Void ratio tracking during triaxial testing

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ABSTRACT: Critical state theory provides a fundamental framework for characterising soil behaviour, with the critical state line (CSL) serving as a reference for assessing and predicting mechanical responses. The CSL defines the ultimate strength of soils and governs deformation characteristics under drained loading (contractive vs. dilative), as well as pore pressure generation under undrained loading (undrained strength). Triaxial testing is widely used to develop critical state models, offering a reliable means to determine drained strength parameters such as the friction angle. However, accurately capturing compressibility characteristics remains challenging, as it requires precise tracking of the void ratio during the various test phases. Despite advancements in testing equipment and procedures, achieving reliable void ratio measurements during triaxial tests remains elusive. This paper critically reviews the mechanics and challenges associated with void ratio tracking in triaxial testing. It explores experimental modifications aimed at improving both forward and reverse tracking methods including optimised specimen preparation, enhanced saturation strategies, controlled squeeze phases, and post-shear specimen freezing. Key insights and recommendations, grounded in experimental evidence, are presented to improve void ratio tracking in triaxial testing, thereby enhancing the reliability of critical state modelling.

1 INTRODUCTION

Critical State Soil Mechanics (CSSM) provides a conceptual framework that describes the behaviour of soils in terms of relatively simple but fundamental soil parameters. Although criticised for lack of practical relevance, it does reasonably account for key features that affect the behaviour of soils.

Numerical methods based on CSSM are becoming the industry standard for design and analysis of complex geotechnical structures including high-risk tailings storage facilities, e.g. Eurocode 7 Geotechnical design (*mandatory*), and the International Commission on Large Dams guidelines (*recommended*).

The first step in developing a CSSM framework is to determine the critical state line (CSL). The CSL describes the ultimate strength of a soil. The CSL is expressed in terms of two stress invariants (mean normal effective stress, p', and deviator stress, q) and one density invariant (void ratio, e). As such, the CSL is a 3D geometrical feature (Figure 7) that is generally viewed in 2D projections, namely the stress plane (q vs p') and the compression plane (e vs p'). The geotechnical parameters that define the CSL are M (slope of the CSL in the stress plane), λ (slope of the CSL in the compression plane), and Γ (elevation of the CSL in the compression plane).

Triaxial testing provides a convenient means to determine critical state (CS) parameters. The simplest and most reliable parameter to obtain from triaxial testing is M that is reliant on stress measurements only. The only significant margin of uncertainty arises from estimating the changing area of the test specimen for which there are well recognised solutions. Figure 8 illustrates the consistency of obtaining M based on 17 standard drained and undrained triaxial tests. It is, however, more challenging to obtain λ and Γ due to significant uncertainties associated with tracking void ratio throughout a triaxial test. Figure 9 illustrates the wide scatter in results that is often encountered. Only 8 of the 18 tests in this figure were usable for defining the CSL. Barring strain localisation in dense drained tests, the main source of uncertainty are errors in void ratio tracking.

The remainder of this paper will focus on the issues regarding void ratio tracking in triaxial tests and how to improve on the uncertainties by modification of testing equipment and/or procedures.

2 STANDARD TRIAXIAL TEST

2.1 Tracking Void Ratio

The void ratio of a triaxial test specimen can be 'directly' measured on the initial prepared test specimen and on the specimen recovered from the cell at the end of the test. All changes in void ratio between these two reference states must be inferred from indirect measurements. These measurements are of the volume of water passing into or out of the test specimen as recorded by electronic flow pumps (modern test equipment). The changes in volume of water are assumed to be equivalent to the change in volume of voids, and ultimately the void ratio, assuming the specimen is fully saturated and the water is incompressible.

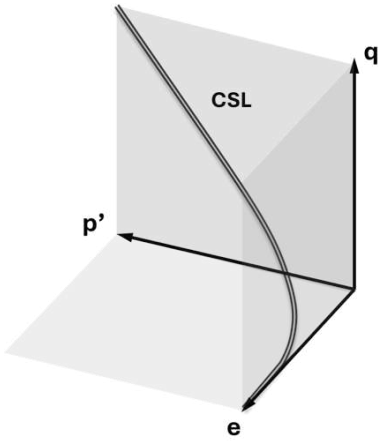

Figure 7. The CSL in invariant space

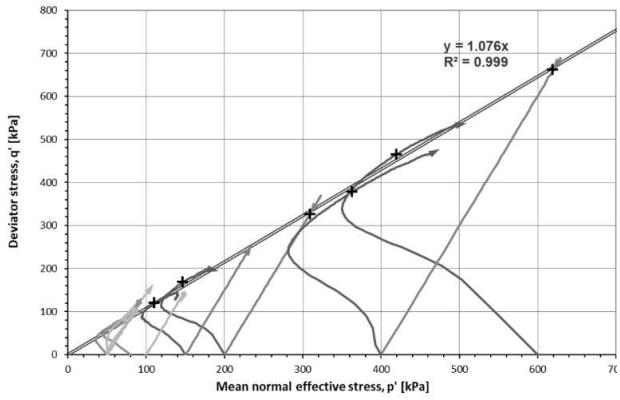

Figure 8. Mapping the CSL in the stress plane based on standard drained and undrained triaxial tests on moist tamped specimens

For CSL testing, the void ratio must be accurately known during the drained or undrained shear phase of the test. To get from the initial state to the shear phase, void ratio must be tracked through the saturation and consolidation phases, this is referred to as forward tracking (FWT). To get from the end state to the shear phase, void ratio must be tracked backwards through the unloading and teardown phases, this is referred to as reverse tracking (RVT).

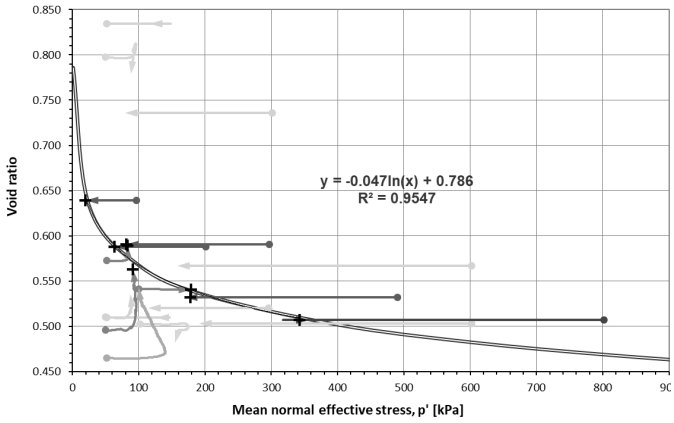

Figure 9. Mapping the CSL in the compression plane based on standard drained and undrained triaxial tests on moist tamped specimens

Each phase of a triaxial test is associated with potential sources of error in tracking void ratio:

- *Preparation* – moisture changes while the specimen is being prepared, typically drying.
- *Saturation* – volume changes that are not captured by the back pressure flow pump, mostly collapse although clayey soils may swell.
- *Consolidation* – no error provided the specimen and measuring equipment is fully saturated.
- *Shear* – cavitation is possible in highly dilative soils but can be managed by maintaining adequate back pressure.
- *Teardown* – loss of solids (dry mass) and a change in the moisture content of the sample when the membrane, porous disks and end cap are removed.

Standardised equipment and test procedures such as those by the American Society for Testing and Materials (ASTM) and the British Standards (BS1377) aim to eliminate or minimise these errors. For example, the loss of solids for a valid test should not be more than 1% to 2%. Some errors are, however, unavoidable such as those that arise during the saturation phase.

Figure 10 illustrates the conceptual changes in void ratio and pore pressure during a standard undrained triaxial test:

- *Preparation* – loss of moisture due to drying and generation/dissipation of excess pore pressure (PP) result in densification of the sample. This reduction in void ratio is irrelevant if the test specimen is weighed (assuming no loss of solids) and its dimensions measured immediately before mounting in the cell.

The specimen state based on the above measurements defines the initial void ratio of the specimen.

- *Saturation* – saturation is achieved by flushing the specimen with CO_2 and deaerated water and then applying differential increments of back pressure (BP) and cell pressure (CP) until an adequate B-value is attained. At the end of this phase the specimen is consolidated with a small differential of

mean normal effective stress and the PP equal to the BP. Most specimens will contract during the process with a resultant reduction in void ratio. Unless the specimen is fully saturated at the end of the preparation stage and connected to a flow pump, there is no reliable means of tracking void ratio during saturation. Sladen & Handford (1987a) showed that errors of up to 20% can result during this phase.

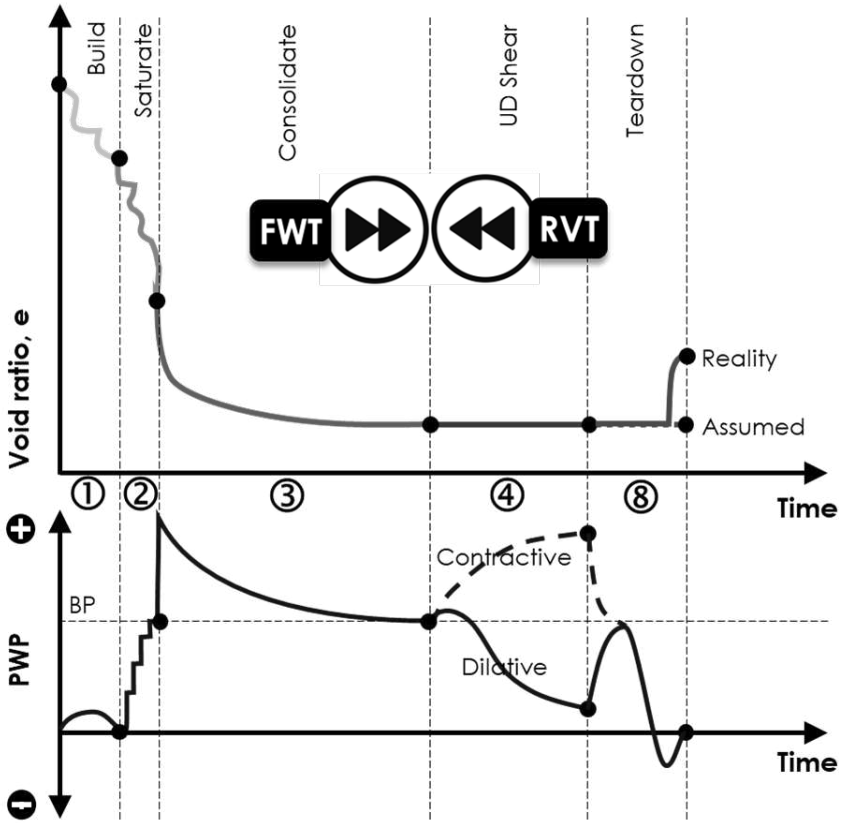

Figure 10. Changes in void ratio and pore pressure during a standard undrained triaxial test

- *Consolidation* – changes in void ratio are accurately reflected by the volume of water crossing the specimen boundary. The figure shows a positive consolidation load increment resulting in the generation and dissipation of excess PPs and a resulting reduction in void ratio.
- *Shear* – the drainage valve to the specimen is closed prior to shear and remains closed for the rest of the test. As such, the water content and void ratio of the specimen remains unchanged during undrained shear. PPs are, however, generated, positive for contractive specimens and negative for dilative specimens.
- During *Teardown*, the pore pressure in the specimen goes through a complex series of changes as the specimen is unloaded while the drainage valve remains closed. As the ram stress is removed the excess PPs are relieved so that the PP in the specimen returns to approximately the BP. Removal of the CP and BP induces a slight negative excess PP in the specimen due to the initial differential in these pressures. By this time, the cell has been disassembled with the closed drainage valve preventing water changes and thereby changes in the void ratio. The last step is to remove the membrane. At this point, the residual suction will dissipate causing the specimen to swell slightly. Drained tests conclude with a similar end state.

By following standard test procedures, FWT of void ratio invariably fails at the saturation stage. Determination of the CSL, therefore, relies on RVT with a few critical assumptions:

1. Insignificant loss of solids, less than 2% or more ideally less than 1%.
2. Full saturation of the specimen until the membrane is removed.
3. No change in the volume of water in the specimen when the drainage valve is closed. For undrained tests this applies from the end of consolidation, through shear to the moment that the membrane is removed during teardown. For drained tests, it applies from the end of shear with volume changes measured during the drained shear stage.

After teardown, the specimen is weighed (bulk mass) and oven dried to determine the mass of water and the mass of solids. The mass of solids is used to verify acceptable losses, whereas the mass of water is used to calculate the void ratio vis-à-vis at the start of

shear. This is only possible within the constraints of the above assumptions. In other words, it assumes that the volume of water (from the mass of water) in the final specimen after teardown is the same as the volume of water in the specimen before shear and that the volume of water equals the volume of voids (saturation). The void ratio during shear can then be calculated from the volume of voids and the mass and specific gravity of the solids.

The accuracy of this procedure is not affected by possible desaturation of the specimen when the membrane is removed as long as the water is held or drawn into the specimen and not expelled. The authors investigated this on silty soils by requesting the laboratory to conduct wax density tests on the final specimens. The results confirmed that the specimens were either near saturation or unsaturated with S_r ranging from 93% to 100% over twenty drained and undrained tests.

Unfortunately, RVT can also fail as evidenced in Figure 9. This typically happens during teardown when:

- the final specimen expels water instead of holding or drawing the water into the specimen;
- excessive loss of solids; and/or
- excess water is drawn into the specimen from low air entry porous stones.

The issue with the porous stones can be resolved by using high air entry stones that are embedded in the pedestal and top cap without extending to the edges, Da Fonseca et al. 2021.

In an ideal world, FWT and RVT should result in a perfect match at the start of the shear phase. This almost never happens. FWT is the least dependable and RVT is used almost exclusively with its own shortcomings. The sections that follow review improvements to both FWT and RVT based on published research and the practical experiences of the authors.

3 FORWARD TRACKING IMPROVEMENTS

The Achilles heel of FWT is collapse volume changes during saturation. These changes cannot be measured reliably via the BP flow pump if the specimen is not fully saturated after preparation.

FWT can be improved by (i) preparing test specimens that are saturated, (ii) by indirect volume change estimates, or (iii) by re-measuring the specimen volume post saturation.

3.1 Specimen Preparation

To improve FWT, the triaxial test specimen must be prepared as close as practicable to fully saturated. In this way any volume changes that occur during the saturation process can be measured via the BP flow pump.

Reconstituted test specimens are generally prepared by compaction (tamping), pluviation (dry or under water), and sedimentation (slurry consolidation) methods. Moist tamping is by far the most popular for CSL testing due to ease, speed, and reliability. It is also the method that leads to the largest 'collapse' volume changes during saturation. Slurry sedimentation provides a better solution for FWT for fine grained soils.

3.1.1 *Moist Tamping*

Very loose and contractive specimens can be prepared consistently with moist tamping. The loose state of the specimen, however, leads to severe collapse and densification during saturation that cannot be measured via the BP volume changes. It is also debatable whether the fabric induced by moist tamping is representative of truly remoulded states or the in-situ fabric in many cases.

With moist tamping, void ratio tracking relies solely on RVT.

3.1.2 *Slurry sedimentation*

Slurry sedimentation can produce very loose test specimens that are fully or practically saturated. In this way, void ratio can be tracked both ways with the desired redundancy.

The slurry sedimentation method developed at Imperial College London (Kuerbis & Vaid 1988; Dominguez-Quintans et al. 2019 & 2023) provides for a practical solution for fine grained soils. In the authors' experience, this method has shown significant promise in improving FWT.

Disadvantages of the method are listed below with suggested mitigations:

- Custom hardware to allow the slurry to consolidate prior to mounting in the triaxial cell. This is a once of inconvenience.
- Inexperience and sometimes unwillingness of laboratories to adopt non-standard techniques. More and more laboratories are adopting the method as testing of mine and industrial tailings has become a high priority.
- Best suited for fine grained soils due to segregation of coarser particles leading to non-uniform distributions of particles. By controlling the slurry density, segregation can be largely prevented.
- Vertical only drainage during sedimentation and consolidation can also lead to non-uniform distribution of density and water in the specimen. The authors investigated this with silty soils and found a reasonable difference of only 1% between the ends of the specimen and the middle third section.
- The top 1 cm of the final specimen can be very loose, even liquefied after preparation. Researchers at the University of Western Australia recommend (personal communications) that the specimen is prepared (sedimented) to the exact height

required for density, as opposed to scraping off the oversize material. It is the scraping action that tends to liquefy the top of the specimen.
- Large volume changes in very loose specimens during saturation can cause practical challenges. To overcome this problem, the first consolidation stages (say up to 50 kPa) can be conducted 'on the bench' using suction from flow pumps connected to the top cap and removable pedestal. This has the added benefit of not tying up the triaxial load frames during these stages.

3.2 Indirect Volume Change Measurement

Volume changes during saturation are typically measured via the BP flow pump. There are, however, alternatives that can be considered including cell volume changes, tracking of axial strain, as well as photogrammetry-based methods.

3.2.1 *Cell Volume*

Assuming the volume of the physical triaxial cell is fixed and constant, specimen volume changes can also be measured indirectly by the change in cell water volume during saturation. Even if the cell water is practically incompressible (deaerated), the cell body is not. This requires careful calibration of the volume changes in the cell body over the range of expected pressures (Head 1988).

Recent developments of this method have been driven by testing of unsaturated soils, e.g. Ahmadi-Naghadeh & Toker (2017), and show promise for improving FWT for conventional CSL testing.

3.2.2 *Axial Strains*

Many laboratories have adopted axial strain tracking to estimate volume changes during saturation and consolidation. To do this, the loading ram is lowered to the top cap at the start of the saturation phase. Contact is maintained by applying a constant and small ram stress. In this way, the ram will track axial deformation of the specimen (axial strain). By assuming/adopting an appropriate deformation mode (right cylindrical, barrelling, etc.), standard area corrections may be applied and the volume change estimated.

The authors' have found this method to be unreliable. Even with the addition of local strain measurement (axial and radial callipers), Escribano Leiva et al. (2019) found considerable discrepancies between global and local volumetric estimates arising from volumetric strain nonuniformities.

3.3 Re-measuring Specimen Dimensions

Another approach, and arguably the most reliable method is to re-measure the volume of the specimen after the saturation stage. The volume changes that are induced during saturation can then be accounted for by the difference between the initial volume and the re-measured volume.

This approach is well suited to methods where the initial specimen is saturated and 'pre-consolidated' on the bench as described above. Alternatively, the cell must be disassembled to take the measurements.

A disadvantage of the method is that the measurements are made with the membrane in place. Manufacturing tolerances, aging and wear, as well as local stretching and thinning of the membrane add to the uncertainty of the measurements. These uncertainties are, however, insignificant compared to the uncertainties associated with conventional methods. Provided that new membranes are used for every test and that the membrane is kept in place against the specimen by maintaining a small level of suction, the errors can be reduced.

3D scanning technologies have been used successfully at the University of Pretoria to measure specimen volume instead of physical measurements of height and diameter, refer Figure 11. This becomes more relevant for post-saturation and for post teardown measurements where the specimen shape may be deformed and non-cylindrical.

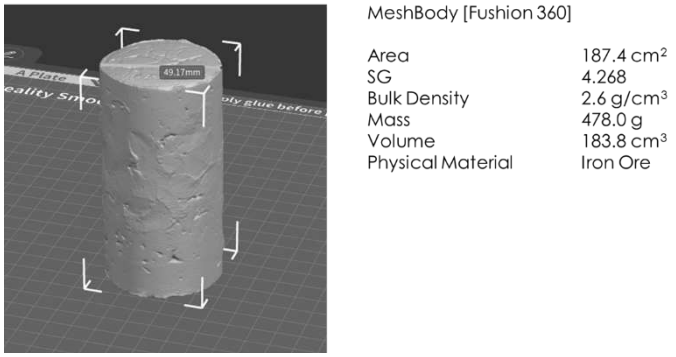

Figure 11. 3D laser scan and volume measurement of a specimen

4 REVERSE TRACKING IMPROVEMENTS

Although the uncertainties associated with RVT of void ratio are significantly less than FWT, further improvements can still be made. This section explores post-shear squeeze and sample freezing as key advancements over conventional test procedures.

4.1 Post Shear Squeeze

At the end of the shear phase, the triaxial specimen can be in a loose or unstable state following dilative drained shear; or very weak (liquefied) following undrained shear.

The post-shear squeeze phase refers to additional consolidation stages that are applied after the shear phase. The objective of the squeeze phase is to reduce the fragility of the specimen before it is removed as part of the teardown phase by:
- 'reorganising' the particles into a dense state;
- removing as much water as possible;
- releasing any excess pore pressures; and

- control the level of residual suction in the specimen during teardown, thus minimising the risk of water loss.

Verdugo & Ishihara (1996) suggested the addition of axial loading and unloading cycles over and above isotropic consolidation to further improve densification of sandy materials.

It is essential for RVT that volume changes are measured continuously throughout the squeeze phase that terminates with closure of the drainage valve.

4.2 Freezing

The final improvement to void ratio tracking, and the most significant, is freezing of the specimen before disassembly (Sladen & Handford 1987b; Been 2016).

By freezing the specimen, interstitial water is locked-in before the membrane is released, ensuring reliability of the moisture content determination at the end of the test.

Disadvantages of the method include:

- Seals and other equipment parts may be susceptible to freeze damage. However, simple modifications to the cell base (detachable), top cap and drainage leads (internal valves), allow the specimen to be easily removed from the cell base and placed in a household freezer. The same modifications work well with the slurry sedimentation method of preparing specimens.
- Once frozen, it can be difficult to remove the membrane. The specimen is, therefore, left to thaw for a few minutes before teardown. It takes some practice and experience to know the ideal thaw time to be able to remove the membrane without losing solids and water.

Over the past two years the authors have been involved in extensive CSL testing of mine tailings as part of the conformance requirements of the (Global Industry Standard on Tailings Management (GISTM). Sample freezing has stood out as most significant improvement to void ratio tracking and the reliability of CSL development.

5 CONCLUSIONS AND RECOMMENDATIONS

Modifications to test equipment and standard procedures have been proposed that can significantly enhance the accuracy of void ratio tracing during both drained and undrained triaxial tests for CSL mapping.

Reverse tracking benefits most from sample freezing at the end of the test, which is recommended as the primary improvement to consider for any triaxial testing that relies on precise void ratio tracking.

Forward tracking is most effectively improved by re-measuring the specimen volume (external dimensions) post-saturation. This can be best achieved by preparing, saturating, and pre-consolidating the test specimen 'on the bench' outside the triaxial cell. Laser scanning technologies offer a convenient and reliable method for these measurements without disturbing the specimen.

Implementing these recommendations minimises systemic errors and can result in substantial time and cost savings for CSL test campaigns.

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