The paper was published in the proceedings of the 10th International Conference on Physical Modelling in Geotechnics and was edited by Moonkyung Chung, Sung-Ryul Kim, Nam-Ryong Kim, Tae-Hyuk Kwon, Heon-Joon Park, Seong-Bae Jo and Jae-Hyun Kim. The conference was held in Daejeon, South Korea from September 19th to September 23rd 2022.

Physical Modelling in Geotechnics

Investigating the conditions required for self-supporting soil arches

T.S. da Silva Burke & S.W. Jacobsz
Department of Civil Engineering, University of Pretoria, South Africa

ABSTRACT: This research used trapdoor studies on partially saturated sands to identify the conditions under which a stable arch can be formed. Particle Image Velocimetry (PIV) was used to identify the arching mechanism above a two-dimensional trapdoor. The size and shape of the arch in soils prepared to various moisture contents were compared to the arching behaviour of a dry soil above the trapdoor. It was found that compacted soils were able to span the trapdoor without the formation of an arch in the soil. Uncompacted, loosely placed soils showed the formation of stable arches, with larger arches corresponding to wetter, and thus weaker, soil. Understanding how and when stable soil arches are able to form in soils is important for being able to investigate phenomena such as the voids that occur prior to the formation of collapse-cover sinkholes.

Keywords: arching, unsaturated soils, trapdoor, sinkhole.

1 INTRODUCTION

Soil arching occurs when there is relative movement in a soil body, and the stresses in the soil rearrange themselves to form an 'arch' over the portion of the soil that has moved and transfer the load to the stable boundaries. A common misconception in the understanding of soil arching in dry, cohesionless soils is that this is a stable and physical structure analogous to a masonry arch. This concept is sometimes used to determine the arching loads, for example by Iglesia et al. (2014). Justification for the use of a stable physical arch is often based on the experimental work of Hewlett and Randolph (1988). However, these tests were conducted with moist sand, and as noted by King et al. (2019), the stable arch is likely to have been a result of soil suction (apparent cohesion) rather than an indication of failure surfaces. In reality, such a self-supporting arch in the soil can only be formed in a particular set of circumstances, i.e. when there is some 'cohesion' in the soil, either true cohesion attributable to cementation of the soil particles, or apparent cohesion resulting from negative pore pressures providing some effective stress 'holding' the soil together in unsaturated soils (Handy, 2015).

The requirement for the formation of a physical arch is thus that the soil has some cohesive strength or bonding. Understanding how and when stable soil arches are able to form in soils is important for being able to investigate phenomena such as the voids that occur prior to the formation of collapse-cover sinkholes. Examples of this include research the work on sinkhole formation in weakly cemented sands (Abdulla and Goodings, 1996; Bronkhorst and Jacobsz, 2014). Jacobsz (2016) investigated cavity propagation in moist sands in a deep soil profile and found that a stable cavity was eventually formed once the initial cavity had propagated upwards in a chimney fashion until the overburden above the cavity was small enough to be supported by the soil.

Unsaturated soil mechanics indicates that the shear strength of moist soils is increased as the suction in the soil increases; the suction generates an apparent cohesion in the soil (Fredlund et al., 2012). A higher moisture content will result in a lower suction in the partially saturated soil; this corresponds to a lower apparent cohesion, and thus lower shear strength of the soil.

Preliminary experiments were conducted on soils at different moisture contents to investigate firstly when self-supporting soil arches are formed, and secondly, where arches were formed to investigate the impact on the shape and size of the arch that forms in the soil.

2 EXPERIMENTAL WORK

Trapdoor model tests were conducted at the University of Pretoria using the rig described by Jacbosz (2016). The model used a 50 mm wide trapdoor; a 200 mm high soil layer was placed over the trapdoor. The soil used was Cullinan sand; this material has sub-angular grains. The properties are shown in Table 1.

Table 1. Selected properties of the sand tested (Archer, 2014)

Property	Symbol	Units	Value
Average particle size	d_{50}	mm	0.135
Peak angle of friction	ϕ_p	°	39
Critical angle of friction	ϕ_c	°	32
Minimum dry density	$\rho_{d,min}$	kg/m^3	1392
Maximum dry density	$\rho_{d,max}$	kg/m^3	1669

A fraction of the sand was dyed black to allow sufficient contrast in the images for Particle Image Velocimetry (PIV) analysis (Stanier et al. 2016). Water was added to the dry sample to achieve a target moisture content (MC); the sample was mixed evenly and allowed to stand to equilibrate before preparation of the final model. Several tests at different target moisture contents were conducted. Two types of tests were conducted: compacted and uncompacted. In the compacted tests, an 85% target relative density was used. The partially saturated sand was prepared in four layers, each compacted to 50 mm thick with a thin layer of the dyed sand between each layer forming a total soil height of 200 mm. In the uncompacted tests, the same material was loosely placed in the model and levelled to the required height. A dry test was also conducted as a baseline. The tests summary is shown in Table 2.

Table 2. Test schedule for moist sand tests

	Target moisture content (%)			
	2.5	7	10	15
Compacted (85% RD)	x	x	x	x
Uncompacted (Loose; 0%RD)	x	x		x

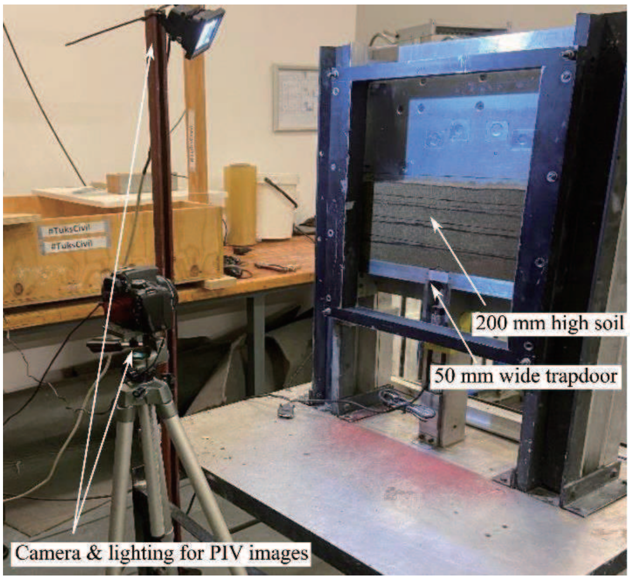

Fig. 1. Experimental setup for trapdoor tests.

3 RESULTS & DISCUSSION

3.1 Dry test

The analysis of the strain results from the dry test showed initial triangular shear localisations, progressing through a series of taller and taller parabolic shear bands until a final chimney-like failure mechanism widely associated with trapdoor studies was reached; the initial and final shear bands formed are shown in Fig. 2. This progression is similar to observations made by da Silva Burke & Elshafie (2021) and Jacobsz (2016) amongst others. The initial shear localisations formed at an average angle of 29.6° to the vertical.

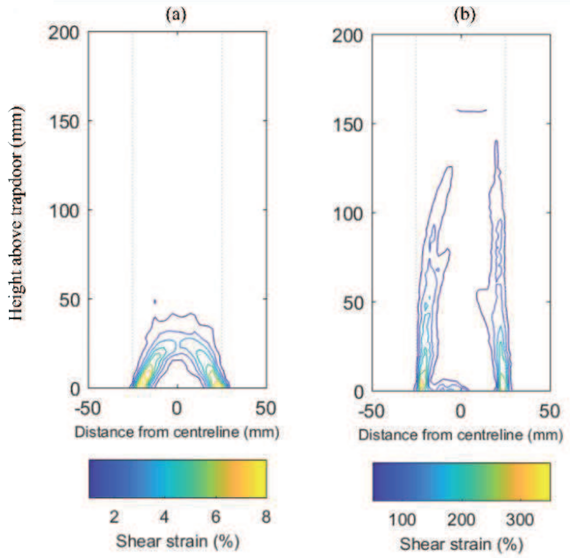

Fig. 2. Shear strains developed in the dry tests at trapdoor displacements of (a) initial and (b) final. The trapdoor width is shown in the dotted line.

3.2 Compacted tests

A series of images for the compacted tests showing the observed soil deformation once the trapdoor was well clear of the base of the soil body are shown in Fig. 3. For the tests with the soil moisture contents of 2.5% and 7% (Fig. 3a and 3b respectively), there was no formation of a soil arch visible against the viewing window. There is, however, some material that has fallen on the trapdoor from within the soil body, with the appearance of slightly more material in the wetter test than in the drier test. The PIV results of these two tests showed no significant movement in the soil body above the trapdoor. In the test conducted at 10% MC (Fig. 3c), the collapse of a small amount of material and formation of a cavity is visible; this does not follow an expected catenary shape or parabolic shape that would be expected in this situation (Hewlett and Randolph, 1988; Alonso et al., 2021). The remainder of the soil body also showed no significant movement.

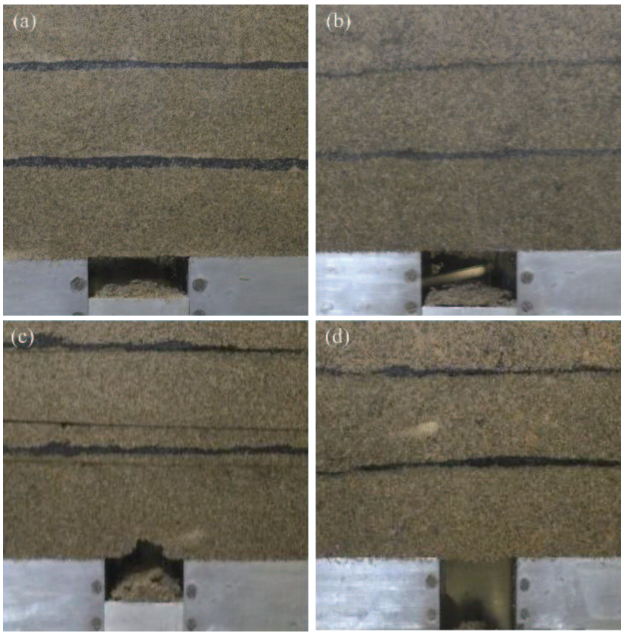

Fig. 3. Final shape of stable arch formed in compacted tests with a target soil moisture content of (a) 2.5%, (b) 7%, (c) 10% and (d) 15%.

The final test with the moisture content of 15% showed a slight deflection of the material above the void, but no formation of a physical arch or cavity (Fig. 3d). The PIV displacement and strain results for this test are shown in Fig. 4. The displacement showed uniformly spaced concentric parabolas; the observed parabolas were slightly asymmetric. The average inclination to the vertical at the edge was 21.8°.

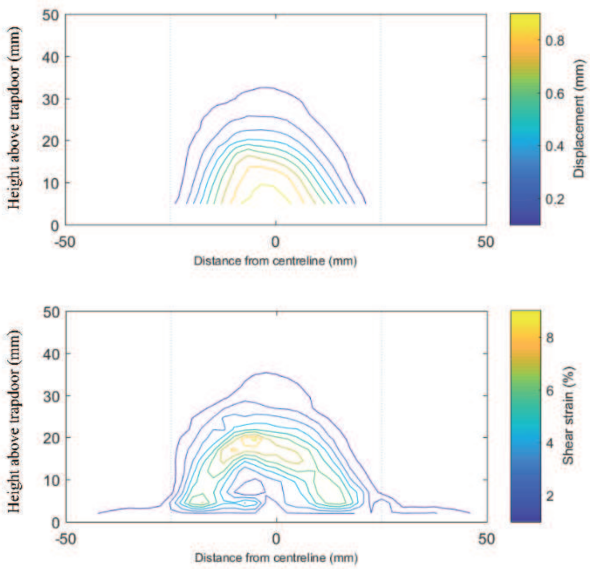

Fig. 4. PIV displacement and strain contours for the compacted test with a target soil moisture content of 15%.

The largest shear localisation formed with a maximum height of approximately 20 mm above the trapdoor (40% of the trapdoor width), and at an average inclination angle of 31.7°. This is similar to the initial inclination of the triangular shear bands in the dry test. However, in the compacted moist tests, there is only one distinct shape in the deformation mechanism, i.e. parabolic, as opposed to the various failure mechanisms that developed in the dry sand.

3.3 Uncompacted tests

Due to the lack of clear development of a cavity in the compacted partially saturated tests, three of these tests were repeated with uncompacted moist sand. Images of the collapsed soil regions are shown in Fig. 5. The 2.5% moist sand (Fig. 5a) did not develop a cavity above the trapdoor; it acted similar to a cemented beam with material falling from underneath and the soil spanning the trapdoor. A very limited amount of displacement was measured in the soil body using PIV, but this was not sufficient to generate significant strains. The 7% and 15% tests both allowed the formation of a cavity and stable arch; the arch shape in the wetter test was larger and steeper, corresponding to a lower strength soil due to the reduced suction.

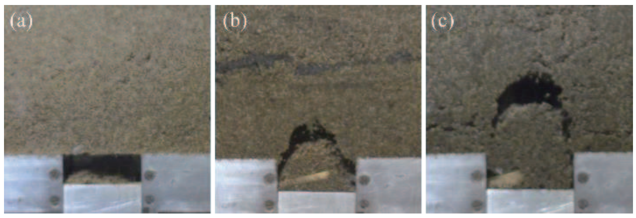

Fig. 5. Final shape of stable arch formed in uncompacted tests with a target soil moisture content of (a) 2.5%, (b) 7% and (c) 15%.

The displacement and shear strain results for the 7% moist test showed that this failure plane as visible from the first increment of trapdoor displacement, i.e. approximately 0.15 mm of trapdoor displacement. The only shear localisation that developed was the same as the failure plane that is visible in Fig. 5b. In contrast, the 15% moist test showed much larger movement within the soil body. This could potentially be due to the wetter soil being placed at a looser equivalent dry density compared to the other two tests. The shear strains developed in the initial test stages and with further trapdoor displacement are shown in Fig. 6a and b respectively. The smaller parabolic shear strains in the latter figure correspond to the failure plane observed in Figure 5c.

A comparison of the failure planes (stable arches) formed in the final two tests is shown in Fig. 7. A parabola has been fit to each arch, and the angle of inclination is 27.8° for the 7% MC, and 15.6° for the 15% MC. The wetter material thus has a much higher and steeper arch due to lower shear strength (reduced apparent cohesion with lower suctions).

3.4 Limitations

It is noted that this series of tests was not conducted at an elevated stress level as would provide fuller extrapolation to field behaviour, and more appropriate comparisons for the size and shapes of the observed arches. However, the results are deemed to be indicative of the expected field behaviour.

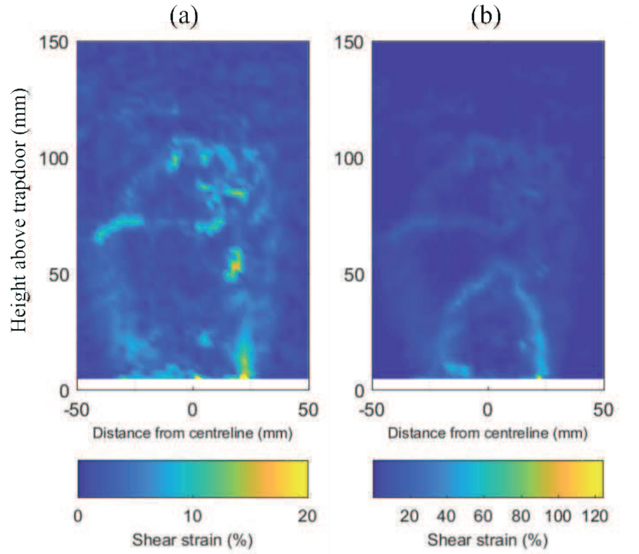

Fig. 6. Shear strains developed in the uncompacted test at 15% moisture content at trapdoor displacements of (a) 1.2 mm and (b) 4 mm.

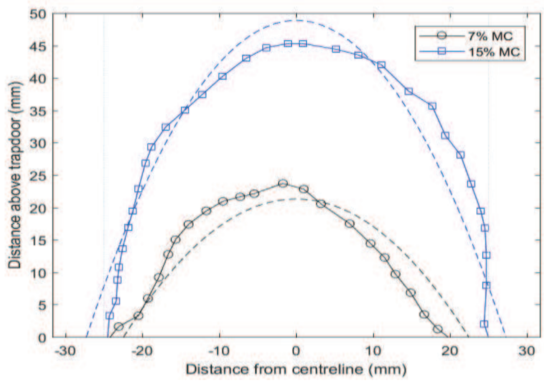

Fig. 7. Failure planes (stable arches) formed in the 7% and 15% uncompacted tests, with best-fit parabolas.

4 CONCLUSIONS

In partially saturated soils, the formation of stable soil arches is possible if the moisture content is sufficient to generate apparent cohesive forces due to suction. It was found that in dense, compacted soils, even with high suctions there was not significant failure of the soil, and the soil was able to span over the trapdoor width. In the uncompacted, loose soils, this was only true at the lowest moisture content (highest suction). Higher moisture content will result in a lower suction in the partially saturated soil; this corresponds to a lower apparent cohesion, and thus lower shear strength of the soil. With a reduction in suction, a cavity was formed with a larger cavity corresponding to a wetter soil. These cavities remained stable under the geometry, loading and soil conditions of the test, and did not propagate to the soil surface causing complete failure. The soil strength was sufficient to support the soil above and span over the cavity as the trapdoor lowered.

ACKNOWLEDGEMENTS

Acknowledgments are given to Ms. Zahra Varachia who conducted the physical experiments and Mr. Jan Vermaak, the geotechnical laboratory technician, for assistance.

REFERENCES

Abdulla, W. A., & Goodings, D. J. 1996. Modeling of sinkholes in weakly cemented sand. *Journal of geotechnical engineering*, 122(12): 998-1005.

Alonso, J., Moya, M., Asensio, L., de la Morena, G., Galve, J. P., & Navarro, V. (2021). A catenary model for the analysis of arching effect in soils and its application to predicting sinkhole collapse. *Géotechnique*, 1-11.

Archer, A. 2014. *Using small-strain stiffness to predict the settlement of shallow foundations on sand*. MEng dissertation. University of Pretoria, Pretoria.

Bronkhorst, W. P., Jacobsz, S. W. (2014). The behaviour of weakly cemented sand beams spanning over openings. In Gaudin, C., & White, D. (Eds.). *Physical Modelling in Geotechnics: Proceedings of the 8th International Conference on Physical Modelling in Geotechnics 2014 (ICPMG2014), Perth, Australia, 14-17 January 2014*. CRC Press. London. 1107 - 1112

da Silva Burke T.S. and Elshafie M.Z.E.B. 2021. Arching in granular soils: experimental observations of deformation mechanisms. *Géotechnique*, 71(10): 866-878.

Fredlund, D.G., Rahardjo, H. & Fredlund, M.D. (2012). *Unsaturated Soil Mechanics in Engineering Practice.* John Wiley & Sons.

Handy, R.L. 2015. Discussion of "Investigation of Soil Arching with Centrifuge Tests" by Geraldo R. Iglesia, Herbert H. Einstein, and Robert V. Whitman. *Journal of Geotechnical and Geoenvironmental Engineering,* 141(7), p.07015009.

Hewlett WJ and Randolph MF (1988) Analysis of piled embankment. *Ground Engineering* 21(3): 12–18

Iglesia G.R., Einstein H.H., Whitman R.V. 2014. Investigation of soil arching with centrifuge tests. *Journal of Geotechnical and Geoenvironmental Engineering*, 140, No. 2, 04013005

Jacobsz, S.W. 2016. Trapdoor experiments studying cavity propagations. In Jacobsz, S.W. (ed.) *Proceedings of the first Southern African Geotechnical Conference, Sun City, South Africa, 5 – 6 May 2016.* Taylor & Francis Group: London. pp. 159-165.

King, L., Bouazza, A., Dubsky, S., Rowe, R. K., Gniel, J., & Bui, H. H. 2019. Kinematics of soil arching in piled embankments. *Géotechnique*, 69(11), 941-958.

Stanier, S. A., Blaber, J., Take,W. A. &White, D. J. 2016. Improved image-based deformation measurement for geotechnical applications. *Canadian Geotechnical Journal*, 53(5), 727-739.