Shear behaviour of a desiccated loess with three different microstructures

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ABSTRACT: Shear behaviour of fine-grained soils is influenced by not only applied stress state variables but also inherent microstructure. Amongst fine-grained soils, the wind-blown origin of natural loess resulted in a special honeycomb structure being different from that of compacted or reconstituted loess. In order to investigate how the initial microstructure affects shear behaviour, loess specimens were prepared with three different microstructures, namely intact, compacted, and reconstituted. In addition, annual climatic record in semi-arid to arid regions where most of loess strata have been formed reveals the dominance of dryness. Therefore, the loess specimens were sheared at low relative humidity by utilizing a humidity controlled shear box chamber. Results clearly indicated a brittle failure mode coupled with high dilation rate for all microstructures considered. Of particular interest is the more dilation and hence peak strength of compacted loess compared with the intact one. This is likely due to more uniform pore size distribution in the former than the latter although the initial void ratio was almost the same. The highest shear strength and hence dilatancy of reconstituted loess which is beyond the stress-dilatancy relationship for course-grained soils arise from combined effects of void ratio and high suction.

1 INTRODUCTION

Shear behaviour of earthen material is one of the fundamental aspects of soil behaviour in soil mechanics discipline. Loess strata with an aeolian geological formation origin are considered as a special type of geomaterial because of its unique metastable structure in natural unsaturated states (Assallay et al., 1997). As loess is widespread in most of continents, it has been recently considered as a prospective engineered material for geotechnical constructions especially in landfill covers (Zhan et al., 2014). However, the microstructure formed in compaction process is different from that of intact loess arise from natural physicochemical processes (Ng et al., 2016). In addition, reconstituted soils are scientifically considered as a reference material for interpreting the behaviour of intact and compacted soils (Burland, 1990). Therefore, three types of microstructures including intact, compacted, and reconstituted were examined in this study, being rarely reported in the literature (Ng et al., 2017a).

Compared with saturated and nearly saturated states, research on the shear behaviour of fine-grained soils at low values of relative humidity (RH) corresponding to nearly dry state is much more limited (Merchán et al., 2011). From a practical point of view, annual record of climatic conditions in Xi′an, China, where the test material was obtained, revealed that the dominant relative humidity is far less than saturated or even nearly saturated conditions (Sadeghi, 2016). According to Fig. 1, imposing 1.5 MPa suction by the axis translation technique (ATT) corresponds to an RH value of 98.9% which is considerably higher than the *in-situ* conditions. These observations suggest the necessity of considering high suctions in studying loess behaviour (Hossen et al., 2017). Therefore, the aim of current study is to provide insight into the microstructural effects on shear behaviour of unsaturated desiccated loess.

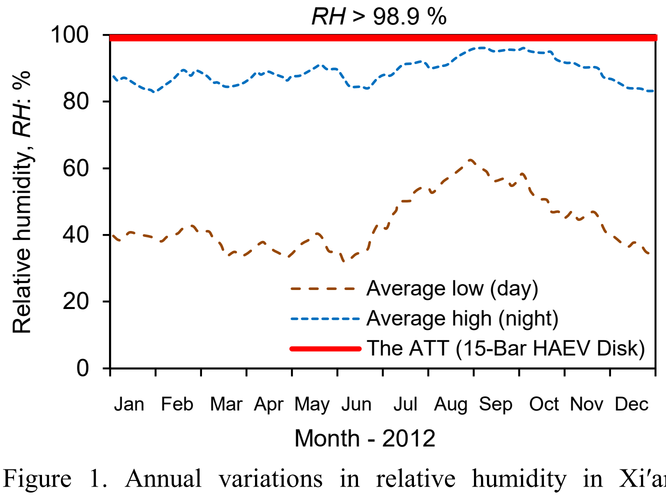

Figure 1. Annual variations in relative humidity in Xi′an, Shaanxi Province of China (https://weatherspark.com/).

2 EXPERIMENTAL PROCEDURES

2.1 *Test material and specimen preparation*

Block loess samples were retrieved from a test pit at 3.5 m in Xi′an, Shaanxi Province of China. The samples were wrapped in three successive layers of alternative cling, cloth, and Paraffin wax. They were preserved inside wooden boxes afterwards. The *in-situ* water content and dry density were determined for eight standard oedometer specimens with the average values of 12% and 12.6 kN/m^3, respectively. The relative compaction (RC) of *in-situ* soil was obtained as 76% compared to the standard Proctor curve. Other compaction characteristics of tested loess can be found in Ng et al. (2017b). According to the Unified Soil Classification System (USCS), the loess was classified as a lean clay (CL) in which silt particles comprise 72% of soil constituents. Details of other physical properties as well as the particle size distribution were reported by Ng et al. (2016).

The intact specimen was directly carved from a block sample by using a scalpel to the target dimensions of utilized shear box (5.08×5.08×2.14 cm^3). The compacted specimen was statically compressed into the shear box mold at a displacement rate of 1 mm/min and to the target dry density and water content as of the *in-situ* loess. Sadeghi et al. (2018) reported detailed preparation and processing of wet loess sample for static compaction. The third specimen type was produced by reconstituting of natural oven-dried loess through mixing it thoroughly with 1.5 times the liquid limit (Burland, 1990). The mixture was thereafter poured into a cylindrical consolidometer and consolidated to 100 kPa vertical stress. After termination of consolidation, the reconstituted specimen was cored from the cylindrical sample (7.0 in diameter) by using a cutting edge sampler specifically designed for the shear box.

All three specimens were immediately weighed after preparation and the remaining soils of each type were oven-dried for measuring the initial water content and hence mass-volume calculations. Test specimens were then put inside a desiccator containing saturated sodium chloride solution for suction equalization. The selected salt solution can impose a suction potential with the nominal value of 40 MPa. Specimens were continuously weighed until suction was equalized by recording constant weight for three consecutive readings.

2.2 *Testing device*

A modified shear box chamber for controlling suction at high ranges corresponding to low values of relative humidity beyond the practical scope of ATT was used in this study. The device controls suction based on the principle of vapour equilibrium technique (Sadeghi et al., 2017). Fig. 2 shows different components inside the chamber for controlling RH in addition to measuring environmental conditions including RH, temperature and hence suction. The chamber is specifically equipped with non-corrosive containers for saturated salt solutions, an RH/temperature probe, and a fan. Details on development and calibration of the device can be found in Sadeghi et al. (2017) and Ng et al. (2017b). In order to make the environmental conditions inside the chamber similar to those inside the desiccator, saturated sodium chloride solution was also poured into the containers. Once the RH/temperature inside the chamber reached the steady state condition, a test specimen was promptly transferred from the desiccator to the shear box and the chamber was sealed accordingly.

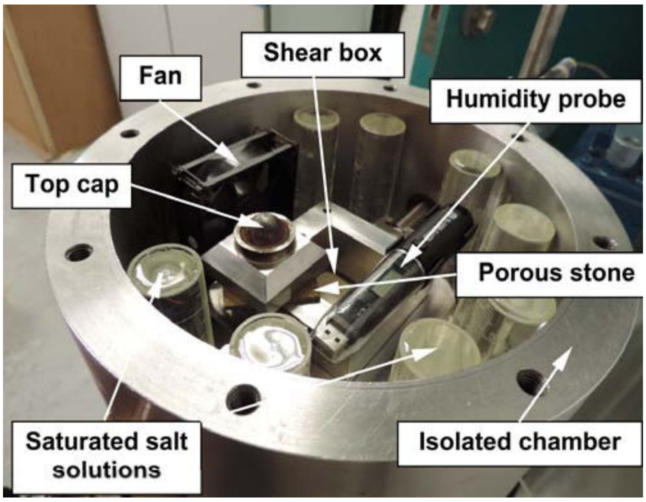

Figure 2. Humidity controlled shear box chamber.

2.3 *Stress path and test program*

Research on shear strength characteristics (Munoz-Castelblanco et al., 2012) and water retention behaviour of unsaturated loess (Sadeghi et al., 2016) has been mainly focused on suction range limited to less than 1 MPa. However, the merit of current study is to examine shearing behaviour of this type of soil at a suction state similar to the dominant *in-situ* conditions annually. It should be noted that high suctions may not be easily developed for depths more than one meter. However, field observations during sampling time up to 7.5 m depth revealed an inverse suction profile because of very deep water table (> 60 m) and a recent irrigation. In other words, Ng et al. (2017c & a) measured and reported *in-situ* suction at 5.5 m and 7.5 m depths as 1.3 MPa and 40 MPa, respectively. As a result, high suction values can be easily found for the considered loess stratum at depths more than one meter. Therefore, it was decided to bring the suction state inside soil specimens to a high value corresponding to relatively low RH in the field. Fig. 3 indicates the stress path followed for conduced shear tests. According to this figure, specimens were first equalized to the target suction of 40 MPa inside the desiccator from the initial state (A–

B). Afterwards, one specimen was transferred from the desiccator to the chamber with the same RH condition (B). The specimen was compressed to the target net stress of 50 kPa being equivalent to the overburden sampling depth of 3.5 m (B–C). The specimen was sheared accordingly with a constant rate of displacement (C–D). A shearing rate as low as 0.0019 mm/min was chosen for all the tests to satisfy drained conditions.

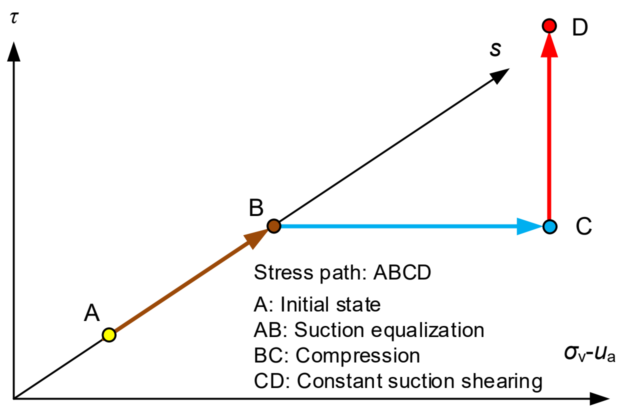

Figure 3. The stress path followed for the direct shear tests.

Three constant-suction shear tests were run on intact, compacted, and reconstituted specimens. Test program and test conditions before shearing are summarized in Table 1. Void ratio, dry unit weight, and degree of saturation were calculated based on final dry weight as well as initial weight and dimensions. It should be noted that specimen volume changes in suction equalization and compression stages were also considered in calculations. Average suction values during the whole shearing process were reported in the last column. Other testing conditions, including the applied net stress, and shearing rate were kept essentially the same for the sake of comparison.

Table 1. Summary of test conditions before shearing.

Specimen	e	γ_d (kN/m^3)	S (%)	s (MPa)
Intact	1.16	12.2	5	35.2
Compacted	1.05	12.8	6	35.4
Reconstituted	0.67	15.8	8	40.8

3 INTERPRETATION OF THE RESULTS

3.1 *Environmental conditions inside the chamber*

Relative humidity and temperature are considered as the environmental variables in this study. The variations in RH, temperature and suction with time inside the chamber for the three tests conducted are plotted in Figs 4a, 4b, and 4c, respectively. Suction was calculated from the record of RH and temperature according to Eq. 1:

$$s = -\frac{RT}{v_{w0} w_v} \ln RH \qquad (1)$$

where s is total suction; R is universal gas constant; T is absolute temperature; v_{w0} is specific volume of water; w_v is molecular mass of water vapour.

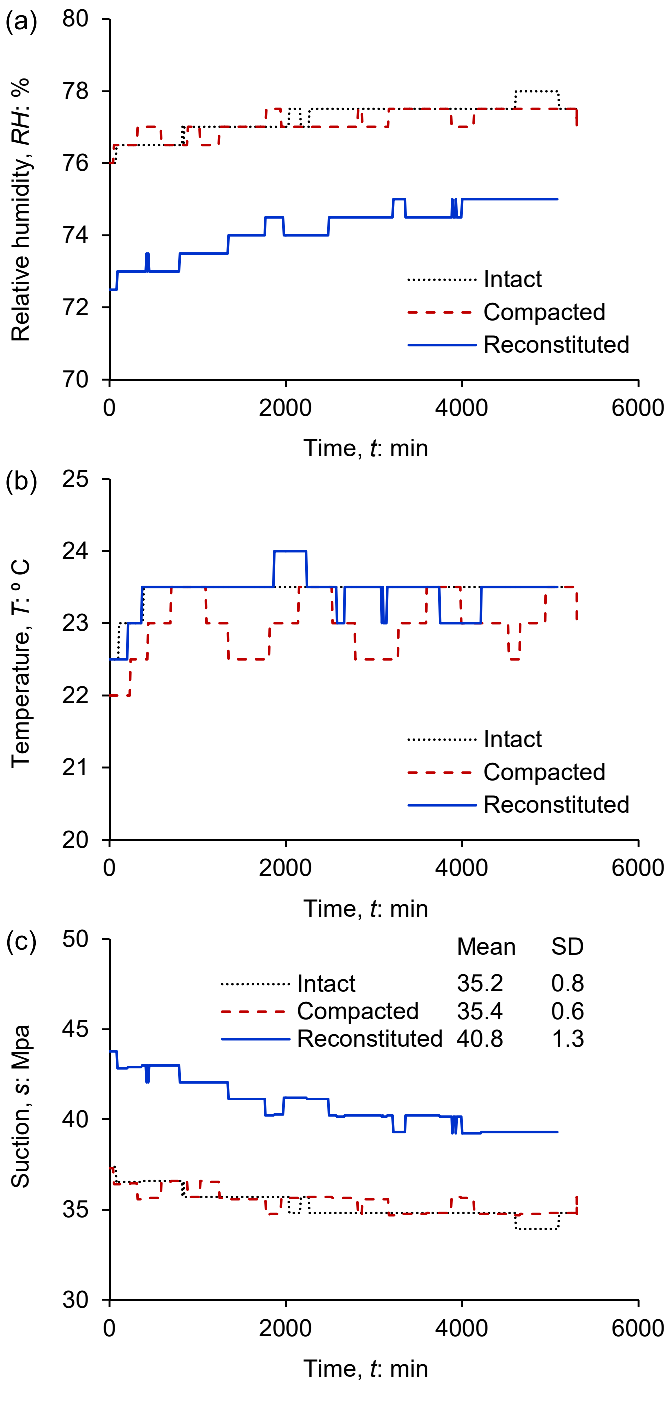

Figure 4. Variations in (a) relative humidity, (b) temperature, and (c) suction with time during shearing stage.

According to Fig. 4a, variations in RH during shearing stage is limited to 2% for the three tests. Although RH variations with time for compacted loess are closely matched with those of intact one, recorder RH values are generally lower in case of reconstituted loess. However, temperature changes for the three tests are very close for the whole shearing stage (Fig. 4b) due to the fact that shear box setup was installed in a temperature controlled room with daily fluctuations of ± 0.5 ^{o}C. Consequently, suction variations are also influenced by variations in RH according to Eq. 1. As shown in Fig. 4c, suction is dominantly higher in the test on reconstituted specimen while there is an excellent agreement between suction changes in the other two tests. This discrepancy in differences in controlled suction is likely caused by degradation of saturated salt solution for the last test which is the test on reconstituted specimen. It is noted that each test lasted for 4–5 days. The lesson learnt is to use fresh saturated salt solution for individual tests in future research.

3.2 *Shear strength and volumetric characteristics*

Fig. 5a indicates shear stress–shear displacement curves of all the tests. The three tested specimens show a peak behaviour at low displacements followed by a reduction in strength towards large displacements while dilation is still in progress. The observed brittleness behaviour is a consequent of desiccating loess specimens to high suction as a similar compacted specimen showed monotonic hardening behaviour under saturated conditions (Ng et al., 2017b). Similar phenomenon of high suction-induced peak behaviour was also reported for other fine-grained soils (e.g. Merchán et al., 2011; Nishimura, 2016). Of particular interest is the influence of loess microstructure on shear strength. According to Fig. 5a, compacted loess shows higher shear strength compared with the intact one and the reconstituted specimen exhibits the highest shear strength. Although compacted and intact specimens had similar initial void ratios, the former shows considerably higher strength compared with the latter. A possible explanation is the relative distribution of micropores and macropores. Intact loess with a honeycomb microstructure has larger macropores (and hence smaller micropores for the same void ratio) than compacted loess, resulted in a lower shear strength for intact specimen compared with compacted one. Qualitative and quantitative proof on their microstructures was provided by Ng et al. (2016).

Variations in volumetric strain with shear displacement for three microstructures are plotted in Fig. 5b. Indeed, the volumetric behaviour with shear displacement is in conjunction with shear strength behaviour. Except the very beginning stage of shearing, all specimens have notable dilation rates continuing towards the end of tests. Corresponding to the results of shear strength, dilation increases as microstructure varies from intact to compacted and reconstituted, respectively. The differences in dilation rate between compacted and intact loess can be explained based on the same postulation for their shear strength. However, the highest dilation and peak strength of reconstituted specimen is attributed to its lowest void ratio. Scanning electron microscopy (SEM) observations of Ng et al. (2017a) on microstructure of reconstituted loess revealed the significant microstructural evolution and modification due to desiccation. The evolved microstructure of reconstituted specimen resulted in the most uniform distribution of pore sizes and the least void ratio amongst the three microstructures considered.

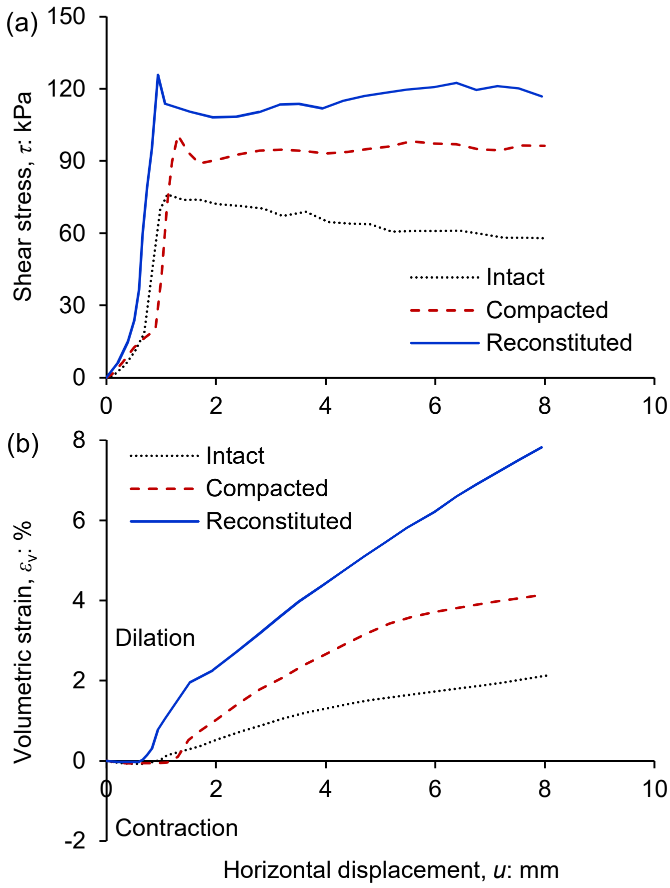

Figure 5. Shear behaviour in terms of (a) shear stress, and (b) volumetric strain against horizontal displacement.

3.3 *Stress-dilatancy relationships*

In order to study volumetric behaviour during shearing in more details, mathematical definition of dilatancy is selected and used as follows:

$$D = -\frac{\delta V}{\delta H} \tag{2}$$

where D is dilatancy; δV and δH are incremental displacements in vertical and horizontal directions, respectively. Dilation is considered positive according to the sign convention followed. Fig. 6a depicts variations in dilatancy with shear displacements for all conducted tests. As shown in this figure, compacted loess exhibits higher dilatancy than intact one and reconstituted loess shows the highest dilatancy, which is also consistent with results of Fig. 5b. The minimum and maximum peak dilatancy occurs in intact and reconstituted specimens, respectively (Fig. 6a).

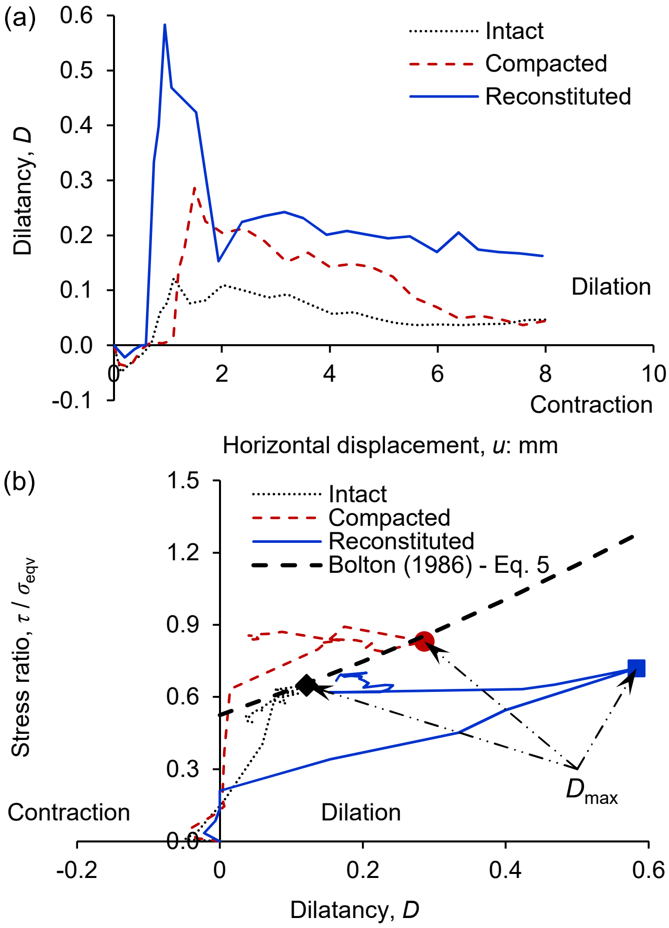

Figure 6. (a) Variations in dilatancy with horizontal displacement, and (b) stress-dilatancy curves.

The stress-dilatancy relationships can be also expressed but the stress ratio need to be defined first. According to Bolton (1986), the stress-dilatancy formulation for saturated course-grained soils can be written under direct shear testing condition as:

$$\tau/\sigma' = \tan\left[\phi'_{cs} + 0.8\tan^{-1}(D)\right] \quad (3)$$

where τ is shear stress; σ' is effective stress; ϕ'_{cs} is critical state friction angle measured as 27.7°. The term on the left hand side of Eq. 3 is the stress ratio for saturated conditions for which the effective stress has a clear physical definition. However, extensive debate has been existed for decades on definition of effective stress for unsaturated soils and a general consensus has not been reached to date. Bishop's single effective stress formulation is one of the widely used approach in which the contribution of suction to effective stress is taken into account by a weighing factor (Bishop, 1959). Following this approach, Alonso et al. (2010) proposed the effective stress for unsaturated soils as:

$$\sigma_{eqv} = \sigma_{net} + s.S^{\alpha} \quad (4)$$

where σ_{eqv} is the equivalent effective stress; σ_{net} is net stress; S is degree of saturation; α is a material parameter. Therefore, stress-dilatancy relationship for unsaturated conditions can be expressed as:

$$\tau/\sigma_{eqv} = \tan\left[\phi'_{cs} + 0.8\tan^{-1}(D)\right] \quad (5)$$

Equation 5 was used to correlate dilatancy with equivalent stress ratio. Stress-dilatancy curves for three microstructures are plotted in Fig. 6b. Solid symbols demonstrate the peak stress-dilatancy. In addition, Bolton's extended correlation for the unsaturated loess is included in the figure with the thick dashed line. It is noted that α=2.25 was obtained based on a regression analysis so that peak stress-dilatancy of intact loess matches the prediction of Eq. 5. The same value for α was used to calculate the equivalent stress ratio for other two microstructures studied. Results indicate that prediction of Eq. 5 is satisfactory for compacted loess. However, reconstituted loess exhibits a peak dilatancy beyond the prediction of Eq. 5. These observations imply that a unique material parameter may not be suitable for all possible microstructures and the equivalent stress ratio should be defined separately for each individual microstructure.

4 CONCLUSIONS

Shear behaviour of unsaturated desiccated loess with different microstructures was examined through conducting a series of humidity controlled direct shear tests. All specimens dilated continuously with a clearly defined peak strength and dilatancy. The peak shear strength and dilation rate increase as the loess microstructure changes from intact to compacted and reconstituted. The more dilation rate of compacted loess compared with the intact one with nearly the same void ratio was attributed to more non-uniform distribution of pore sizes in intact loess resulted in a honeycomb microstructure. Reconstituted loess, on the other hand, had the highest dilation rate and peak strength because of its lowest void ratio at the same net stress and suction. Results also revealed that classical stress-dilatancy relationship for saturated course-grained soils may not give satisfactory predictions for a desiccated fine-grained soil unless the contribution of suction to the stress ratio is properly defined.

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