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Normalisation techniques for slowly-converging soils

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Abstract

The existence of a unique normal compression, NCL, and critical state line, CSL, for clean sands and clays in the state plane, v-lnp', is generally assumed. Recently, some soils of either complex grading or mixed mineralogy did not exhibit this convergent type of behaviour in the state plane at typical stress and strain levels. This investigation proposes different normalisation techniques for non-convergent soil mixtures consisting of fractally-graded single mineral sands, either quartz or calcium carbonate, with very large amounts of non-plastic fines. For the mixtures, the typical normalisation techniques do not work because a straight NCL, parallel to the CSL, could be defined only in the region of very low specific volumes and extremely high stress levels. Similarly, a normalisation based on an equivalent pressure $p'_{e,CSL}$ taken on a unique straight CSL could not be applied because of the existence of curved and multiple CSLs.

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Keywords: transitional soils; state boundary surface; fractally-graded sands

1. Introduction

The state boundary surfaces SBS are normalised plots which envelope all the possible states of a soil. Different methods of normalisation have been used according to the soil type (Fig. 1). Generally, for fine-grained materials the current pressures are divided by an equivalent pressure taken on the NCL or CSL [1] while for sands the state parameter Ψ, equal to the distance of the current specific volume from its equivalent on the CSL is often used [2].

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When dealing with natural soils, the SBS is one of the tools used to quantify the effect of structure on their behaviour. Cotecchia and Chandler [3] found a unique SBS for different clays when normalised by the sensitivity, by volume (p^*_e taken as appropriate on the isotropic compression line ICL or NCL) and by the intrinsic strength (M equal to the stress ratio at critical state). They also found that the difference between the SBS of reconstituted and natural clays was only in size and not in shape.

Soils of rather complex grading or mineralogy may show multiple NCLs and CSLs in the state plane. Martins et al. [4] named this category "transitional" because the mode of behaviour was between a standard critical state framework for clays and a breakage dominated framework for clean sands. For transitional soils, the final state in compression and shearing depends on the initial density of the samples and convergence might not be reached in conventional laboratory testing. However, convergence must eventually occur at the minimum density, i.e. specific volume equal to 1. One of the main shortcomings of transitional soils is the quantification of structure of intact samples because of the lack of a reference reconstituted material with which compares the natural counterpart. Ferreira and Bica [5] proposed for their transitional soil from reconstituted Botucatu sandstone samples a stress normalisation based on an equivalent pressure taken on individual CSLs, and Shipton and Coop [6] attempted a normalisation based on the state parameter Ψ again on an infinite number of individual CSLs for their transitional gap-graded mixtures. This research shows examples of normalisation techniques on fractally-graded sands with large amounts of non-plastic fines. It aims to continue the research of Altuhafi and Coop [7] who found that the soil behaviour in compression evolved when the grading curve GSD moved from uniform to well-graded. The evolution of the GSD could be represented by the fractal theory, which is often used to describe the fragmentation process [8]. In the present work, the materials can be classified as transitional, but we described them as slowly-converging because the compression and shearing paths showed a tendency to converge, although at very large stresses and strains. The aim is to provide effective methods of normalisation for slowly-converging soils.

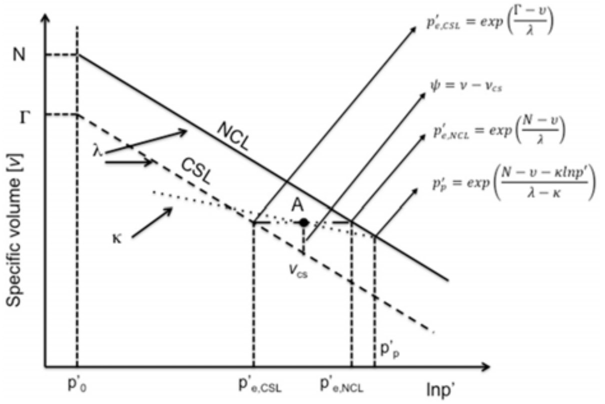

Fig. 1. Different techniques of normalisation by pressures and state parameter Ψ.

2. Materials and methods

The GSDs of the materials are shown in Figure 2, where the Leighton Buzzard sand (LBS) is a quartz sand from the UK while the LMS is a crushed limestone from China. The labels CD and D4 stand for the fractal dimensions, 2.59 and 2.74 respectively, used to control the sand fraction. Silt was added to complete the gradation of the material but it was not controlled to be fractal. The fractal dimensions were calculated as 3-n, where n is the slope of the bi-logarithmic graph of the percentage finer passing through a known sieve mesh size and the particle diameter (Fig. 2b). The GSDs were anchored at 600 µm and the fractal sand fraction was formed adopting the mass method [7].

The one-dimensional compression tests were carried out in front loading oedometer frames, using either single drainage rings of 50mm diameter or floating rings of either 30 or 20mm diameters, which allowed to reach stress levels of 20 and 40MPa. The triaxial tests were conducted in stress-path apparatuses of Bishop and Wesley type. A degree of saturation greater than 0.96 was obtained by circulating carbon dioxide, flushing distilled water and applying back pressures of at least 200kPa. Suction cups were connected to the load cells prior to compression to eliminate errors due to misalignment between the load cell and the sample [9]. Shearing took place at rates increasing from 0.05%/h up to 0.4%/h. The oedometer and triaxial samples of LBS and LMS were prepared using the dry compaction method because neither wet pluviation nor moist-tamping could be adopted due to the fines segregation in the former and the large matrix suction developed by the fines in the latter. The existence of non-convergent type of behaviour might be caused by an inaccuracy of the calculation of the initial specific volumes which can lead to erroneous results. To reduce this possibility, the calculations of the initial specific volumes were based on multiple independent measurements of weights and dimensions of the samples [10]. The specific gravity Gs of the LBS mixtures was found to be equal to 2.61 and that of the LMS to 2.72.

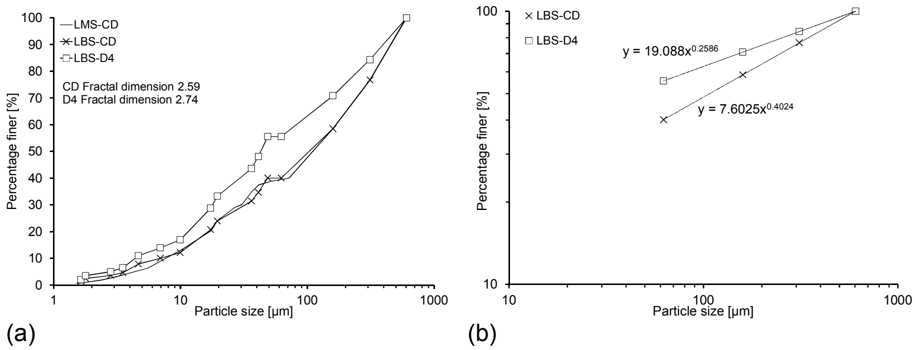

Fig. 2. (a) Fractal grading curves (CD and D4) of LMS and LBS with the addition of the sedimentation curves of the LBS and LMS silts; (b) examples of fractal grading curves in the bi-logarithmic plane.

3. Results

3.1. Compression and shearing behaviour

The oedometer data of LBS-CD and D4 are shown in Figure 3. The compression paths of LBS-CD converge slowly probably defining a unique NCL at stresses larger than 10MPa and very low specific volumes less than 1.35. This behaviour is accentuated for the samples of LBS-D4 since the paths still depend on their initial density even at around 40MPa. The data show that the LBS-D4 maintains a looser packing than LBS-CD, even if it has a larger amount of fines. This is not surprising because a transition between sand dominated behaviour and fine dominated behaviour may occur when adding fines [11]. Materials can still densify if the sand grains are still in contact and the fines fill the voids, but when fines exceed a threshold, the sand grains are dispersed in the fines matrix and the assembly reaches looser states. Minh and Cheng [12] investigated the packing related to the increase of fractal dimension using DEM and they found that the value of fractal dimension at which samples stop densifying was equal to 2.3, in this study, that value is equal to around 2.57.

In Figure 3b, the compression paths of LMS-CD show different slopes according to the initial densities of the samples and the loose specimens have steeper paths than the dense ones. Each NCL was extrapolated to estimate the convergence, but it is unlikely that there can be a unique NCL as the paths must curve to become asymptotic to v=1. This departs from the typical soil behaviour, in which the NCL is well defined covering a wide range of stress levels and specific volumes.

The shearing behaviour of LBS-CD samples in the state plane is shown in Figure 4. The LBS-CD defines as many CSLs as the initial specific volumes although only few examples are plotted. The use of lubricated end-platens does not change the slowly-converging behaviour. Generally, the samples are all contractive even test D10 which was sheared at 5MPa from a relative dense state. The LBS-D4 and LMS-CD samples showed a similar behaviour, therefore their graphs are omitted for brevity.

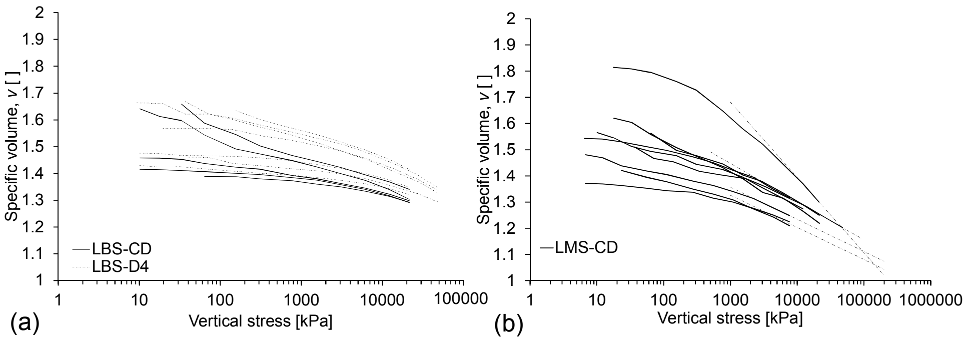

Fig. 3. One-dimensional compression paths of (a) LBS-CD and LBS-D4 samples, (b) LMS-CD.

The Gudehus function [13] was used to estimate the shape of the CSLs, which were curved for each material:

$$v_i = 1 + e_{i0} \cdot \exp^{-(3p'/hs)^n} \tag{1}$$

where v_i is the current specific volume on the CSL, e_{i0} is the maximum void ratio, p' is the mean effective stress, hs is a pressure parameter accounting for the granular hardness and n is an exponent between 0.3 and 0.5. For each soil, e_{i0} varied according to the initial specific volume of the samples, while hs and n were maintained constant for the different values of e_{i0}. The values of hs and n were 18MPa and 0.4 for the quartz gradings, and 95MPa and 0.5 for the LMS-CD. The fact that the same set of parameters could be chosen to fit the data for both LBS gradings might reveal that the Gudehus function reflects the material properties and it is independent of the change of gradings.

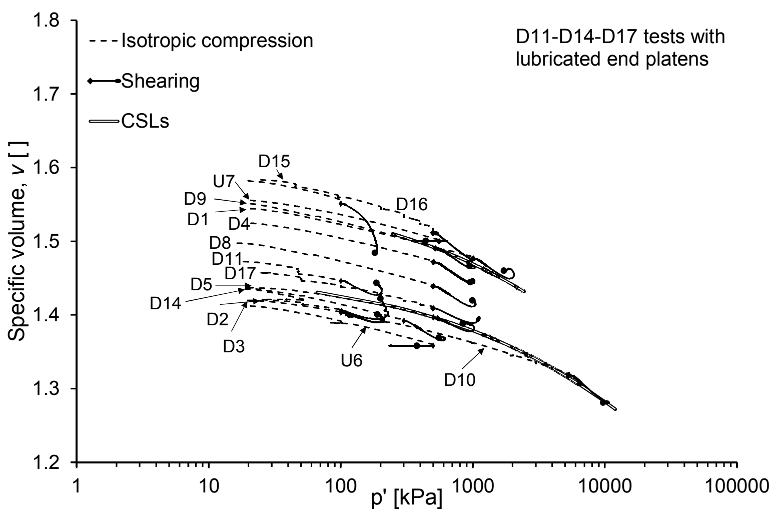

Fig. 4. State plane for triaxial tests on the LBS-CD samples and examples of CSLs.

3.1. Normalisation techniques and state boundary surfaces

Given the patterns of compression and shearing, a normalisation of the shearing data based on an equivalent pressure p'_e , taken on a straight NCL could not work because the NCLs could not be defined in the v-lnp' plane; similarly, a normalising pressure, $p'_{e,CSL}$, could not be taken on a unique straight CSL because of the multiple and curved CSLs. Figure 5a shows an attempt to normalise the stresses of tests on LBS-CD based on $p'_{e,CSL}$ taken on the uppermost CSL. The lack of a unique SBS demonstrates that this approach cannot work. All the samples lie on the dry side of the critical and if a unique CSL exists, then the definition of SBS on the wet side would require extremely high pressure tests. Since, the compression paths were nearly parallel to the CSLs (Fig. 4) so it is not even clear what pressure would be needed to reach the wet side. When the normalisation was based on the $p'_{e,CSL}$ taken on individual and curved CSLs, a unique SBS could be defined for all the materials (Fig. 5b-d). The critical state line of LBS-CD, LBS-D4 and LMS-CD reduces to a point of coordinates (1, 1.38), (1, 1.42) and (1, 1.56), respectively. On the dry side, the Hvorslev surfaces are well defined and lie below the tension cut-off line. On the wet side, the Roscoe surfaces of LBS are less well defined because of the lack of a consistent number of tests lying on the wet side and the tendency of the tests lying on the wet side to move to the dry side as shearing progresses, e.g. test D5 of LBS-D4 (Fig. 5c).

The Roscoe surface of LMS is well defined mainly by the loosest samples, but when approaching the critical state, its shape cannot be determined accurately because of the lack of the experimental data. Despite the lack of data, the shapes of the Roscoe surface are tentatively proposed in the plots. Figure 6 shows the state boundary surfaces of LBS-D4 and LMS-CD obtained by the normalisation based on the state parameter, Ψ. Also this parameter was calculated considering individual CSLs. The SBSs are well defined by the dense samples on the dry side and by the loose samples on the wet. The critical state lines reduce to a point of coordinates (0, M). On the dry side, the SBSs envelop the peak stress ratios of the samples and the denser the sample, the higher the peak stress ratio. For LBS-D4, the shape of the SBS on the dry side can only be assumed because only test D7 occupies the negative part of the plot.

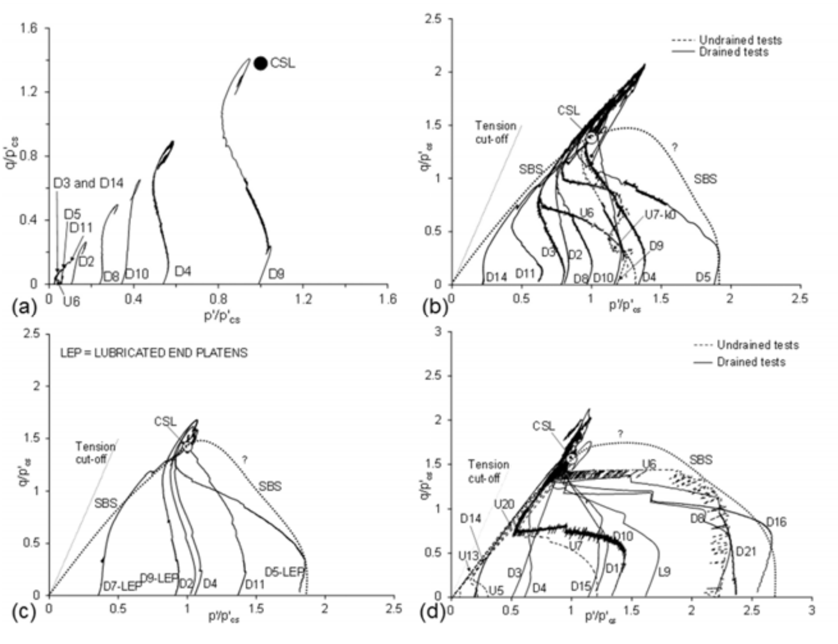

Fig. 5. Normalised stress paths of (a) LBS-CD considering a unique CSL, (b) LBS-CD, (c) LBS-D4, (d) LMS-CD considering a $p'_{e,CSL}$ taken on individual CSLs.

4. Conclusions

Three different materials were tested in compression and shearing, covering a wide range of stress levels and initial densities. All of them were classified as slowly-converging soils, in the sense that convergence to a unique NCL or CSL would eventually occur but at too large stresses and strains to define them. Typical normalisation techniques could not be applied to the slowly-converging soils because of the lack of a well defined unique NCL or CSL. In order to obtain a unique SBS, two methods were attempted. A stress normalisation based on $p'_{e,CSL}$ taken on individual CSLs could not defined well a SBS on the wet side as well as on the dry side, mainly because of the tendency of the samples lying on the wet side to move to the dry side during shearing. The state parameter normalisation gave a better definition of the SBS on both sides. It is suggested to attempt both normalisation techniques when dealing with slowly-converging soils, but individual CSLs should always be taken into account.

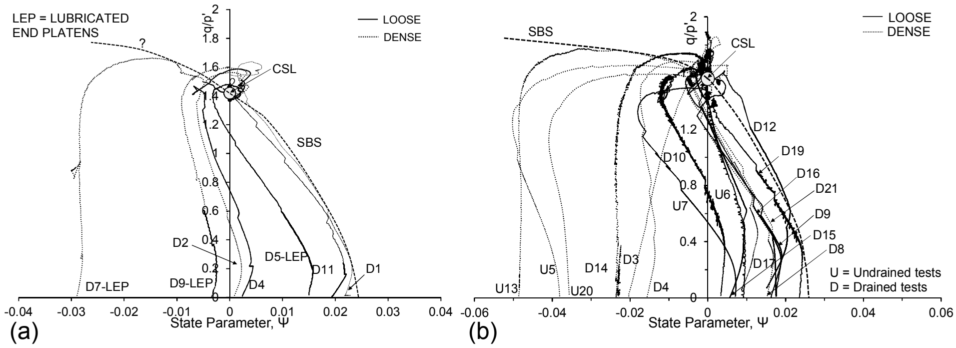

Fig. 6. Normalised stress-paths of (a) LBS-D4 and (b) LMS-CD based on the state parameter Ψ taken on individual CSL.

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