

Visualisation of soil arching in unsaturated soils

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ABSTRACT: For the formation of stable underground voids, unsaturated or cemented soils are needed to sustain the tensile stresses generated around the void. Addressing the overburden thickness and conditions of soil required for a stable arch to form is a critical aspect related to the assessment of voids which could ultimately lead to sinkholes. The formation and progression of arching mechanisms is typically monitored using shear and volumetric strains in soil. This research considers an alternate representation using the strain rotations in a soil mass around a stable void to identify the extent of the soil engaged in the stress-redistribution mechanism. For laboratory floor (1g) tests, it was shown that continuous arches occur above the void for a height of approximately half the void width. Additional secondary stress-redistribution mechanisms are evident on vertical planes extending from the void edge, although these do not form continuous arches. The impact of soil density, overall soil height and moisture content on the results are considered. The same investigation conducted on the geotechnical centrifuge did not show the formation of stable voids highlighting the limitation and additional consideration required in the application of theory developed from 1g tests.

1 INTRODUCTION

The formation of collapse sinkholes requires the initial presence of a void supported by arching in the overburden material above the void transferring the soil and applied loads to stable material adjacent to the void (Jennings et al. 1965). A disruption to the otherwise stable arching mechanism, for example due to additional overburden load or loss of strength in the overburden material, results in the collapse of the void and propagation to the surface.

The ability of the soil to arch over the void depends on the cohesive strength of the soil; this is either due to cementation or due to suctions which generate apparent cohesive strength in unsaturated soils (Jacobsz 2016). One of the most common triggers for the formation of sinkholes is the presence of water, either the erosion of the void such that the overburden thickness is insufficient to support the self-weight and applied loads, or the saturation of the soil resulting in the loss of the required suction strength to support the arch (Jennings et al. 1965). Understanding the conditions under which a soil is able to support the formation of a stable arch is thus critical to understanding when sinkholes are likely to be triggered.

Trapdoor studies, as first used by Terzaghi (1936), have been used extensively to study arching mecha-

nisms and transfer of load in predominantly dry, cohesionless soils. Selected examples include laboratory studies by Ladanyi & Hoyaux (1969), Vardoulakis et al. (1981), and Chevalier et al. (2012); geotechnical centrifuge studies have been conducted by Dewoolkar et al. (2007), Costa et al. (2009) and Iglesia et al. (2014) amongst others. A study on propagation mechanisms in moist sands was conducted by Jacobsz (2016) highlighting the development of a chimney failure mechanism as opposed to the funnel mechanism adopted in evaluation of sinkhole zones of influence (Buttrick & Van Schalkwyk 1995).

Arching theory as developed by Terzaghi (1936, 1945) describes the transfer of load that occurs on vertical planes from the void edge. This is separate to the formation of a stable arch above a cavity. One of the first physical experiments to show the formation of stable arches was the small-scale studies by Hewlett & Randolph (1988) using compacted moist sand. These results were used to develop a theory for the transfer of load in the soil layer of piled embankments using semi-circular arches; the work was further developed more recently by van Eekelen et al. (2013) and van Eekelen & Brugman (2016). This model is often used to determine the minimum embankment height for the formation of a complete arch (Ye et al. 2020, Pham 2020), but this does not take

into consideration the thickness above the void required to support the arch.

The aim of the current study was to use observations of strain rotations in trapdoor tests in moist sands to understand the extent of the soil engaged in the load transfer mechanism outside of the formation of the stable void formed. The size and shape of the stable arch formed and the stress-redistribution zone were investigated for various densities and moisture contents of the soil.

2 EXPERIMENTAL METHODOLOGY

2.1 Trapdoor setup

Plane-strain trapdoor tests were conducted at 1g using a trapdoor with a width of $B = 50$ mm as shown in Figure 1; further details of the rig are as per Jacobsz (2016). The trapdoor was controlled with an electronic actuator and lowered at a constant rate until the material collapsed. Once the collapse had occurred, the trapdoor was lowered further to clearly show the size and shape of the remaining cavity. Images were taken of the soil deformation throughout the lowering of the trapdoor. These were analysed using the particle image velocimetry (PIV) detailed by Stanier et al. (2016) to determine soil displacements and strains.

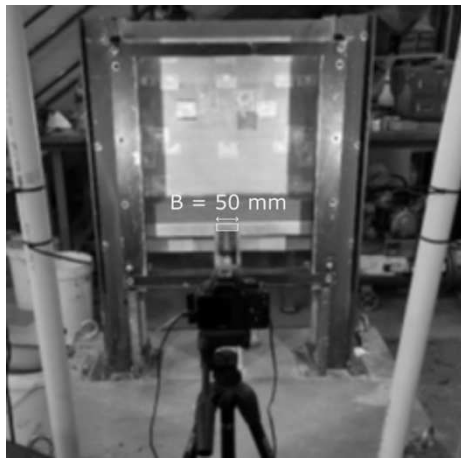


Figure 1. Experimental setup of trapdoor test

2.2 Material properties

To observe the void formation, a moist compacted dense sand layer was prepared in the model. The properties of the sand are shown in Table 1. The maximum and minimum densities were determined according to ASTM 4253 and 4254 respectively.

Table 1. Soil properties

Property	Symbol	Units	Value
Average particle size	d_{50}	mm	0.787
Specific gravity	SG	-	2.658
Minimum dry density	$\rho_{d,min}$	kg/m ³	1562
Maximum dry density	$\rho_{d,max}$	kg/m ³	1818
Minimum void ratio	e_{min}	-	0.4577
Maximum void ratio	e_{max}	-	0.6961

The sand was thoroughly mixed at a target moisture content. The material was weighed and compacted into the test rig in layers of known height to achieve a target relative density.

To determine the unsaturated properties of the soil, the soil water retention curve (SWRC) was measured using a tensiometer to measure the suction and scale to measure the weight of the sample which was converted to the gravimetric moisture content once the dry weight of the sample was determined at the end of the test. The test setup is shown in Figure 2; the results were logged continuously for several days until a residual condition was reached. The results are shown in Figure 3. Due to the coarse nature of the sand, the measured porewater pressures show low suction capacity of the soil. The results show an estimated air entry value of 1.67 kPa at a moisture content of 18.7%

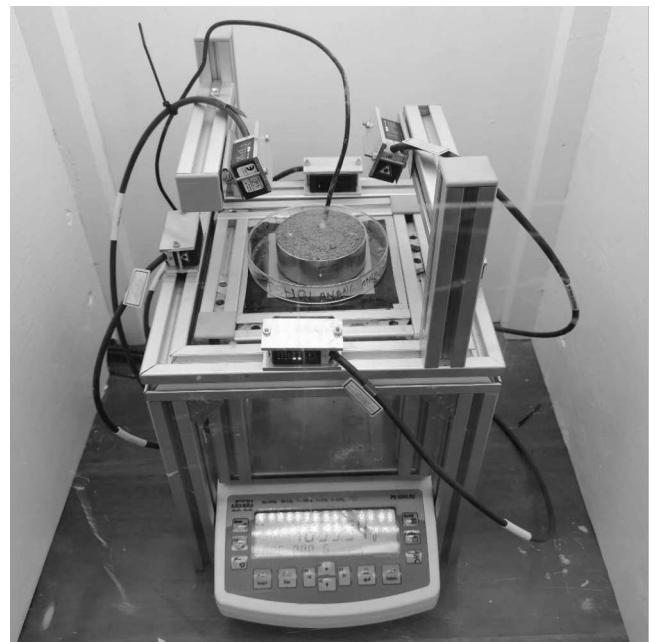


Figure 2. Test setup for determination of soil water retention curve

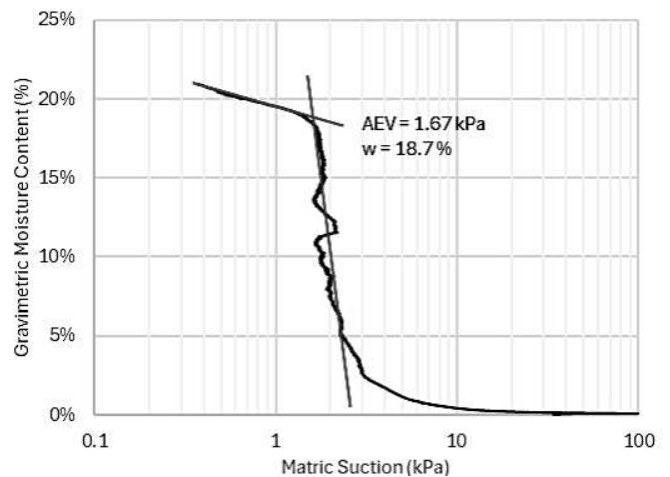


Figure 3. Soil water retention curve showing estimated air entry value

2.3 Test schedule

Two separate test series of three tests each were conducted to compare the effect of varying density and varying moisture content. The first series had a constant soil height, H , of 100 mm and target moisture content of 5%. The target relative densities of the tests were 50%, 25% and loose (0%). The second series had $H = 200$ mm and a target relative density of 50%; the target moisture contents of the tests were 5%, 10% and 15%. A visual representation of the schedule of tests is shown in Figure 4; tests RD50 and MC5 allow the comparison of the H/B ratio on the size and shape of the void and stress redistribution mechanisms evident.

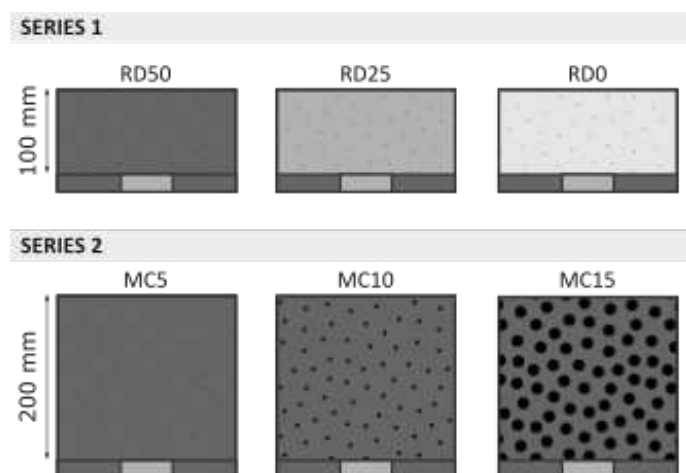


Figure 4. Visual representation of test schedule

3 RESULTS & DISCUSSION

3.1 Stable arches

Photographs of the size and shape of the stable arches formed in the tests are shown in Figure 5. Differences in the appearance of the sand are due to changes in the lighting setup between the two test series. All of the cavities that formed were stable under the self-weight of the soil and soil conditions in a general parabolic shape; there was no propagation to the surface to cause complete collapse.

Comparisons of the stable arch size and shape are shown in Figure 6 using the best-fit parabola to the observed void. The effect of relative density shows little difference between 50% and 25%, but a larger increase in the height of the void for the loose soil. The variation in moisture content also showed little difference in the arch size; interestingly, MC10 had the highest arch, and not the wettest test (MC15) as may have been expected. Comparing MC5 and RD50 which were conducted with the same relative density and moisture content, but differing heights of soil, shows an almost identical cavity shape and size.

3.2 Displacements

Plots of the displacement profiles for the first and last test in each series are shown in Figure 7; the scale has been limited to 0.5 mm to highlight the displacement occurring within the overburden soil. The collapsed soil is represented by the bright yellow zone, the parabola fitted to the stable void is shown in a solid white line, and the vertical extensions from the trapdoor edges are shown in the dotted white lines.

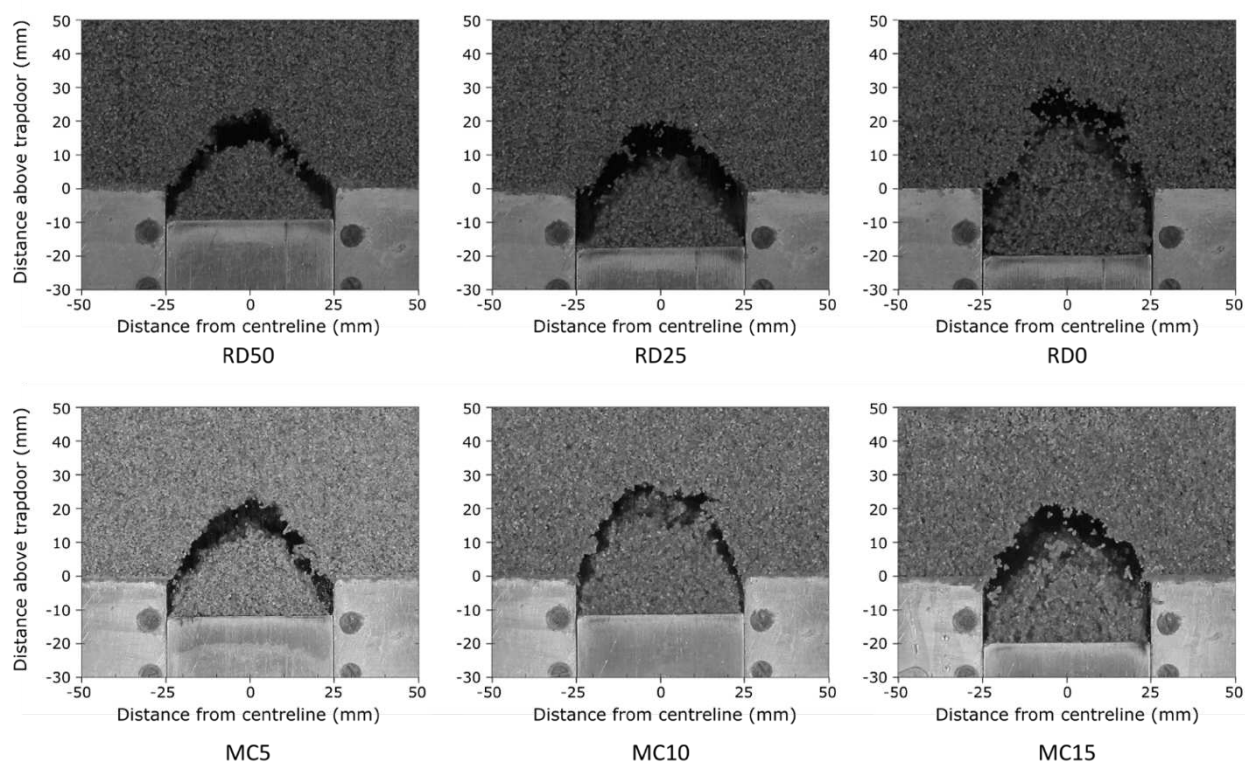


Figure 5. Photographs of the collapsed soil region and stable void formed with the lowering of the trapdoor in the tests conducted.

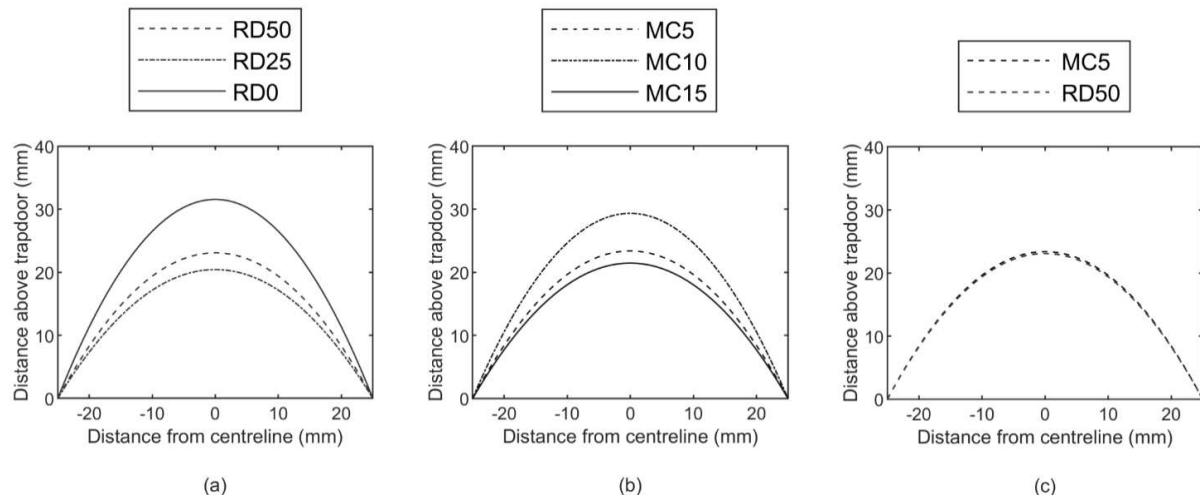


Figure 6. Comparison of the size of the parabola fitted to the stable voids observed in the tests conducted (a) variation in relative density (b) variation of moisture content and (c) variation in soil height (MC5, $H/B = 2$; RD50, $H/B = 4$).

The results show that for the test series where relative density was varied (series 1), there was much greater movement in the overburden soil for the loose tests compared to the compacted tests. Similarly, with the variation in moisture content, the wetter test also had more movement in the overburden, although less than for the loose soil. Test MC5 showed almost no observable movement outside of the cavity.

strain only, and do not give an indication of the principal strain ratio. In tests on dry material, the rotations form continuous convex arches across the trapdoor bound by vertical extensions from the trapdoor edges (da Silva Burke & Elshafie 2021b).

The results of the strain rotations from the six tests conducted are shown in Figure 8. The rotations are visualised both with lines showing the orientation of the principal strain at each location to help visualise where ‘complete’ arches are formed by the rotations, and with a colour scale to emphasize regions where there is a consistent rotation in one direction.

The majority of the results show that the rotations are bound by the vertical extensions from the trapdoor edges; exceptions are the loose test (RD0) which shows some asymmetric movement, presumably due to material variability in the prepared model, and the wet test (MC15) which shows large variation in rotation throughout the depth. These correspond to the observations in the displacement plots that showed that these two tests had the largest displacements in the overburden soil.

For the remaining tests, the rotations appear to form continuous arches up to a height of 50 mm ($H = B$) in the soil body; above this level, there is still some rotation evident around the vertical extensions but not forming continuous arches up to a height of approximately 75 mm ($H = 1.5 B$). These results are clearer in the second series (MC5 and MC10) than in the first series (RD50 and RD25). These results give an indication of the height of soil above the collapsed void required to ensure that the load is transferred across the void and that surface collapse does not occur.

The strain rotations do not form continuous circular or parabolic arches that extend into the abutments; rather they appear to be supported primarily on frictional shear planes extending vertically from the trapdoor edges, similar to the behaviour observed in dry trapdoor tests (da Silva Burke & Elshafie 2021b).

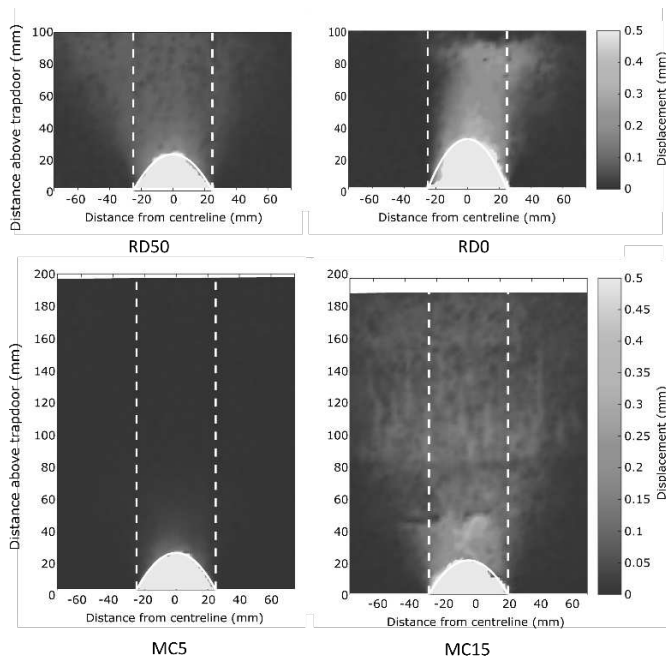


Figure 7. Displacement plots from PIV results

3.3 Strain rotations

The rotation of principal strains was derived from the PIV strain data as per da Silva Burke & Elshafie (2021a). These results were used to give an indication of where stress redistributions occurred in the soil as indicated by regions where there is a consistent and not random orientation of principal strains. Note that these results show the direction of the major principal

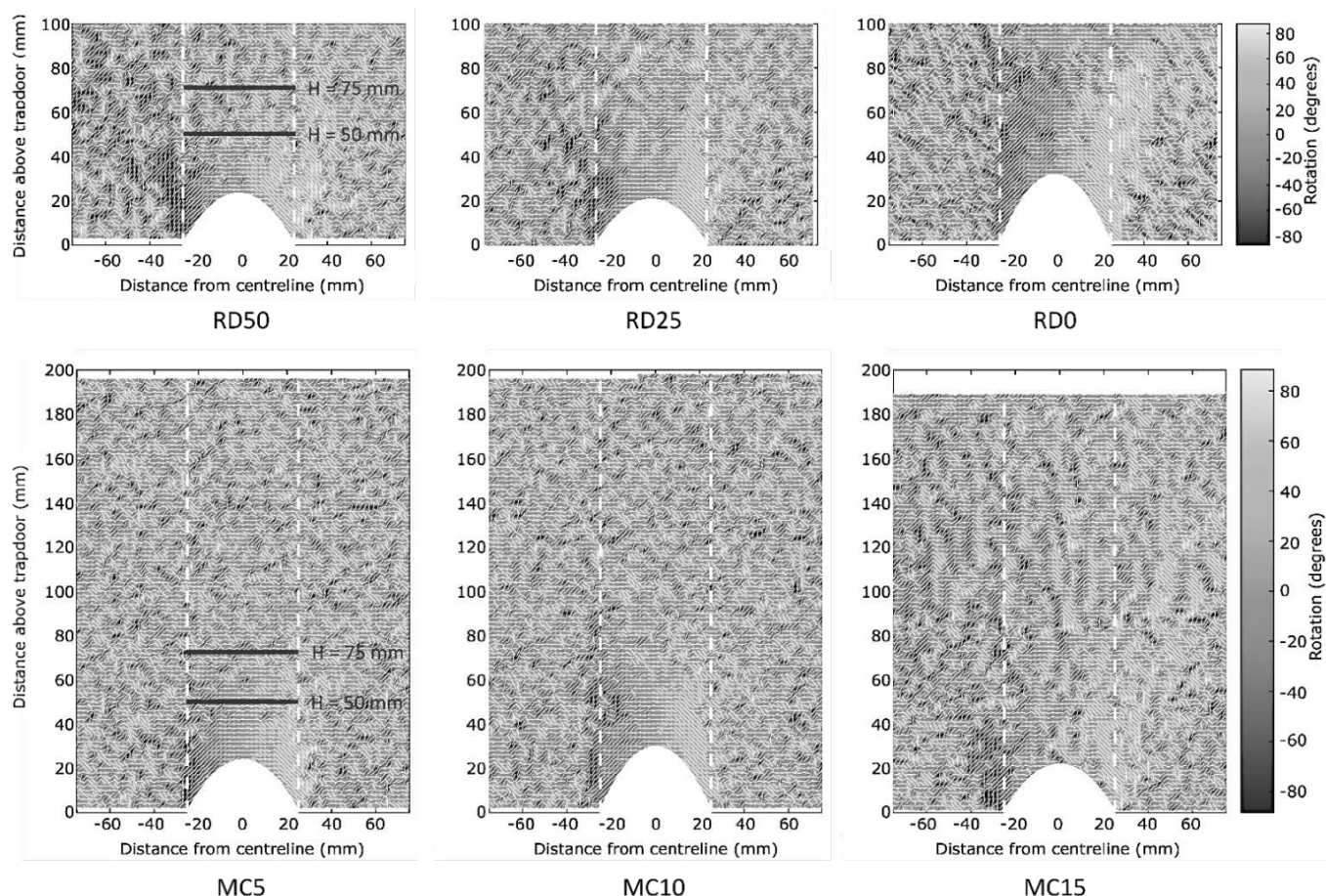


Figure 8. Rotation of principal strain from -90° (anticlockwise rotation) to 90° (clockwise rotation); vertical extensions from the trapdoor edges shown in dashed white lines. The collapsed soil region using the fitted parabola is excluded from the results.

4 LIMITATIONS

The primary limitation of laboratory floor (1g) tests in soil arching problems is the unrealistic stress regime; the reduced self-weight of the soil and increased dilatancy as a result of the low confining stress gives an artificial representation of the ability of the soil to support a stable cavity. 1g tests are useful to explore indications of what might occur, but only the results from centrifuge tests can realistically be used to give full-scale predictions of the arching behaviour. A centrifuge test of the same setup as MC5 was conducted to compare the behaviour. The results showed that for this soil, a void was not able to form and the soil collapsed into the void with a similar progression of arching mechanisms as is understood for dry soils; the results are shown in Figure 9. The shear strains formed a series of parabolic arches extending to vertical shear planes at the conclusion of the test. The strain rotations showed similar behaviour to that observed for dry sands with continuous arches resulting in stress redistributions between the vertical extensions from the trapdoor edges.

Prior work on fine-grained soils by Jacobsz (2016) showed the eventual formation of a stable void in the centrifuge. This highlights the importance of the material characteristics and stress dependency in understanding the process of stable void formation.

5 CONCLUSIONS & RECOMMENDATIONS

Common understanding of load-transfer mechanisms in overburden soil above voids suggests that stress is redistributed along arches that extend into and are supported by the abutments adjacent to the void. The results of the strain rotations suggests that this is not the case, and that the load transfer is supported on a frictional plane extending vertically from the edge of the void, as simulated by the trapdoor. The rotations also showed that a soil height at least equal to the void width is required to support the stable void, with additional stress redistributions occurring for a further half of the void height along the vertical planes, although not forming complete arches. In the case of wet and loose soils, much more movement was observed in the overburden soil and the strain rotations consequently did not follow the same pattern noted for the drier and/or denser tests, even though the actual size of the cavity was similar. This reinforces the need to characterise the density and moisture of the soil to determine its ability to support a stable void. Further tests at an appropriate stress level with a fine-grained and/or cohesive soil with corresponding detailed analysis of the unsaturated soil behaviour are required to further explore this effect.

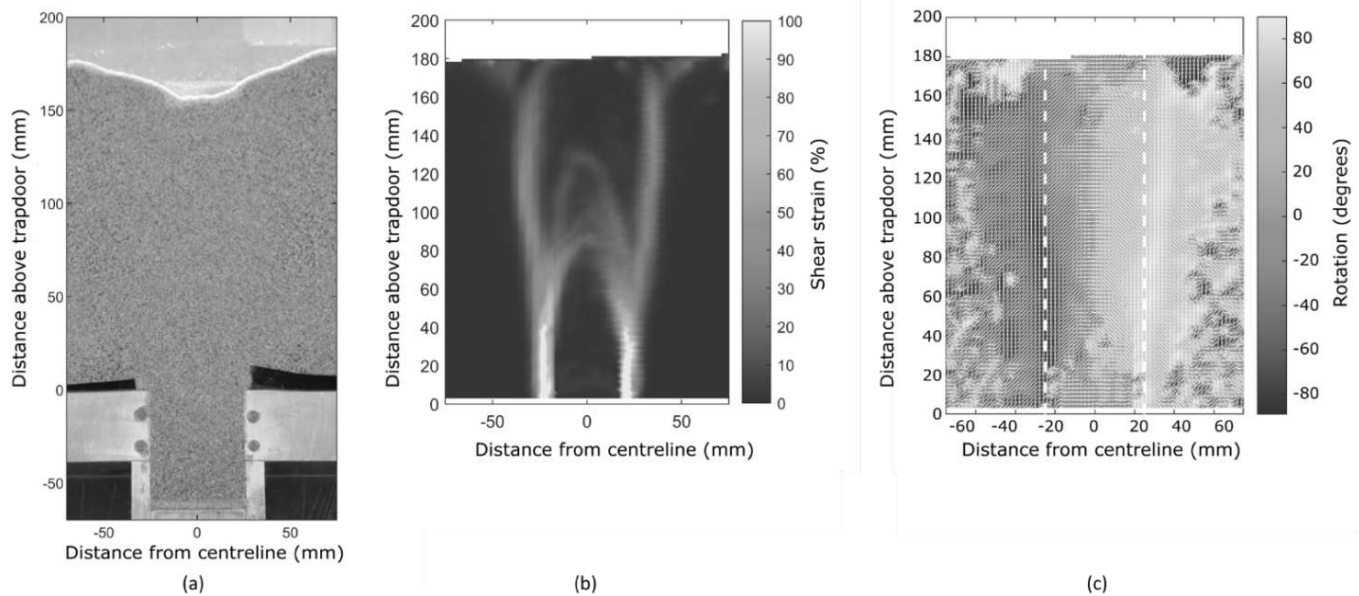


Figure 9. Centrifuge results (a) collapsed soil at the end of the test (b) shear strain localisations, and (c) rotations of principal strains

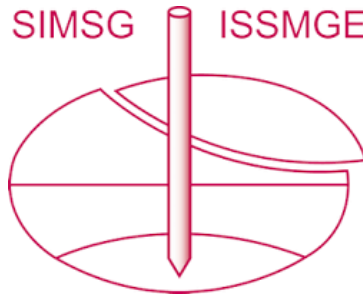
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