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Influence of effective stress on swelling pressure of expansive soils

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Abstract. The volume change and shear strength behaviour of soils are controlled by the effective stress. Recent advances in unsaturated soil mechanics have shown that the effective stress as applicable to unsaturated soils is equal to the difference between the externally applied stress and the suction stress. The latter can be established based on the soil-water characteristic curve (SWCC) of the soil. In the present study, the evolution of swelling pressure in compacted bentonite-sand mixtures was investigated. Comparisons were made between magnitudes of applied suction, suction stress, and swelling pressure.

1 Introduction

The volume change and shear strength behaviour of soils are controlled by the effective stress. The excess pore water pressure is equal to the difference between the externally applied stress and the effective stress in case of saturated soils. However, the impact of the negative pore water (or soil suction) on the effective stress for unsaturated soils is not straight-forward since the distribution of external stress within unsaturated soil systems occurs either via the water phase, or via the air phase, or even via both water and air phases depending upon the range of suction under consideration.

Recent advances in unsaturated soil mechanics have shown that the effective stress as applicable to unsaturated soils is equal to the difference between the externally applied stress and the suction stress [1]. The suction stress embraces the van der Waals attractive force, the double-layer repulsive force, the surface tension, and the solid-liquid interface forces due to pore water pressure.

The suction stress of unsaturated soils either can be measured in the laboratory from tensile strength tests or can be calculated based on the shear strength tests, or even can be calculated based on theoretical considerations. The suction stress characteristic (SSCC) curve of a soil (i.e., the relationship between suction stress and degree of saturation or suction or water content) can be established based on the soil-water characteristic curve (SWCC) of the soil [2].

The suction stress approach has been applied to determining the shear strength behaviour of unsaturated soils [2, 3] and the volume change behaviour of soils during the drying process [4]. At this stage, very limited studies are available on the swelling pressure development of unsaturated soils as affected by the suction stress, particularly in the context of a change in the suction stress on account of a change in suction and its influence on the effective stress of swelling soils.
The main objective of the study was to explore the impact of changes in the effective stress for swelling soils during the wetting process based on the suction stress approach.

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2 Methods

Laboratory tests were carried out on highly compacted bentonite-sand mixtures [5]. Compacted specimens were prepared by mixing bentonite and sand in equal proportions by dry mass (50% bentonite and 50% sand). The Material properties of the bentonite and the sand used in the mixtures are presented in Table 1 and Table 2, respectively.

The specimens were prepared at predetermined water contents and dry densities. The compacted bentonite/sand specimens (dia. = 50 mm and a height = 20 mm) had the following compaction conditions: (i) dry density = 2.056 Mg/m³, water content = 9.1%, and suction = 22.7 MPa and (ii) dry density = 2.042 Mg/m³, water content = 9.1%, and suction = 22.7 MPa. Three out of the five specimens were further oven dried prior to testing them in a specialised oedometer. Oven drying caused an increase in the dry density and suction of the specimens.

The specimens were then step-wise wetted by decreasing suction. Both axis-translation and vapour equilibrium techniques were adopted for this purpose. The swelling pressure at each applied suction was mea sured.

Table 1. Properties of Calcigel bentonite

Specific gravity of soil solids (-)	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)
2.65	130	97	33

Table 2. Properties of the sand

Specific gravity of soil solids (-)	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)
2.65	0.25	0.40	0.70

Suction controlled tests on compacted bentonite specimens were carried out using several devices developed at the Technical University of Catalonia, Barcelona (or UPC), Spain [6]. The device used is also known as the UPC-isochoric cell. The device with an exchangeable pedestal (either a corrosion-resistant porous disk for vapour equilibrium technique or a high-air-entry ceramic disk (air-entry value = 1,500 kPa) for axis-translation technique), can be used to control suction of specimens during the wetting process under isochoric condition. Table 3 shows details of the bentonite specimens tested (i.e., dry density, water content, suction, and the techniques used to control suction).

Table 3. Details of the 50% bentonite/50% sand specimens (50B) tested

Sp. No.	[a]Initial compaction conditions; [b]Specimen conditions before testing			Suction control technique step-wise used (Vapour equi-librium technique (VET) or Axis-translation technique (ATT))
	Dry density (Mg/m3)	Water content (%)	Suction (MPa)	
1	2.056 [a] 2.056 [b]	9.0 [a] 9.0 [b]	22.7 [a] 22.7 [b]	VET for suctions 10.5, 5.5, 4.25, 3.3 and 2.2 MPa and water circulation (suction = 0 MPa)
2	2.038 [a] 2.038 [b]	9.3 [a] 9.3 [b]	22.7 [a] 22.7 [b]	ATT for suctions 0.5, 0.3, 0.1 and 0.05 MPa and water circulation (suction = 0 MPa)
3	2.042 [a] 2.072 [b]	9.1 [a] 0 [b]	22.7 [a] 1000 [b]	VET for suctions 10.5, 5.5, 4.25, 3.3 and 2.2 MPa and water circulation (suction = 0 MPa)
4	2.005 [a] 2.072 [b]	9.3 [a] 0 [b]	22.7 [a] 1000 [b]	VET for suctions 39.4, 10.5, and 5.5 MPa
5	2.052 [a] 2.072 [b]	9.1 [a] 0 [b]	22.7 [a] 1000 [b]	ATT for suctions 0.7, 0.2, and 0.05 MPa

3 Results

3.1 Presentation of results

The set of equations used for the calculation of effective stress is presented in the following paragraph. Based on the degree of saturation values of the soil specimens at various applied suctions, the effective degree of saturation values were calculated from eq. (1). The suction – degree of saturation SWCCs of the soils were then transformed into the suction – effective degree of saturation SWCCs. The suction – effective degree of saturation SWCCs were best-fitted using van Genuchten (1980) [7] model (eq. 2). The air-entry fitting parameter (α) and the pore-size parameter (n) were obtained. The parameters α and n were used to calculate the suction stress as a function of the effective degree of saturation using the closed-form expression (eq. 3) [2]. Equation (3) is applicable for S_e between 0 and 1. The effective stress corresponding to any suction stress can be calculated from eq. (4).

For the bentonite/sand specimens, the applied stress during the isochoric swelling pressure tests was zero; however, a decrease in suction caused a development of total stress (i.e., swelling pressure). In this case, at any applied suction, the suction stress is subtracted from the total stress (i.e., the measured swelling pressure) to obtain the effective stress.

$$S_e = \frac{S - S_r}{100 - S_r} \tag{1}$$

$$S_e = \left\{ \frac{1}{1 + [\alpha(\psi)]^n} \right\}^{\frac{1}{1-n}} \tag{2}$$

$$\sigma^s = -\frac{S_e}{\alpha} \left[S_e^{\;n/(1-n)} - 1 \right]^{1/n} \tag{3}$$

$$\sigma' = (\sigma - u_a) - (\sigma^s) \tag{4}$$

3.2 Discussion of results

The swelling pressure (i.e., total stress) at each applied suction was measured. Fig. 1 presents the measured swelling pressure vs. applied suction plots for the bentonite/sand specimens (50B-specimens) of this study. For comparison, the corresponding results of pure bentonite (100B specimens) are also shown.

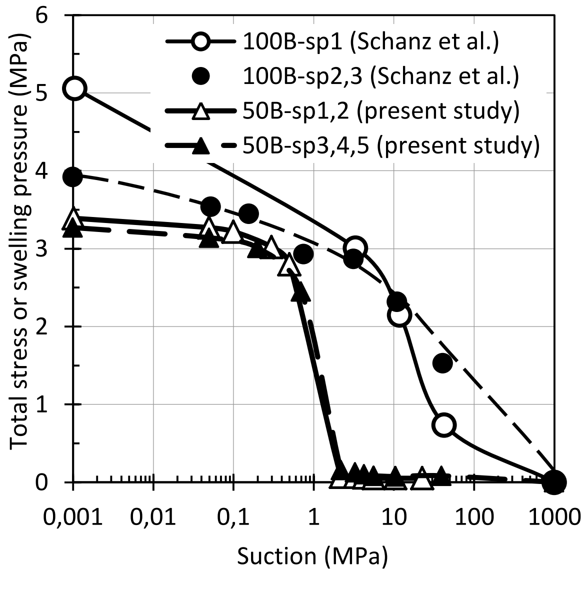

Figure 1. Suction control swelling pressure test results of bentonite/sand specimens 1 to 5 of the present study (50B) and of pure bentonite specimens (100B) (for comparison).

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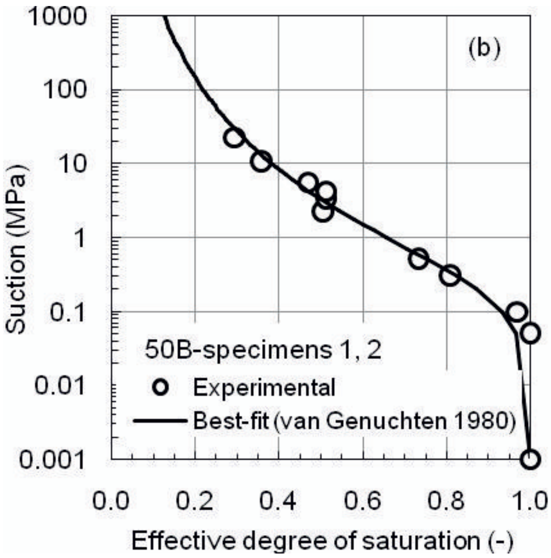
For the bentonite/sand mixtures (50B-sp1,2 and 50B-sp3,4,5) swelling pressure was found to slightly increase due to a decrease in suction to about 2 MPa, whereas at suctions smaller than 2 MPa, swelling pressure was found to significantly increase until reaching the maximum swelling pressure at zero suction corresponding to the saturated state. For the 100-B specimens, an increase in swelling pressure was observed over the full suction range.

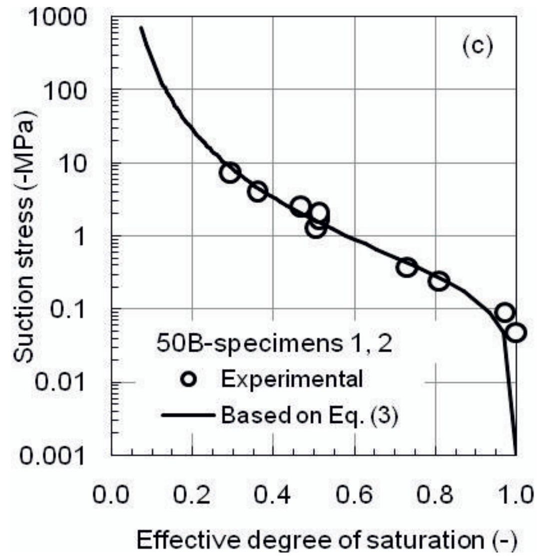
Figures 2 and 3 show the suction – degree of saturation SWCCs (Figs. 2a and 3a), the suction – effective degree of saturation SWCCs (Figs. 2b and 3b), the SSCCs in terms of the effective degree of saturation (Figs. 2c and 3c), and the SSCCs in terms of suction (Figs. 2d and 3d) for the combined results of specimens 1 and 2 and specimens 3, 4 and 5 of Calcigel bentonite/sand mixture (50B/50S), respectively.

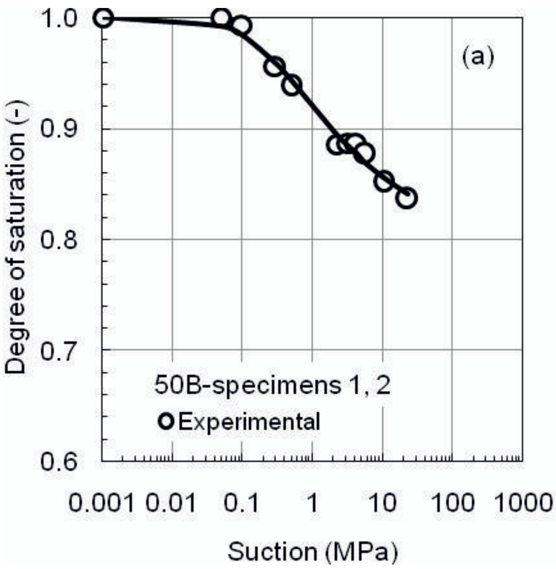
The fitting parameters obtained from the best-fit SWCCs are shown in Table 4. The results presented in Figs. 2(d) and 3(d) show that the suction stress increased (i.e., the magnitude of suction stress decreased) with a decrease in suction for the bentonite/sand specimens.

Table 4. SWCC fitting parameters for the bentonite/sand specimens.

Parameter	Specimen 1 and 2	Specimens 3, 4 and 5
*S*r (-)	0.769	0.000
α (-)	5.071	0.444
n (-)	1.245	1.326







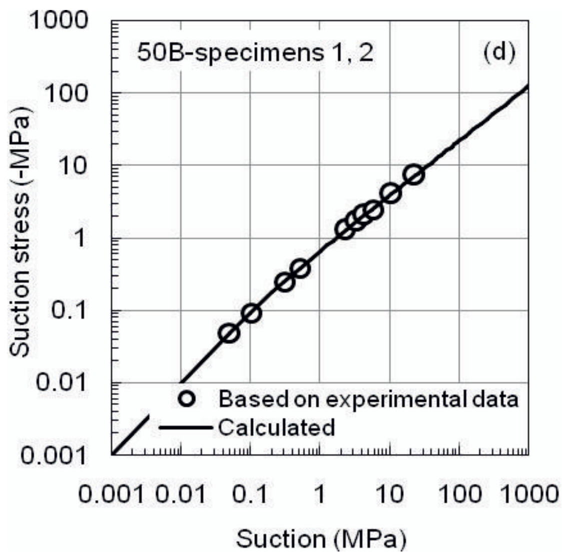


Figure 2. SWCCs and SSCCs of Calcigel bentonite/sand (50B-specimens 1, 2): (a) suction – degree of saturation SWCC, (b) Suction – effective degree of saturation SWCC, (c) SSCC in terms of effective degree of saturation, and (d) SSCC in terms of suction (log-scale)

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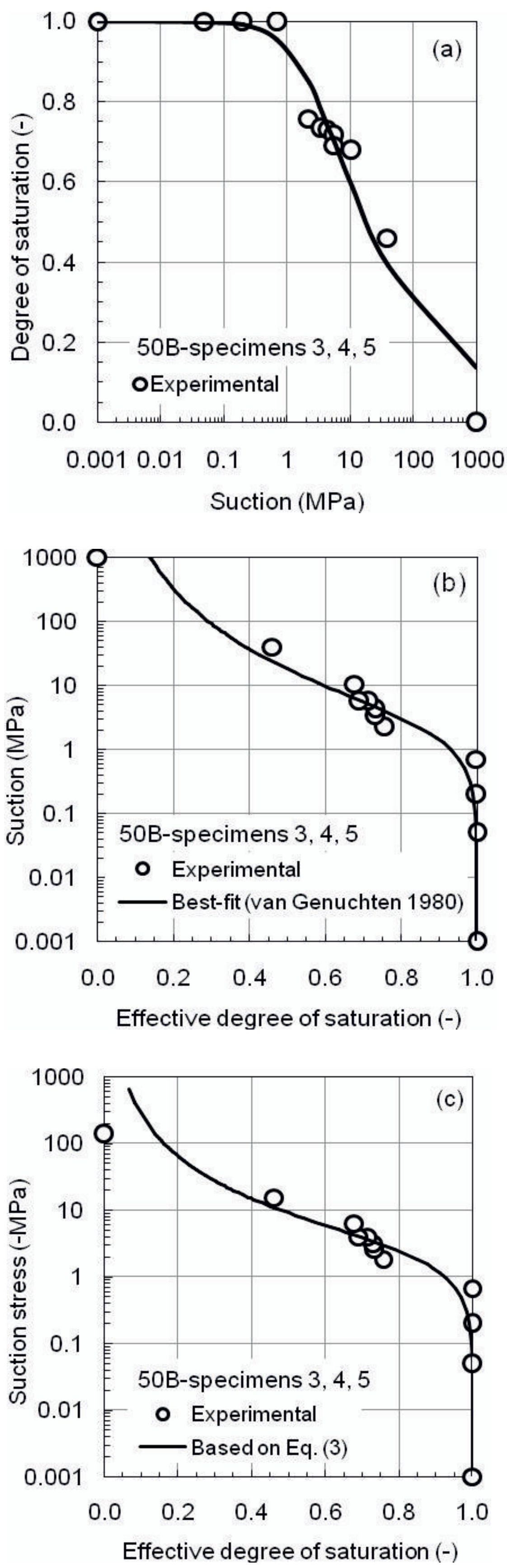

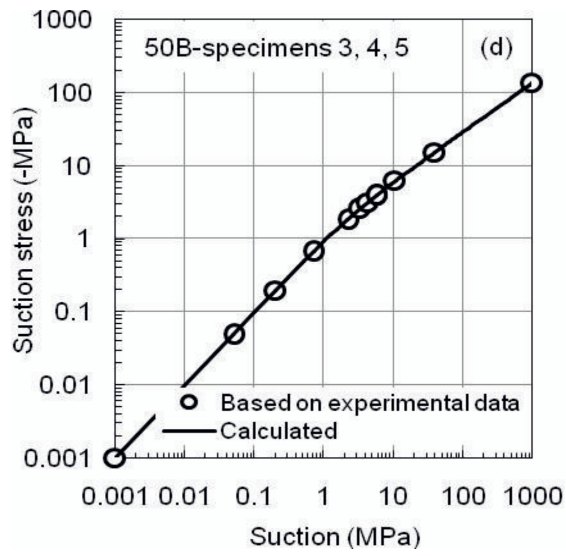

Figure 3. SWCCs and SSCCs of Calcigel bentonite/sand (50B-specimens 3, 4, 5): (a) suction – degree of saturation SWCC, (b) Suction – effective degree of saturation SWCC, (c) SSCC in terms of effective degree of saturation, and (d) SSCC in terms of suction (log-scale)

Baille et al. (2014) stated that for bentonites, a decrease in suction causing an increase of suction stress leads to decreasing the effective stress. Figures 4 and 5 show the combined plots of suction versus suction stress and effective stress versus swelling pressures (total stress) for compacted Calcigel bentonite/sand (50/50) specimens. The equivalent plot of results for pure bentonite is presented in Fig. 6. The results presented in Figs. 4 and 5 show that, at any applied suction the magnitude of suction stress is greater than the magnitude of swelling pressure. At saturation (i.e., at zero suction), the swelling pressure (i.e., the total stress) and effective stresses are equivalent since the excess pore water pressure was zero and the suction stress reduced to zero.

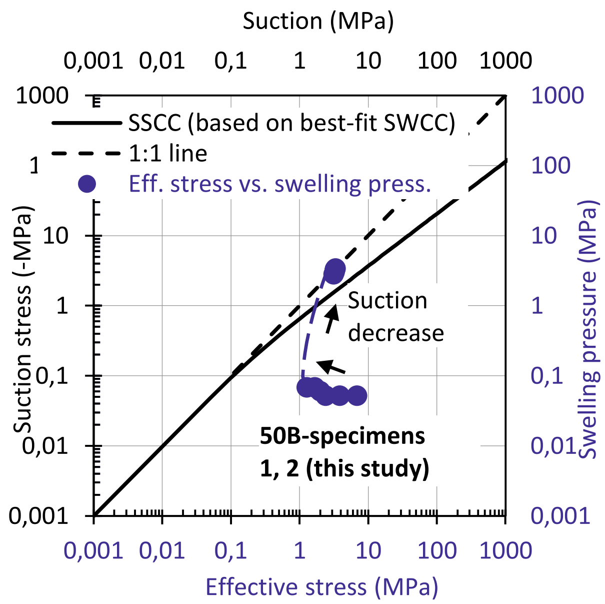

Figure 4. Influence of a change in suction on suction stress and effective stress of Calcigel bentonite/sand mixture (50B-specimens 1, 2).

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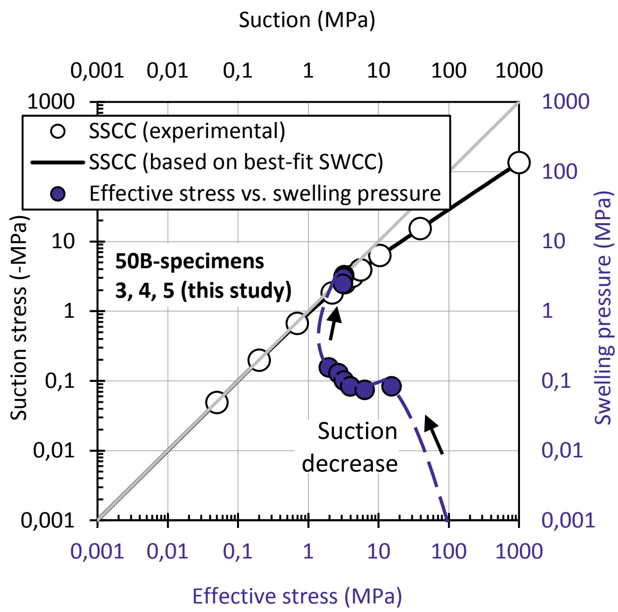

Figure 5. Influence of a change in suction on suction stress and effective stress of Calcigel bentonite/sand mixture (50B-specimens 3, 4, 5).

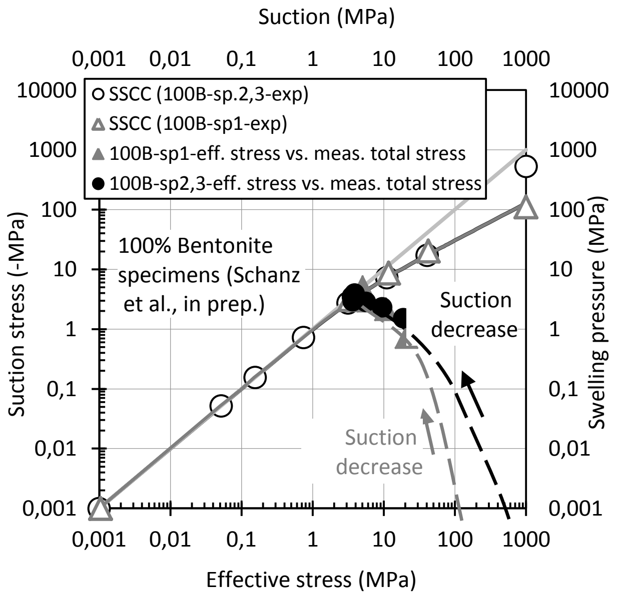

Figure 6. Influence of a change in suction on suction stress and effective stress of pure Calcigel bentonite (100B-specimen 1 and 100B-specimens 2, 3) from Schanz et al., submitted.

This observation is similar for the pure bentonite (100B) and the 50/50 bentonite/sand mixture. The effective stress of the pure bentonite decreased continuously upon wetting which was manifested on the development of swelling pressure (see Fig. 6). It is also visible in Fig. 6 that for similar scaling of the suction stress axis and the swelling pressure axis, the final swelling pressure at saturated state reached the suction stress line at the point where the latter deviates from the 1:1 line, corresponding to the air-entry value. This was also found for the specimens 3, 4, 5 shown in Fig. 5, whereas the final measured swelling pressure was found to be greater than suction stress at air-entry for specimens 1, 2 in Fig. 4. The dashed lines in Figs. 4, 5 and 6 indicate the effective stress-swelling pressure path during suction decrease. For the pure bentonite (Fig. 6), a continuous increase in swelling pressure was manifest by a decrease in effective stress. For the bentonite/sand mixtures, a different effective stress-swelling pressure path was observed. In Fig.4 an increase in swelling pressure was accompanied by a significant decrease in effective stress for a suction stress smaller than 1.2 MPa. For a suction stress greater than 1.2 MPa, both the swelling pressure and the effective stress increased, which is not consistent. In Fig. 5, after an initial increase in swelling pressure, it slightly increased at suction stresses between 15 and 1.8 MPa accompanied by a decrease in effective stress. Again, for suction stress greater than 1.8 MPa, an inconsistency was observed; both the swelling pressure and effective stress increased. Considering the global behaviour of the bentonite/sand mixtures from the initial to the final point of the swelling pressure-effective stress path (i.e., ignoring the intermediate points), a decrease in effective stress manifest by an increase in swelling pressure was observed, which is concurrent with the behaviour observed for the pure bentonite. However, the interpretation of the various stages between initial and final state need further consideration.

4 Conclusions

The investigation clearly showed that, at high suctions, the swelling pressures developed were smaller than the corresponding applied suctions. However, at smaller suctions, the swelling pressure and the magnitude of suction stress were found to be similar indicating that at zero water pressure the effective stress is equivalent to the swelling pressure for highly plastic clays.

References

1. N. Lu, W.J. Likos, J. Geotech. and Geoenviron. Eng. ASCE, **132**, 131-142, (2006).
2. N. Lu, J.W. Godt, D.T. Wu, Water Resources Research, **46**, W05515 (2010).
3. S. Oh, N. Lu, Y.K. Kim, S.J. Lee, S.R. Lee, J. Geotech. Geoenviron. Eng. ASCE **138**, 47-57 (2012).
4. W. Baille, S. Tripathy, T. Schanz, Vadose Zone Journal. **13**, doi:10.2136/vzj2013.06.0112, (2014).
5. S.S. Agus, Y.F. Arifin, S. Tripathy, T. Schanz, Acta Geotechnica, DOI 10.1007/s11440-012-0189-0, (2012)
6. E. Romero, Characterisation and thermo-hydro-mechanical behaviour of unsaturated Boom clay: an experimental study, PhD thesis, Universitat Politècnica de Catalunya (1999).
7. M. T. van Genuchten, Soil Sci. Soc. Am. J. **44**, 892–898 (1980).
8. T. Schanz, S. Tripathy, W. Baille, Consequences of effective stress changes on the volumetric behaviour of unsaturated soil. In prep.