Strain Softening response of loose unsaturated tailings samples in undrained triaxial tests

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Abstract. For a soil that is contractive and strain softening at fully saturated conditions the question remains on which degree of saturation can trigger a strain softening response. A common engineering practice is to adopt a saturation threshold (e.g., 85%) and then assume a fully saturated response when saturation is above that value. This study aims to understand how the strain softening response change when tailings are not fully saturated and to propose a systematic method for determining the saturation threshold. A restraint when preparing unsaturated loose samples is that it is likely to have collapse during flashing, thus changing void ratio and making comparisons between different degrees of saturation problematic. A simple procedure to obtain loose samples at different degrees of saturation but at similar post-flushing void ratios is explained and preliminary results of undrained shear strength obtained for gold tailings in triaxial device are presented and discussed.

1 Introduction

Tailings storage facilities (TSFs) failures have caused almost 3,000 deaths in the last century, with 486 of those in the last decade while also causing environmental damage [1]. This unfortunate record shows the importance of research in the tailings field.

The phreatic level inside a TSF indicates the position where pore water pressure is greater than the atmospheric pressure (usually adopted as the zero reference). Determining its location is critical for stability analyses and is mainly influenced by deposition method, permeability of the different materials (e.g., tailings, embankments, drains, natural soil), management techniques and, the climate [2]. The behaviour of the material below the phreatic level (saturated) is often associated with an effective stresses analysis and assigned undrained strength parameters (see [3]), and the saturated area may be prone to liquefaction under some conditions [4].

A broad definition of liquefaction is presented by Jefferies and Been [5], this being a phenomenon in which soil loses much of its strength or stiffness for a generally short time but commonly long enough to have catastrophic consequences. Verdugo and Ishihara [6] also suggest that flow failure is characterized by a rapid increment of pore water pressure followed by a sudden loss of strength that achieves a residual value. Figure 1 (modified from [7]) presents different types of responses in saturated samples tested under stress controlled triaxial compression, where the test A is an example of liquefaction, and test B of limited liquefaction.

Although the liquefaction concept has generally been developed and investigated for saturated soil and tailings, studies assessing liquefaction in partially saturated soils have also been conducted and can be helpful - particularly for TSFs adopting technologies where the water is partially removed. An early study was performed by Wheeler [8] showing that the undrained shear strength of a soil can be increased or decreased by the presence of large gas bubbles, depending on the value of the consolidation pressure and pore water pressure, being most affected by a low value of consolidation pressure and high back pressure. He et al [9] studied desaturation as a means for mitigation of liquefaction susceptibility, and tests were developed using Ottawa sand to determine the undrained strength under triaxial compression and extension on samples of relative density (Dr) between 8.7% and 31.3% desaturated by means of gas generation to a degree of saturation (S) between 87.5% and 100%. At lower S a substantial increase in the undrained shear strength was obtained, with a transition from strain softening to strain hardening, and the induced pore pressure was also limited. If the same results are considered from a conservative analysis point of view, it can be stated that strain softening, and pore pressure generation are still a concern in sand samples with S lower than 100%, especially in loose samples.

In the field of tailings, Fourie et al [10] showed for a sand tailing that the liquefaction potential under undrained loading may be reduced by the presence of occluded gas bubbles within the voids, limiting the amount of induced pore pressure. Świdziński et al [11] presents the undrained resistance of a sandy copper tailing from the Żelazny Most TSF for samples with different Skempton B value, that are in turn used to estimate the degree of saturation. To reach those B

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values the samples were prepared by moist tamping and then saturated by different means. The studies conducted by Bella ([12] and [13]) present the results of the silt fraction passing through a 74 μm sieve of Stava fluorite tailings, where samples above 90% of *S* showed liquefaction, and the sample with *S*=88.9% did not liquefy, according to the researcher criteria (although that test looks like Type B in Figure 1). That sample also had a void ratio 0.12 higher than the average of the rest of the samples. It is possible that the void ratio reached in that sample (TXT_5 in [13]) was due to a limited collapse in the saturation stage – thus preventing the study from isolating the effects of *S*. Indeed, the plastic collapse induced by wetting phenomenon in loose samples, largely reported in the literature (e.g. [14]), creates a problem for this kind of test programs, as the different degrees of saturation will produce a range of different void ratios that will make comparisons difficult.

The references quoted above are mostly for sands. Fewer research was found for silts or sandy silts, but one example is the study developed by Maleki and Bayat [15], where dry sand, silt and kaolinite were mixed to produce the material that was then tested under constant water content condition, under different matric suctions, void ratios, and net confining pressures, finding that shear strength increases because of increasing matric suction, observing strain softening in some cases.

In this study, a test program was conducted to obtain the undrained response of loose unsaturated sandy silts gold tailings for samples prepared with a methodology that aims to produce void ratios that are as similar as possible to facilitate direct comparisons. The results are discussed in relation to determine a saturation threshold that could be considered to define an equivalent saturated behaviour, or a liquefaction prone response when *S* is above that value.

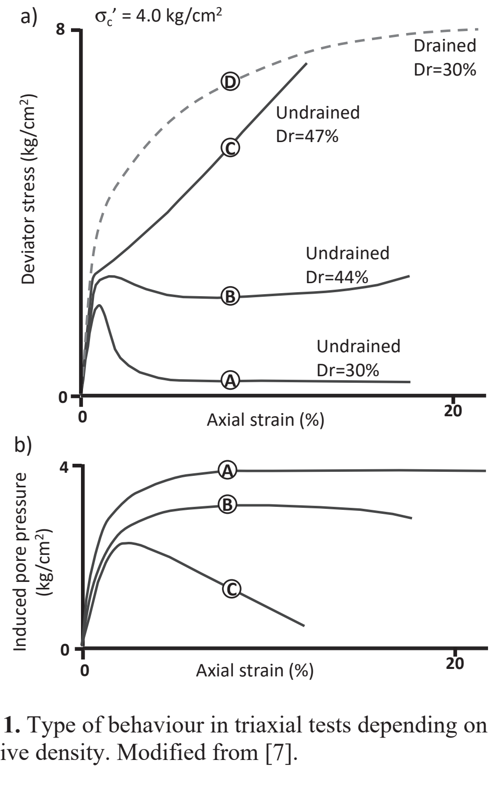

Fig. 1. Type of behaviour in triaxial tests depending on relative density. Modified from [7].

2 Materials and Methods

2.1 Materials

The material used in this study consists of sandy silt gold tailings obtained from the surface of an active TSF. Tests for these tailings, although from other batches, have been performed for previous studies, including a round robin to determine the critical state line [16], calibration chamber tests [17] and a comparison between the behaviour in torsional shear hollow cylinder device (TSHC) and direct simple shear device (DSS) [18]. The properties of this material are summarized in Table 1. The material was prepared to a gravimetric water content (GWC) of about 10% and stored in plastic bags.

Table 1. Index Properties of the material.

Property	Values
Specific Gravity, G_s	2.78
Liquid limit w_l	18% [16]
Plastic limit w_p	16% [16]
Plasticity Index	2%
%<75 μm	55%
%<38 μm	39%

The test plan program included tests to determine the saturated critical state line and tests to determine the liquefaction behaviour of partially saturated samples.

2.2 Tests for Conventional triaxial tests

Conventional triaxial tests were performed with a focus on the determination of the saturated critical state line (CSL). This included the testing of 5 loose samples, three under drained condition and 2 under undrained condition, in a range of confining pressures between 50 and 500 kPa and following state of the art practices as stated by Reid et al [16] and da Fonseca et al [19].

2.3 Pre-collapsed samples methodology

As indicated above, the aim of the procedure is to achieve samples that have a similar void ratio and a density as low as possible, while avoiding a divergence in the void ratio obtained post-saturation. A second issue considered in the methodology is that, when samples are saturated, they are prone to undergo densification, even when only lightly disturbed, as there is no apparent cohesion to give strength to the sample. To prevent this, samples should be isolated during the process of saturation and drying. The methodology adopted to prevent both issues is presented here, and illustrated in Figure 2:

1. Preparation of sample by moist tamping in an acrylic tube. A GWC of 10% and a target preparation void ratio of 1.10 were adopted. The

dimensions of the samples prepared were 66 mm of diameter and 132 mm high. Filter papers were added at the bottom and top of the samples, and a geotextile was attached to the bottom with the aid of a rubber band, to enable drainage during subsequent stages.

2. Samples in the acrylic tube were placed in a bucket, and a vertical load of 5 kPa was applied on top of the samples. The bucket had a porous stone on its base to enable drainage.
3. The bucket with the sample inside was placed in a cool oven (~50 degree C), where the bucket was filled with distilled water to a level higher than the top of the sample, but lower than the acrylic tube, to allow upward flow.
4. The water in the bucket was left overnight and then removed through syphoning.
5. Once the sample was dry enough, it was extruded from the acrylic tube. Three criteria were used to decide whether the sample was ready to extrude: (1) colour of sample, (2), humidity of geotextile attached at the bottom, and (3), mass of the acrylic tube/sample/geotextile system to calculate the GWC (the extrusion failed if the sample was too wet or too dry).

The whole process from preparation to extrusion took 5 days, and after the extrusion, the sample was measured, weighted, covered with cling wrap and taken to the triaxial device. If the top surface of the sample was uneven, it was trimmed to achieve a level surface before measuring.

A process of re-saturation of the samples was undertaken when the sample was placed in the triaxial cell. A total of 5 samples were prepared and on 4 samples ICU tests were performed in the triaxial device. For the re-saturation stage, three of the samples were again flushed using the back pressure pump of the triaxial setup, until 30 cm^3 of overflow water was collected. Then these samples were subjected to 100, 300 and 1000 kPa back pressure to achieve different *S*. For the sample subjected to 300 kPa back pressure, the consolidation stage was combined with the increase of back pressure to impose a different path of saturation. Two samples were not re-flushed, but only subjected to back pressures of 100 and 300 kPa and then consolidated to 200 kPa of radial minus back pressure. To have an additional comparison, another sample was prepared using conventional methods, but with the flushing of the sample being performed after the consolidation stage.

Cell calibration was employed during the triaxial tests to track the change of volume of the samples during the test, meaning that deaired water was employed in the whole system, and bubbles from the cell were removed before the triaxial testing. Also, end of test freezing was performed for every sample to have an accurate measure of GWC and mass of solids. With this information (volume of water at the end of test, volume of solids and total volume of sample), the void ratio can be estimated throughout the test, while the degree of saturation can be estimated through the shearing stage. A maximum void ratio difference of 0.02 was obtained when comparing the void ratio estimated using cell calibration and the one calculated with the *GWC*Gs* relation for saturated samples, which was deemed acceptable for this study. The Skempton B value was calculated both after the saturation stage, and/or after the consolidation stage (noting that the *S* is known at this point).

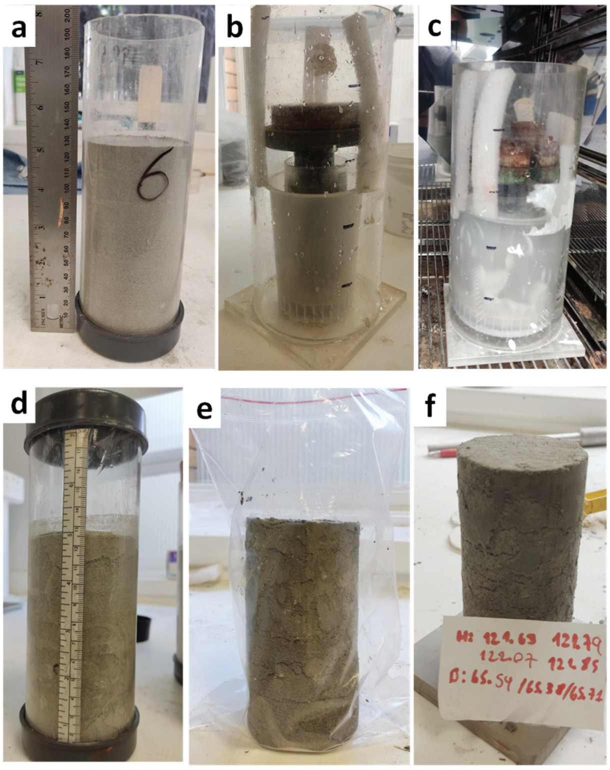

Fig. 2. Methodology to prepare pre-collapsed samples. (a) moist tamping in acrylic tube, (b) setup to saturate sample, (c) sample flushed inside 50°C oven, (d) sample after drying, (e) extruded sample and, (f) measurements before triaxial test.

3 Results

The determination of the critical state line (CSL), presented in Figure 3, was developed to have the saturated behaviour as a reference framework for this material. In fact, the unsaturated test program will be compared to the CIU 200 sample. As expected, the CSL obtained lies near the CSL obtained in [16], being a material from the same TSF.

The results of the unsaturated plan tests are presented in Figure 4. From plots (a) and (b), it is noted that there is a notable increase in the shear resistance with the decrease of *S* for both peak and residual strengths (for example, the level of shear resistance obtained for the sample with *S* is close to the CIU 500 conventional sample, although at different strains). It can also be seen that the axial strain that mobilizes the peak shear strength is bigger as *S* decreases. Plot (c) presents the evolution of pore pressure during the shearing stage, where at higher *S*, the development of pore pressure is faster (i.e., at lower axial strains) and closer to the confining pressure. Finally, plot (d) shows the starting *S* (or at end of consolidation), and its evolution during the shearing stage. For the partially saturated tests, there is a marked increase in *S* at the beginning of the shearing stage, followed by a steadier phase, which is related to the void ratio evolution during the test.

The reason for preparing an additional sample was that it was observed that the void ratios obtained with this saturation and drying methodology were consistently higher than the void ratio obtained in the conventional saturated tests, resulting also in some partially saturated samples having a residual shear strength greater than the CIU 200 conventional sample. Then, to evaluate if a completely saturated sample, with a different saturation history could achieve a higher void ratio, the additional sample was prepared using a conventional moist tamping methodology, but it was flushed after the consolidation stage, meaning that it was consolidated in a partially saturated state. This test indeed presented a void ratio higher than the other saturated samples (Figure 5), and a lower peak and residual shear strength as well (Figure 4)

An unexpected observation was that, although all the samples were prepared at the same target void ratio of 1.10, the void ratio after consolidation obtained in every case was higher than the one obtained in a conventional saturated procedure, including the saturated samples. This could be showing a saturation-history dependence of the saturated void ratio (or zero-suction ICL). This phenomenon has not been found to be described in previous literature and is not included in consulted constitutive models (e.g., [20,21]) and must be further explored.

In relation to the development of liquefaction in the unsaturated samples, the definitions presented for this term at the introduction of this article indicated that it is a loss in shear strength that is rapid. All the tests performed were strain softening, although at different degrees, having the shape of the 'Test A' presented by Casagrande, or 'Test B', for the sample starting at *S*=64%. A pore pressure excess ratio (r_u) greater than 80% is achieved at less than 5% of axial strain for the samples with *S* of 92% or greater (Figure 6.a). For the sample starting at *S*=79% a r_u of 80% is also reached, but at around 25% of axial strain, i.e., there is still a loss of shear strength but cannot be considered a rapid failure. The sample starting at *S*=64% reaches a r_u slightly above 50% at near of 20% of axial strain.

Although common in cyclic analysis (e.g., [22]), setting a threshold of r_u (horizontal lines included in Figure 6.a) can be a useful tool to decide if liquefaction was attained in saturated or partially saturated samples. Where this threshold will be placed can depend on the risk of the project. An 80% r_u threshold for the tests performed would mean considering elements of this particular tailings with a $S \geq 79\%$ as liquefiable in an stability analysis. A second useful analysis is to evaluate the brittleness, which quantifies the amount of strain softening developed in the test. Figure 6.b shows that the samples with $S \geq 79\%$ have a higher brittleness than the CIU 200 sample (conventional), indicating that elements of soils with those level of saturation should be included as liquefaction prone areas in stability analysis.

Table 2. Triaxial compression test performed

Test ID	Method	e_0
CIU 200	Conventional MT for CSL	1.18
CIU 500	Conventional MT for CSL	1.18
CID 50	Conventional MT for CSL	1.17
CID 200	Conventional MT for CSL	1.11
CID 400	Conventional MT for CSL	1.15
Reflushed+BP100	MT Pre-collapsed. CIU	1.10
Reflushed+BP300	MT Pre-collapsed. CIU	1.10
No-reflushed+BP100	MT Pre-collapsed. CIU	1.10
No-reflushed+BP300	MT Pre-collapsed. CIU	1.10
Reflushed+BP1000	MT Pre-collapsed. CIU	1.10
Flushed after consolidation	Conventional MT flushed after consolidation. CIU	1.03

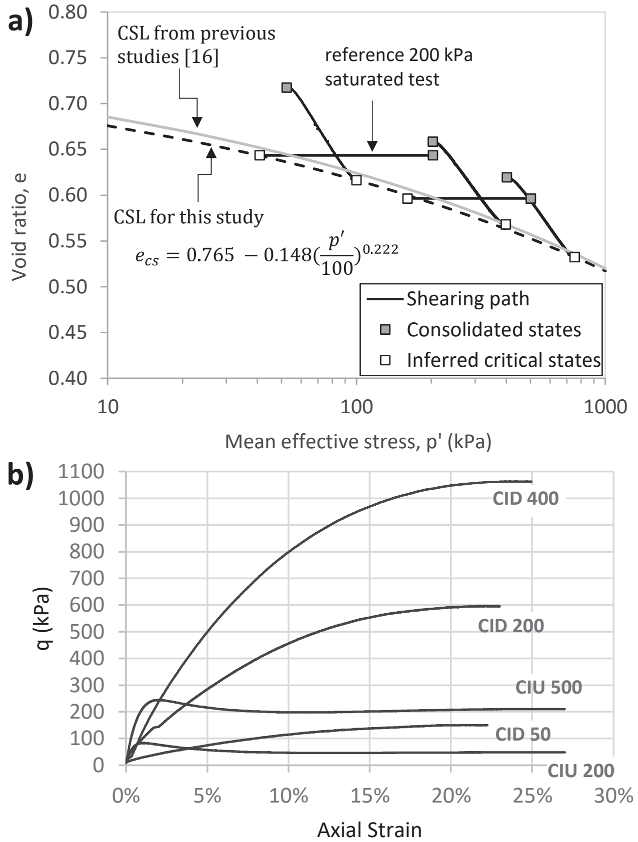

Fig. 3. Results of saturated conventional triaxial program. (a) Critical State Line (CSL), (b) q vs axial strain.

4 Conclusions

A methodology was proposed in this study to prepare already flush-collapsed loose samples aiming to have samples with different *S* but similar high void ratios. The only especial requirement for this method is cell calibration, but suction is not controlled nor measured. The prepared samples had similar void ratios after collapse and extrusion, but the void ratio after the second flushing continued to vary, meaning that the method can still be improved to achieve a more complete collapse.

The results of this study can have two applications. The first one is related to the decision of where to define zones prone to liquefaction in a stability analysis profile, depending on its *S*, or where to draw the phreatic surface having in mind a conservative approach. In that respect, the results suggests that for this material, and for the void ratio selected, from 80% of degree of saturation an element of tailings has a "Test A" type of behaviour, reaching a r_u of 80% under undrained conditions and a brittleness assimilable to a conventional saturated test. The second application is related to the increase of strength that can be obtained upon desaturation of tailings to increase the safety of the TSF. The results obtained show that, as expected, there is an increasing gain in peak and residual strength with desaturation, despite the occurrence of potential liquefaction. However, the results also showed that the triaxial test prepared with a conventional procedure reaches a lower void ratio than the saturated samples prepared with the suggested method, which leaves an open question regarding the saturation-history effect on the final saturated void ratio.

More tests will be needed to understand the change in the liquefaction behaviour under undrained conditions for different tailings, different densities, confining pressures and stress paths, and define liquefaction/saturated behaviour thresholds.

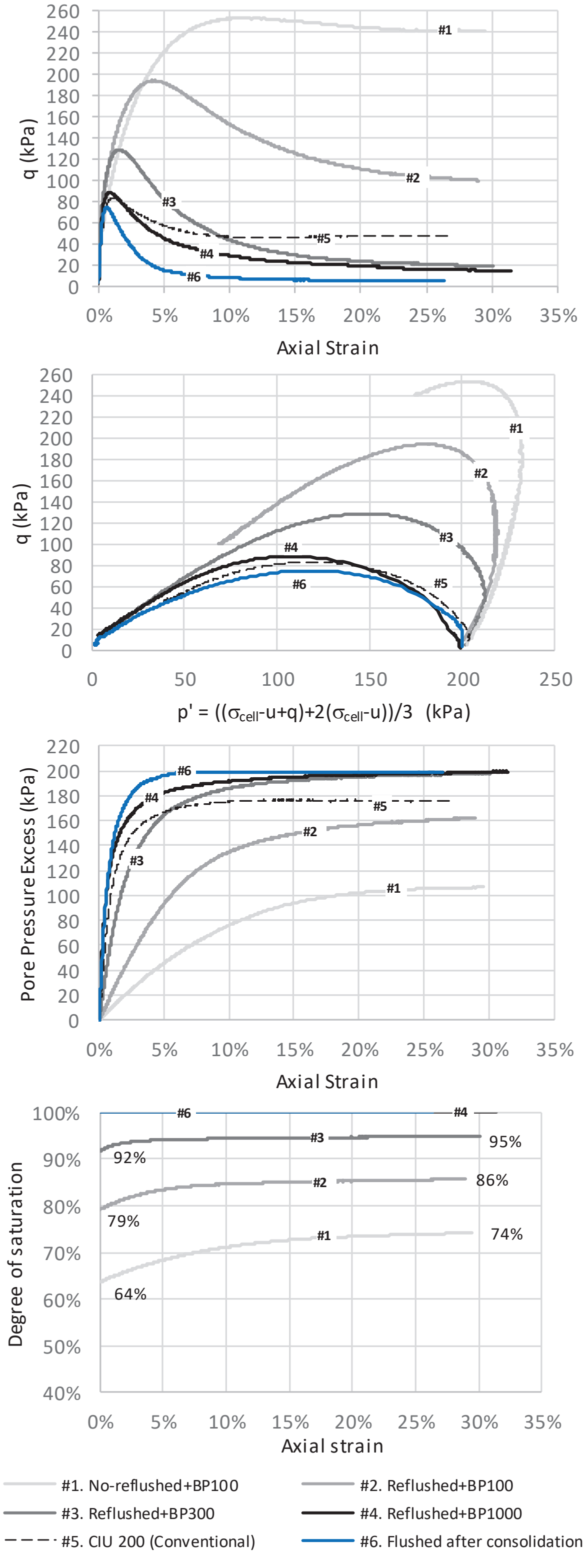

Fig. 4. Results of unsaturated triaxial program. (a) shear strength vs axial strain, (b) q vs p' (suction not considered in the definition), (c) pore pressure excess, (d) evolution of *S*.

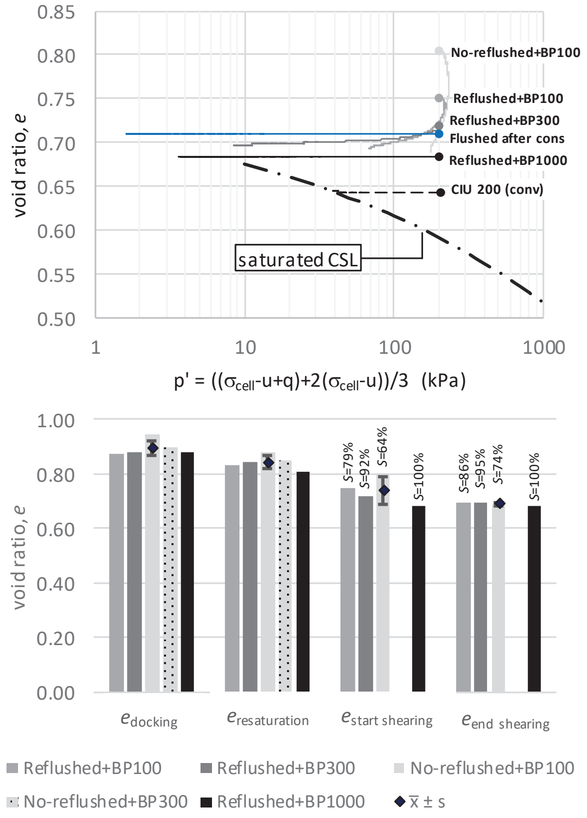

Fig. 5. Evolution of void ratio in (a) shearing stage in e-log(p') space, (b) through the whole test.

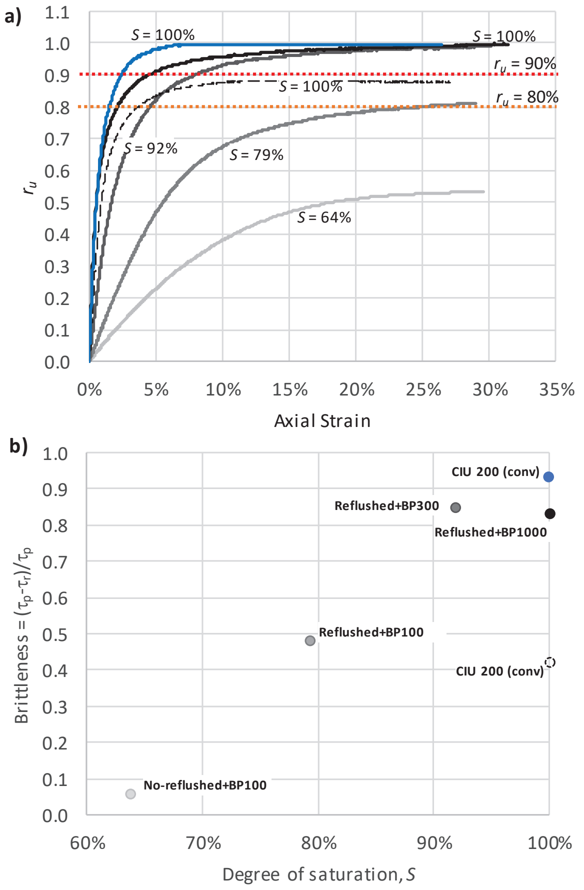

Fig. 6. (a) r_u and (b) brittleness as indicators of liquefaction/strain softening behaviour.

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