Transitional behaviors in well-graded coarse granular soils

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Abstract: Drained triaxial compression tests were carried out for a well-graded coarse granular soil (CGS) to investigate the effect of the initial specific volume on the location of the critical state line (CSL). A family of parallel CSLs in the $v \sim \log p'$ plane was observed for the well-graded CGS, indicating that it exhibited transitional behavior. The degree of transitional behavior was quantified from the relationship between the intercepts of the CSLs and the initial specific volumes, giving a value of 0.59, which indicated a substantially transitional behavior. The observations of the CSL pattern in the CGS illustrated that transitional behavior could be extended to large-sized granular soils, beyond the usual transitional soils that have been observed so far, which generally have gradings between those of clean sand and plastic clay.

Keywords: coarse granular soil; stress-strain relationship; critical state line; specific volume; transitional behavior

Introduction

Clean sands can be described within a framework of critical state similar to that for clays (Been and Jefferies 1985). Their normal compression lines (NCLs) and critical state lines (CSLs) are unique. However, more recent research has identified that many soils exhibit a transitional mode of behavior, which cannot be described within a simple critical state framework. These transitional soils, such as gap-graded soils (Martins et al. 2001; Ferreira and Bica 2006), well-graded silty clay (Nocilla et al. 2006) and well-graded sands (Altuhafi et al. 2010; Altuhafi and Coop 2011), have gradations and modes of behavior between that of clean sand and plastic clay. The distinct feature of transitional behavior is that unique NCLs and CSLs cannot be identified (Martins et al. 2001; Ferreira and Bica 2006; Nocilla et al. 2006).

Martins et al. (2001) found that the compression curves in oedometer tests of the gap-graded Botucatu residual sandstone did not converge to a unique NCL even though the stress was up to 6 MPa. Ferreira and Bica (2006) then confirmed that convergence to a unique NCL could still not be observed even if the compression was taken to 24MPa, and also that reconstituted samples of the soil did not define a unique CSL. Nocilla et al. (2006) pointed out that transitional behavior was not confined to gap-graded soils as they observed that their well-graded clayey silts also showed transitional behavior with non-unique NCLs and CSLs. For well-graded glacial sediments, Altuhafi et al. (2010) identified that the compression paths did not converge to a unique NCL, but that a unique CSL was observed, suggesting that whatever fabric of the soil that caused the non-convergence during compression could be destroyed during shearing. Shipton and Coop (2012) observed that non-convergent compression behavior tended to exist in soils of mixed grading and mineralogy, while Shipton and Coop (2015) found that the sample preparation method, overconsolidation, stress level and fines plasticity did not affect the transitional mode of a sand with fines, although the fines plasticity could influence the degree of this transitional behavior. Ponzoni et al. (2014) proposed two parameters to quantify the degree of non-uniqueness of the NCLs and CSLs. These soils exhibiting the transitional behavior have gradations between those of clean sands and plastic clays. Whether or not this transitional behavior could be extended to other larger-sized granular soils has not previously been studied.

The main objective of the current study was therefore to investigate the transitional behavior of a well-graded coarse granular soil (CGS) through a series of drained triaxial tests, investigating in particular the CSL pattern and in addition quantifying the degree of the transitional behavior through the parameter P defined by Ponzoni et al. (2014). The possible reasons for this transitional behavior are also discussed.

Triaxial compression tests

Triaxial compression tests were conducted on a well-graded CGS from the western region of China. The CGS is widely used in rockfill-dams, railways and pavement engineering in China. The main mineralogy of the CGS is sandstone. Fig. 1 shows the grain size distribution (GSD) with a maximum size of 60 mm. The grain shape of the CGS is characterized by the percentage of the flat, elongated and flat-elongated particles according to ASTM (2010), which was found to be 9.5%. The uniformity and curvature coefficients are calculated as 5.53 and 1.31. Consequently, the CGS with a fines content of 1.8% is categorized as a well-graded gravel. Fig. 1 shows that the grading deviates greatly from those of the typical silty soils (Nocilla et al. 2006; Ponzoni et al. 2014) which exhibited transitional behavior.

The tests were conducted through a large-size conventional triaxial apparatus. The height and cylinder diameter of the specimen were 600 mm and 300 mm, respectively. The values of the initial specific volume v_0 used in the tests were mainly divided into four groups, i.e., 1.187~1.193, 1.242~1.245, 1.283~1.286 and 1.315~1.319. The required initial dry densities ρ_d could be obtained from $\rho_d = G_s \rho_w / v_0$, where $\rho_w = 1\times10^3$ kg/m^3, and the specific gravity G_s of the CGS is 2.69, giving average values of ρ_d for the four groups of 2.26, 2.16, 2.10 and 2.04 kg/m^3. The required amount of material determined for the desired density was divided into five parts for compaction, each layer being compacted using an automatic vibrator with a 70 Hz frequency, but using different compaction times to obtain different initial specific volumes. The specimens were saturated, obtaining B-values over 0.96. A wide range of confining pressures (0.2~1.6 MPa) was used for each group, and after applying the confining pressure the specimens were sheared under drained conditions with an axial-displacement rate of 1 mm / min. The volume change of the specimens was measured from the volume of the expelled water. The tests were ceased at an axial strain of 15%, which was the maximum in this large-size apparatus, at which the samples showed a slight-bulging failure mode without any obvious shear bands.

Extension of stress-dilatancy curves

The critical state line (CSL) in the $q \sim p'$ plane was found to be unique (as shown in Fig. 2), with a critical state stress ratio M_{cs} equal to 1.64. It was observed in Fig. 3 that the stress ratio η $(=q/p')$ and dilatancy d $(=-\mathrm{d}\varepsilon_{\mathrm{v}}/\mathrm{d}\varepsilon_{\mathrm{s}})$ at the end of test states (i.e., Point A) were very close to the critical state (i.e., the zero-dilatancy line d =0). But a small extrapolation to the critical state as suggested by Carrera et al. (2011) was necessary. And Point B in Fig. 3 gives the critical state stress ratio of 1.64.

Critical state line

The CSLs of the CGS in the $v \sim \log p'$ plane are shown in Fig. 4. During shearing, the specific volume of the CGS decreased a little then increased for smaller confining pressures (e.g., p_0=0.2 MPa) while it decreased monotonically under larger pressures (e.g., p_0=1.6 MPa). The comparison of the curves in Fig. 4 shows that the critical state points (CSPs) of the CGS at the same confining pressure varied significantly with the initial specific volume. These differences are too large to be explained by any inaccuracy in the small extrapolations to critical states.

Groups of drained tests at the same confining pressure p_0 have been selected in Fig.5. If a unique CSL existed in the $v \sim \ln p'$ plane, drained tests at the same p_0 but different v_0 should converge to a unique v at the critical state. However, Fig. 5 shows that although there are some reductions in the differences of specific volumes, the test paths tend to become parallel at the critical state for each group of tests, indicating that the CSL of the CGS was dependent on the initial specific volume. In Fig.5 small extrapolations are made from the end of test states to constant volumes, but it is clear that incomplete testing could not be responsible for the lack of convergence.

For non-plastic soils, e.g., the Toyoura sand (Verdugo and Ishihara 1996) or Stava silty tailings (Carrera et al. 2011), the CSL in the $v \sim \log p'$ plane is generally found to be nonlinear. The test data in Fig. 6 also show a somewhat nonlinear trend especially at lower specific volumes. Li and Wang (1998) proposed a nonlinear CSL for these granular soils, which could be expressed as

$$v = \Gamma_{\mathrm{s}} - \lambda_{\mathrm{s}} \left(p'/p_{\mathrm{a}} \right)^{0.7} \tag{1}$$

where Γ_{s} and λ_{s} are fitting parameters (Li et al. 1999). The material constants Γ_{s} and λ_{s} (as shown in Fig. 7) can be directly determined from the linear fitting of the test data on v versus $\left(p'/p_{\mathrm{a}} \right)^{0.7}$ (Li et al. 1999). The value of λ_{s} is 0.011 for the CGS.

The nonlinear CSLs of the CGS move downwards with a decrease in the initial specific volume. Therefore, the intercept of these CSLs is dependent on the initial specific volume. These CSLs remain parallel, indicating that the CGS has a transitional behavior as has previously been observed in soils with smaller particles (Ferreira and Bica 2006; Nocilla et al. 2006; Altuhafi et al. 2010; Altuhafi and Coop 2011; Ponzoni et al. 2014; Shipton and Coop 2015).

Quantification of transitional behavior

Ponzoni et al. (2014) defined a parameter P to quantify the degree of the CSL non-convergence and to quantify transitional behaviors, which is the gradient of the relationship between the linear CSL intercept and v_0. And the definition will be extended for the nonlinear CSLs. The parameter P has a limiting value of 1 for perfectly transitional behavior in which CSLs have the same offsets of specific volume as the initial values, while P =0 when there is a unique CSL no matter what the initial specific volume is (Ponzoni et al.

2014). To obtain the P value of the CGS, a separate value of Γ_s was calculated for every test by projecting back its critical state in the $v \sim \log p'$ plane using λ_s of 0.011. The relationship between Γ_s and v_0 for every sample (as shown in Fig. 8) can be described as

$$\Gamma_s = \Gamma_{0s} + P v_0 \tag{10}$$

where Γ_{0s} is the intercept of the line. The values of Γ_{0s} and P are 0.60 and 0.59, respectively.

The P of 0.59 for the CGS is close to the P of 0.58 for the clayey silt sediments from Lido in the Venice Lagoon with a clay fraction of 10-20% (Ponzoni et al. 2014), which illustrates that a transitional behavior can exist not only in well-graded silty soils but also in well-graded coarse granular soils. Consequently, the transitional mode of behavior may be more common than previously realized.

Discussion

Ponzoni et al. (2014) pointed out that differences in specific volume at similar stress states can only be supported by differences in the soil fabric. However, different sample preparations have not been found to lead to any significant difference in the transitional behavior of soils (Nocilla et al. 2006; Shipton and Coop 2012, 2015). Shipton and Coop (2015) also showed that the transitional behavior of the clayey sand was not linked to anisotropy. A true critical state should be defined where a unique fabric and specific volume are reached. Nevertheless, transitional behavior (i.e., the family of parallel CSLs) can be very robust and not easily broken down by simple stress paths like triaxial compression (Ferreira and Bica 2006; Shipton and Coop 2015).

Unlike previously observed transitional soils with significant fines (Martins et al. 2001; Ferreira and Bica 2006; Nocilla et al. 2006; Altuhafi et al. 2010; Shipton and Coop 2012; Ponzoni et al. 2014; Shipton and Coop 2015), the CGS possesses a very small fines content (1.8% by weight) and a large amount of large-sized grains (95% larger than 1 mm in Fig. 1). Thus, the CGS does not have a grading between that of clean sand and plastic clay, which is the usual range for transitional soils. Nevertheless, it did exhibit the transitional mode of behavior. The grain shapes of the CGS were angular (or subangular) for grain sizes smaller than 10 mm, while the grain shape were rounded (or subrounded) for grain sizes larger than 10 mm. The smaller-sized angular grains could provide a cushion for the larger-sized rounded grains, and the soil fabric responsible for the transitional behavior may be related to this relationship between the different grain sizes and grain shapes. While no distinct fabric could be observed, the effect could hardly be destroyed under shearing even though the confining pressure was up to 1.6 MPa (as shown in Fig. 5). It seems that the angular (or subangular) grains ranging from 0 to 10 mm (18%) in the well-graded CGS played a similar role to that of plastic or non-plastic fines in other transitional soils (Nocilla et al. 2006; Ventouras and Coop 2009; Ponzoni et al. 2014; Shipton and Coop 2015). In other words, a well-graded CGS can also exhibit transitional behavior. However, further research is necessary to explain how the transitional behavior of the CGS relates to its fabric.

The current study identified that the CSL of the well-graded CGS in the $v \sim \log p'$ plane was dependent on the initial specific volume, indicating the correct ultimate volume changes could not be predicted assuming a unique CSL. The parallel non-unique CSLs should be used for the precise determination of the ultimate deformation of the earth structures using these materials.

Conclusions

A series of drained triaxial compression tests were conducted to investigate the critical state behavior of the well-graded CGS. It was observed from the tests that the CSLs in the $v \sim \log p'$ plane were not unique but dependent on the initial specific volume. A decrease in the initial specific volume led to a downward movement of the CSL. The parameter P for evaluating the degree of transitional behavior was quantified as 0.59, indicating that the well-graded CGS exhibited a clear transitional behavior. This shows that the transitional mode could exist not only in soils with the gradings between those of clean sands and plastic clays but also in large-sized granular soils beyond the boundary of clean sands.

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Notation

The following symbols are used in this paper:

G_s =Specific gravity;

ρ_d =Dry density;

p' = Mean effective stress (kPa);

p_0 =Initial confining pressure (kPa);

p_a =Atmospheric pressure (kPa);

q =Deviatoric stress (kPa);

η =Stress ratio;

ε_a =Axial strain (%);

ε_v =Volumetric strain (%);

v =Specific volume;

v_0 =Initial specific volume;

Γ_s =Intercept of the nonlinear CSL;

λ_s =Slope of the nonlinear CSL;

P =Degree of the CSL convergence in the depiction of transitional behavior.

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Figure Caption List:

Fig. 1. Initial gradations of silts and coarse granular soil

Fig. 2. CSL of CGS in $q \sim p'$ plane

Fig. 3. Extension of stress ratio-dilatancy curve

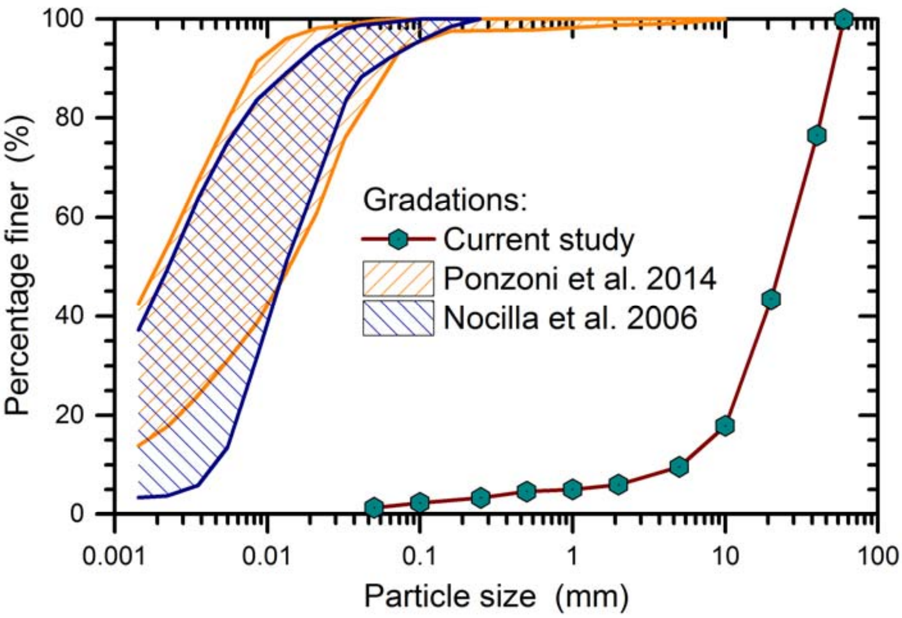
Fig. 4. Variations of specific volumes at different initial densities and pressures: (a) v_0=1.187~1.193; (b) v_0=1.242~1.245; (c) v_0=1.283~1.286; (d) v_0=1.315~1.319

Fig. 5. Variations of specific volumes with axial strain: (a) p_0=0.2 MPa; (b) p_0=0.4 MPa; (c) p_0=0.8 MPa; (d) p_0=1.6 MPa

Fig. 6. Nonlinear CSLs of CGS in $v \sim \log p'$ plane

Fig. 7. Determinations of material constants for CSL in $e \sim \left(p'/p_{\mathrm{a}}\right)^{0.7}$ plane

Fig. 8. Quantification of transitional behavior for CGS with nonlinear CSLs



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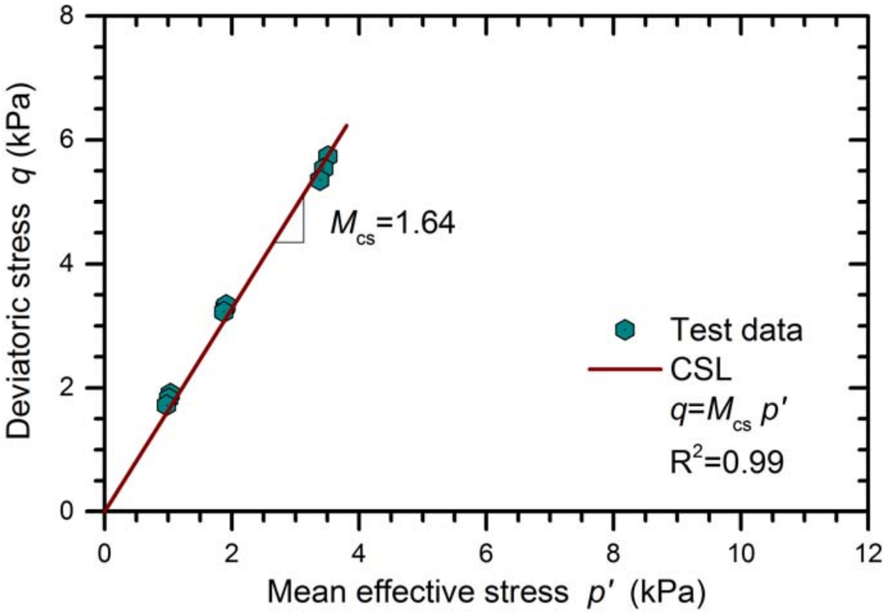

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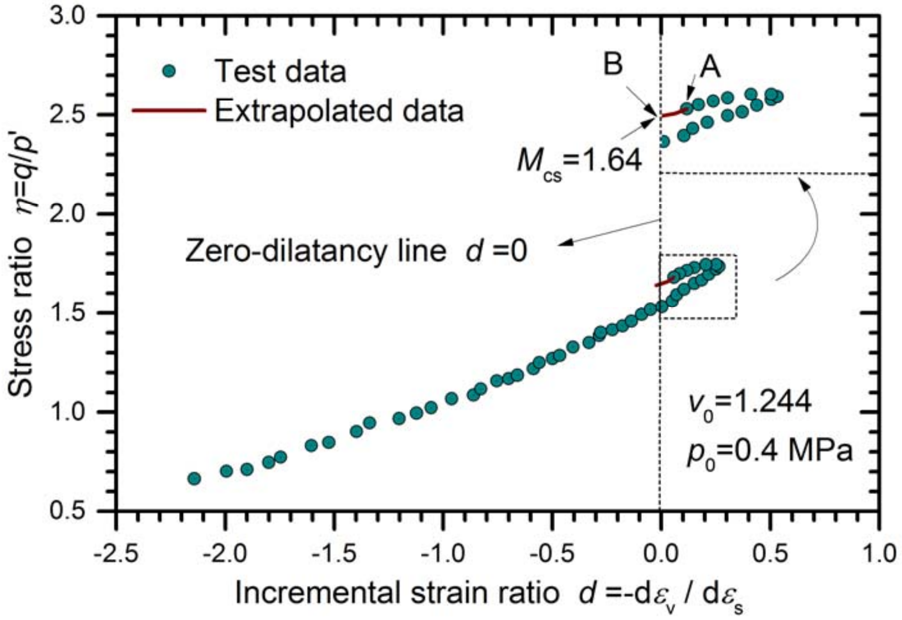

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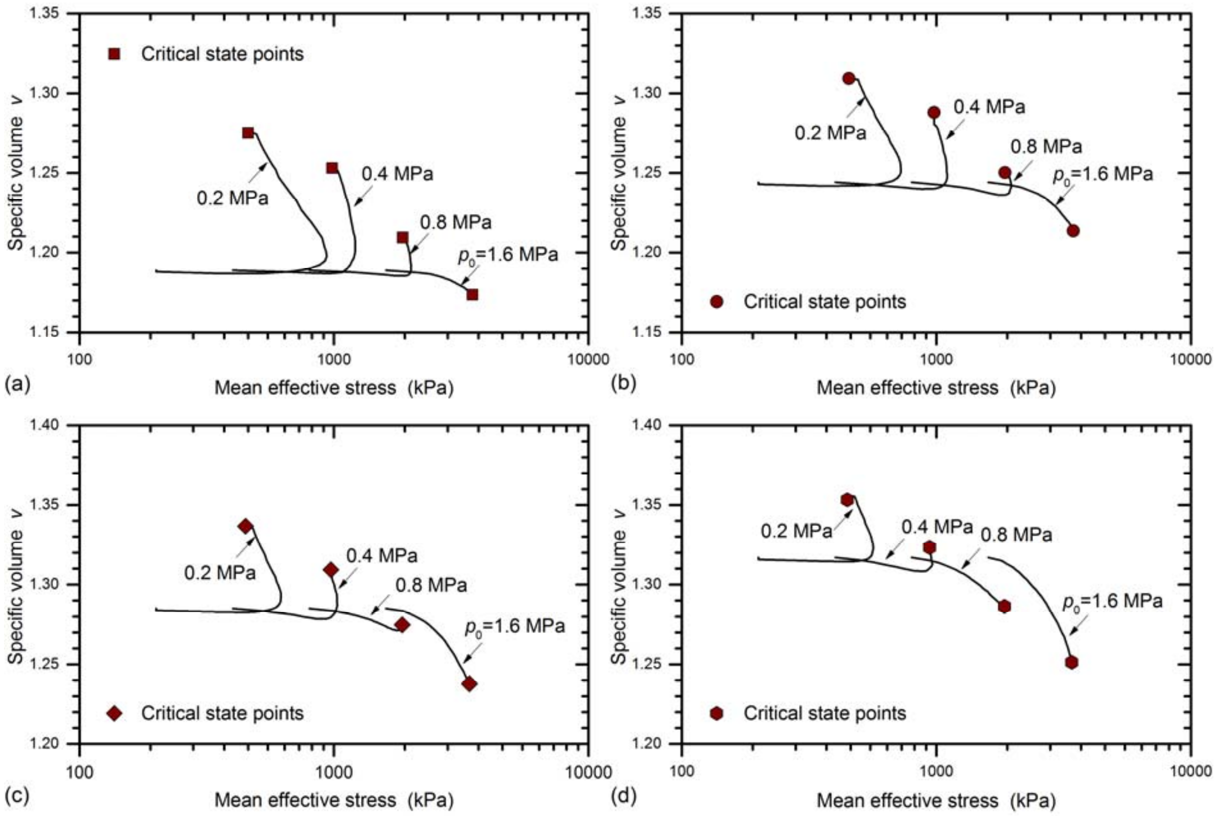

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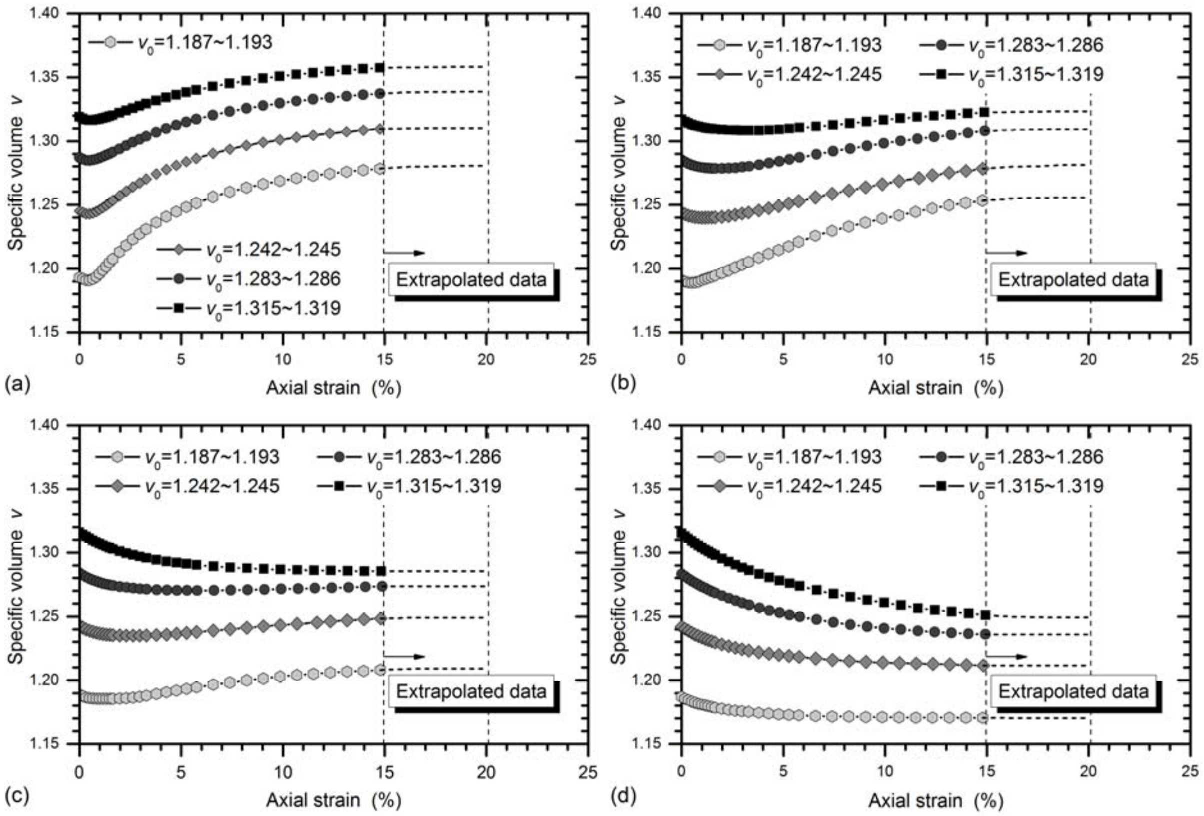

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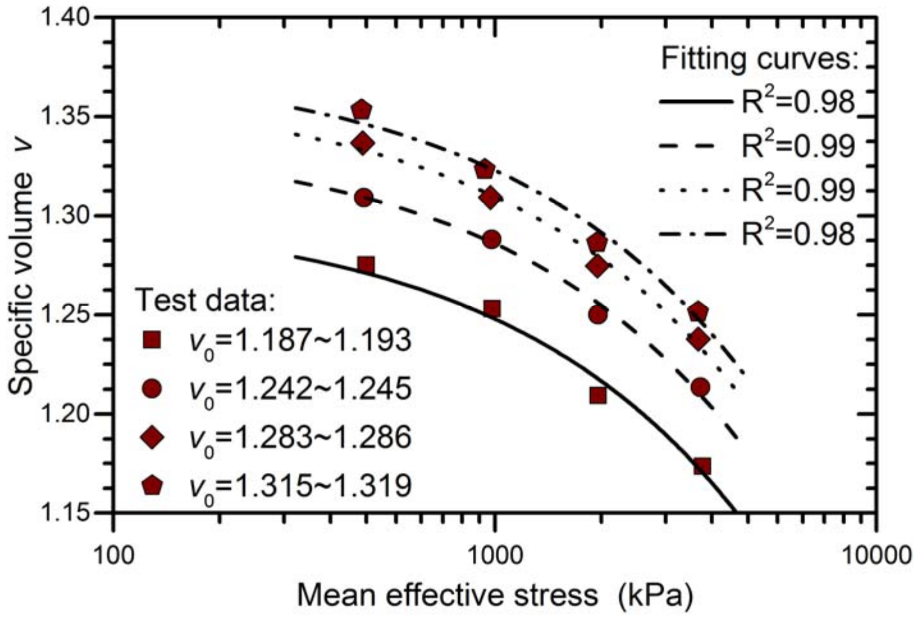

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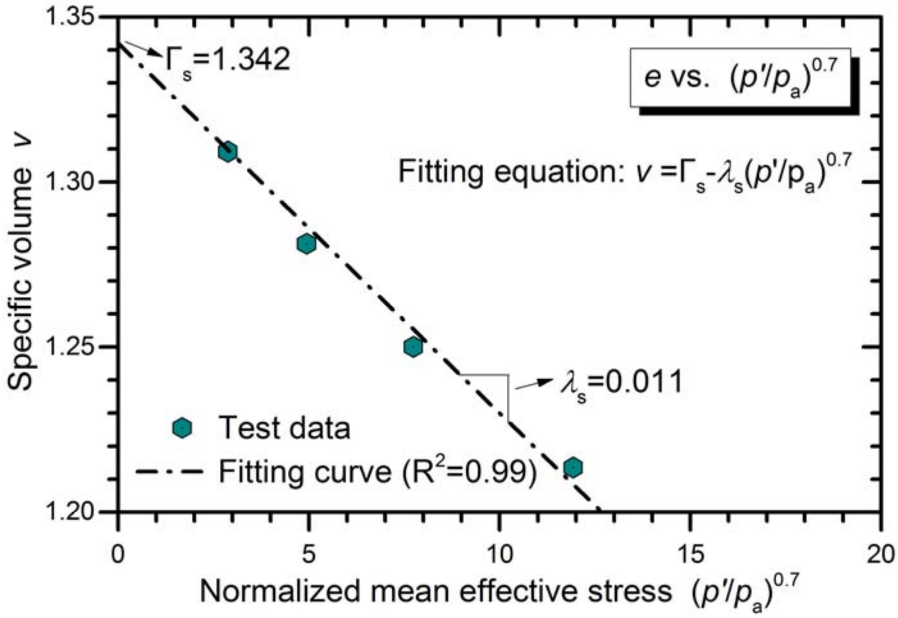
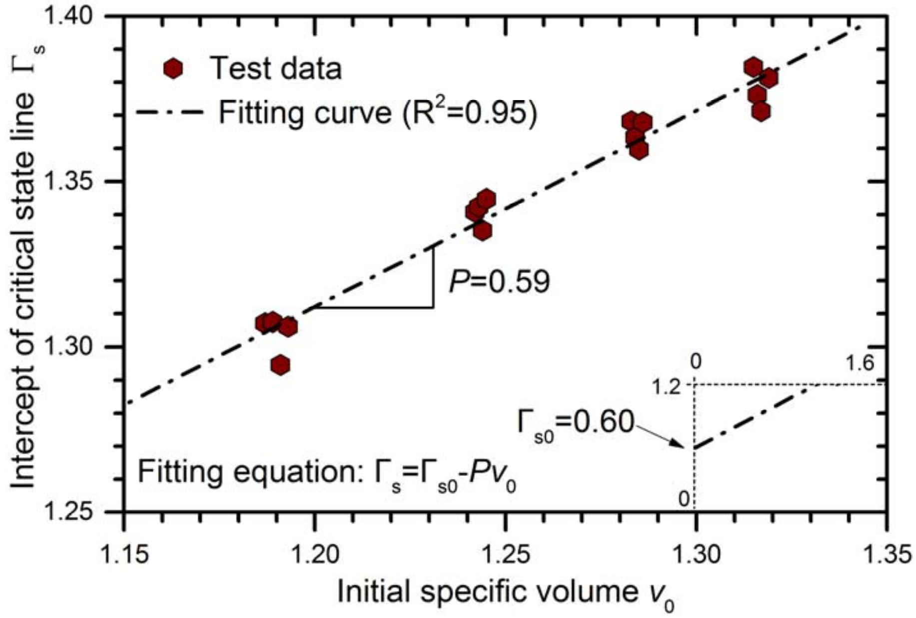


Fig. 7. Determinations of material constants for CSL in $e \sim (p'/p_a)^{0.7}$ plane



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