the mean total stress, was increased to 50 kPa while the gravimetric water content was kept constant. In the second stage, suction of either 1 or 50 kPa was applied to the specimen and subsequently maintained for equalisation. The process generally took between 10 and 15 days to reach suction equilibrium, which was reflected by a daily water content change of less than 0·04% (Sivakumar, 1993). In the last stage, the specimen was sheared at the given mean net stress and suction.

TESTING MATERIAL AND SPECIMEN PREPARATION

Blocks of loess were sampled from a site at the Loess Plateau in Shaanxi, China. The sampling depth was 5·5 m below ground. The physical properties of Shaanxi loess are given in Table 2. The material is classified as clay of low plasticity (CL) according to the Unified Soil Classification System (ASTM, 2006).

Intact specimens for triaxial testing were prepared by hand trimming with a lathe to a cylinder 76 mm in diameter and 152 mm high. The intact specimens had an average water content of 5·88 ± 0·58% and an average dry unit weight of 12·56 ± 0·49 kN/m^3. Compacted specimens were prepared from oven-dried loess powder which was moistened with de-aired water so that the gravimetric water content was equal to that of the intact specimens. The mixed soil was then passed through a no. 16 (1·18 mm) sieve and kept in a sealed plastic bag inside a humidity- and temperature-controlled container for moisture equalisation. The soil was then statically compacted in eight layers into a split mould, targeting the average dry density of the intact specimens. In addition, it should be noted that the average unit weight of the intact specimens was determined from four intact specimens

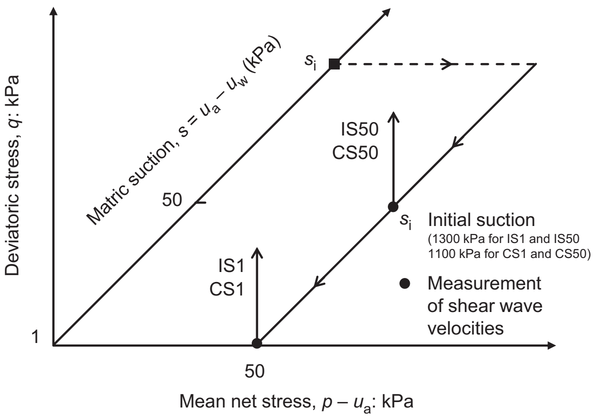

Fig. 2. Stress path of suction-controlled triaxial tests

Table 2. Index properties of Shaanxi loess

Description	Value
Soil type (ASTM, 2006)	Lean clay (CL)
Specific gravity, G_s	2·69
Particle size distribution: %	
Clay fraction	28·0
Silt fraction	71·9
Sand fraction	0·1
Atterberg limits: %	
Liquid limit	36
Plasticity index	17
Maximum dry unit weight: kN/m^3	16·8
Optimum water content: %	18·1

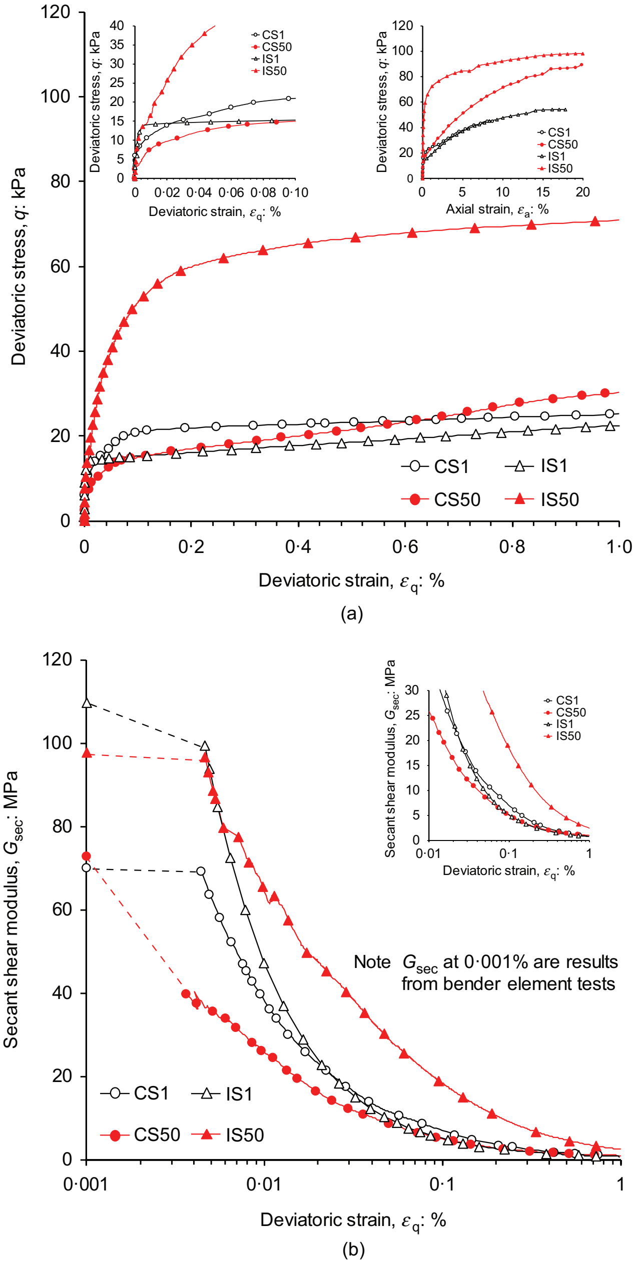

Fig. 3. (a) Stress–strain relations and (b) variations of secant shear moduli during shearing of intact and compacted loess

from the same block sample, even though only two intact specimens were tested in the current study. The dry unit weight of all the intact specimens ranged from 12·07 to 13·05 kN/m^3, which is equivalent to the initial void ratio ranging between 1·023 and 1·184. The compacted specimens were prepared targeting to the average dry unit weight of all the intact specimens. The compacted specimens had the initial dry unit weight of 12·12 and 12·17 kN/m^3, equivalent to the void ratio of 1·168 and 1·178. The tested intact specimens were slightly denser than the compacted specimens at as-compacted state. Based on the void ratio function proposed by Hardin & Black (1968), the estimated differences in initial shear modulus of the intact and compacted specimens before suction equalisation are likely to be around 20 and 13% at suction of 1 and 50 kPa, respectively. As will be shown later, the shear modulus difference induced by effects of structure was significantly larger than these. It is therefore clear that the difference in initial unit weight did not affect the key conclusions of the current study.

Based on soil water retention curves of intact and compacted loess in Ng *et al.* (2016b), the intact and compacted specimens were estimated to have initial suctions of 1300 and 1100 kPa, respectively. Therefore, all specimens were subjected to wetting during the suction application and equalisation stage. Soil states at each stage are summarised in Table 1.

EXPERIMENTAL RESULTS

Influences of structure on small strain stiffness at various suctions

Figure 3(a) shows the stress–strain relations of intact and compacted specimens at suctions of 1 and 50 kPa. At small deviatoric strain (less than 0·025%), the intact specimens (IS1 and IS50) have larger deviatoric stress and shear moduli than the compacted specimens (CS1 and CS50). As shearing continues, the compacted specimen exhibits slightly higher deviatoric stress than the intact specimen at deviatoric strain between 0·025 and 5% when suction is equal to 1 kPa. At strain larger than 5%, the deviatoric stress of the intact specimen IS1 and compacted specimen CS1 almost overlaps (with a difference less than 2%). At suction of 50 kPa, the stress–strain curves of the intact and compacted specimens tend to gradually converge with increasing strain. However, slight difference in shearing responses remains until the end of shearing.

Figure 3(b) shows the shear modulus degradation of intact and compacted specimens at suctions of 1 and 50 kPa. Regardless of suction level, the intact specimens (IS1 and IS50) have larger shear moduli than the compacted specimens (CS1 and CS50) at small deviatoric strain (less than 0·025%). Consistent with the measurements of the Hall-effect transducers, the initial shear moduli at deviatoric strain

Table 3. Ratios of secant shear moduli of intact specimen to those of compacted specimen and volumetric strain at different deviatoric strains

Suction: kPa	Specimen identity	Deviatoric strain, ε_q, at 0·001%		Deviatoric strain, ε_q, at 0·01%		Deviatoric strain, ε_q, at 0·1%	
		Volumetric strain, ε_v: %	$\frac{G_{s,int}}{G_{s,com}}$	Volumetric strain, ε_v: %	$\frac{G_{s,int}}{G_{s,com}}$	Volumetric strain, ε_v: %	$\frac{G_{s,int}}{G_{s,com}}$
1	CS1	0	1·57	0·002	1·24	−0·010	0·72
	IS1			0·007		0·135	
50	CS50	0	1·34	0·001	2·16	0·095	3·44
	IS50			0·002		0·023	

of 0·001% of the intact specimens deduced from bender elements are approximately 57 and 34% higher than those of the compacted specimens at suctions of 1 and 50 kPa, respectively. As shearing continues, the shear moduli of the intact specimen at suction of 1 kPa approach those of the compacted specimen at the same suction. The measured moduli are nearly the same at deviatoric strain exceeding 0·025%. The converging shear responses of the intact and compacted specimens suggest progressive destruction of the initial structure with plastic straining, as illustrated by Leroueil & Vaughan (1990) for saturated soils. At suction of 50 kPa, the difference between the intact and compacted specimens in terms of the shear modulus degradation gradually decreases with increasing strain, confirming that the effects of structure diminished with increasing deviatoric strain. At the lower suction of 1 kPa, the shear response curves of the intact and compacted specimens converge within the small strain range. However, at the higher suction of 50 kPa, the responses continue to differ until the end of shearing, as shown in the insert in Fig. 3(a). In other words, differences between the responses of the intact and compacted specimens vanish at smaller deviatoric strain as suction decreases, implying that the presence of suction helps maintain the effects of structure.

The ratio of secant shear moduli of the intact specimen to that of the compacted specimen $G_{s,int}/G_{s,com}$ at a given deviatoric strain is summarised in Table 3. At very small strain of 0·001%, the shear moduli of the intact specimen are consistently larger than those of compacted specimens at both suctions of 0 and 50 kPa. This is because the shear modulus of unsaturated soil is a function of net stress, matric suction, void ratio and inherent soil structure (Ng & Yung, 2008). In the current study, intact and compacted specimens are sheared at the same net stress and suction as well as similar void ratios (with a difference of less than 2%), but the intact specimen is expected to have a stiffer inherent soil structure. When soil specimens are subjected to continuous shearing, at suction of 1 kPa, the ratio $G_{s,int}/G_{s,com}$ decreases from 1·57 at a deviatoric strain of 0·001% to 0·72 at a deviatoric strain of 0·1%. On the contrary, at a suction of 50 kPa, the ratio $G_{s,int}/G_{s,com}$ increases from 1·34 at a deviatoric strain of 0·001% to 3·44 at a deviatoric strain of 0·1%. The different stiffness degradation patterns of intact and compacted specimens may be explained by the volume change behaviour observed during shearing. As shown in Table 3, at a given deviatoric strain, the specimens IS1 and CS50 contract more than the specimens CS1 and IS50, respectively. A larger volumetric contraction would induce more significant degradation of the inherent soil structure (Rouainia & Wood, 2000; Baudet & Stallebrass, 2004). Thus, the shear moduli of the specimens IS1 and CS50 degrade faster than those of the specimens CS1 and IS50, respectively.

The different behaviours of intact and compacted loess are attributed to their structural differences. Fig. 4 shows the result of SEM analysis of the intact and compacted loess conducted by Ng *et al.* (2016a). Both the intact and compacted loess appear to be flocculated with visible inter-aggregate pores. Their structures resemble those of soils compacted dry of optimum, which are found to be dominated by silt with clay aggregates distributed around the silt grains (Delage *et al.*, 1996). In the intact specimen, the clay aggregates accumulate mostly at the inter-particle contacts. Joints between silt and clay aggregates are indistinct, implying that the clay aggregates are firmly and smoothly attached to the silt grains in the intact specimen. In contrast, grain contacts in the compacted specimen can be easily identified. Clay aggregates abound on the grain surfaces, indicating that they adhered loosely and randomly to the grain surfaces of the compacted specimen. The higher concentration of clay aggregates forming at inter-particle contacts in the intact loess enlarges the contact area, preventing slippage at silt contacts and stiffening the soil skeleton.

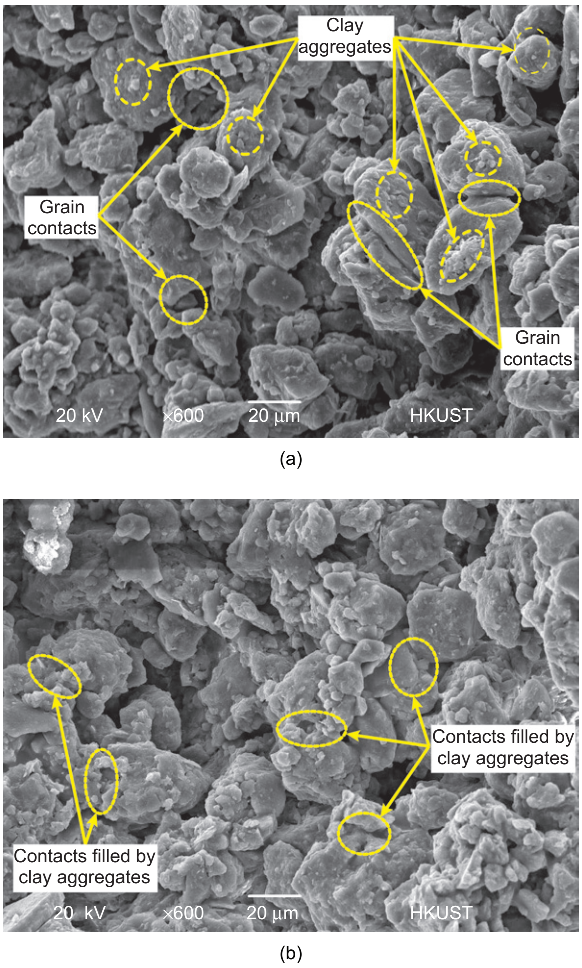

Fig. 4. SEM images of the test soil: (a) compacted loess; (b) intact loess (modified from Ng *et al.*, 2016a)

Influences of suction on small strain stiffness of soils with different structures

Results of the compacted specimens show that the initial shear moduli of the specimens CS1 and CS50 are at close range at about 71 MPa. At deviatoric strain between 0·001 and 0·6%, the compacted specimen exhibits larger deviatoric stress and shear modulus at lower suction. This observation contradicts previous studies, which have generally revealed that the shear modulus of unsaturated soils decreases or remains unchanged with decreasing suction (Ng *et al.*, 2009; Khosravi & McCartney, 2011; Biglari *et al.*, 2012). The discrepancy can be explained as follows: as suction decreases, only swelling or a slight collapse is observed in those studies, whereas the compacted loess specimens in this study exhibit large volumetric compression. As shown in Table 1, during suction equalisation the void ratios of the compacted loess at suctions of 1 and 50 kPa decrease by 14·8 and 8·4%, respectively. The above observation suggests that soil hardening owing to wetting-induced densification outweighed the effects of softening (i.e. initial shear stiffness decreases with decreasing suction) because of a reduction in suction. This substantial densification in compacted loess results from saturated loess's steeper normal compression line (i.e. 0·167) than those of other soil types (e.g. 0·073 for saturated Zenoz kaolin).

As shearing continues, the deviatoric stress of the compacted specimens at higher suction outgrows those at lower suction. The influence of suction in this strain range conforms to the well-accepted suction-hardening effect, resulting in increases in deviatoric stress and shear moduli at the same deviatoric strain as suction increases. Wetting compression affects the shear response only at small strain and disappears as shearing continues.

For the intact specimens, the initial shear moduli at suctions of 1 and 50 kPa (IS1 and IS50) were determined from bender element testing to be 110 and 98 MPa, respectively. The responses deduced from the Hall-effect sensors overlap until the deviatoric strain of 0·005% is reached, suggesting that the change in shear moduli with decreasing suction is negligible. This is likely to be because, unlike the compacted specimens which show significant wetting compression, the intact specimens exhibit slight swelling during suction equalisation (Table 1). Explained within the Barcelona basic model (BBM) proposed by Alonso *et al.* (1990), the intact loess subjected to hydro-mechanical loading–unloading initially has larger yield stress than the compacted loess. The wetting paths of the intact specimens are located well inside the loading collapse yield curve, resulting in swelling during wetting. In the absence of larger soil strain during wetting, the stable structure of the intact specimens (see Fig. 4) is preserved. Effects of soil structure dominate soil behaviour in this strain range, while effects of suction on soil stiffness are relatively less important.

From the deviatoric strain of 0·005% onwards, the deviatoric stress and shear moduli of the intact specimens at higher suction outgrow those at lower suction. This suction response at a relatively large strain is consistent with the observed behaviour of the compacted loess in this study. This indicates that the effects of structure are presumably eliminated at large strain.

CONCLUSIONS

At suctions of 1 and 50 kPa, the intact loess in this study exhibits 57 and 34% higher small strain shear moduli than compacted loess, respectively. As revealed by SEM images, this is likely to be because more clay aggregates accumulate at inter-particle contacts in intact loess, stiffening the soil skeleton.

Unlike other compacted soils such as lean kaolin and clayey silt, the compacted loess in this study is stiffer at 1 kPa than at 50 kPa when deviatoric strain is between 0·001 and 0·6%. The observed increase in shear moduli with decreasing suction can be attributed to the substantial contraction of the compacted loess during wetting, inducing significant strain hardening. On the other hand, the shear moduli of the intact loess at deviatoric strain below 0·005% remain almost unchanged, with only slight swelling observed during wetting. The effects of soil structure are likely to dominate the behaviour of the intact loess. The effects of suction, however, play a minor role in the small strain shear moduli of the intact loess. Regardless of suction and the type of specimen, the differences attributable to both soil structure and wetting-induced contraction narrow rapidly with continued shearing.

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