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Moisture and suction changes pre and post construction in expansive clays during recent extreme climate

D. Lopes
Victoria., Australia

A.M.A.N. Karunarathne
Engineer, Swinburne University of Technology, Australia

R.I. Brown
Chartered Engineer Australia

ABSTRACT: Between 1997 and 2010 Australia experienced a very severe drought which was followed by wide-spread floods and a number of shorter climate variations. During these events the authors tested the performance of many newly built houses and paid particular attention to changes in soil suctions and moistures with respect to ground movement. This paper summarises the results from the Conditioned Core Shrinkage tests (CCS) and 'companion' Soil-Water Characteristic curves (SWCC) carried on samples collected in the western and northern suburbs of Melbourne, Australia collected between 2005 and 2016 during which time many thousand houses did not meet the Australian Standard design requirements and many suffered severe damage. AS2870 uses two important, but only loosely undefined soil suction conditions as part of a design model; namely 'Normal' (where the surface soil suction is within the limits of 1.2 pF) and 'Abnormal' where it is >1.2 pF. The authors used their soil records and measurements of damage and wall and floor distortion to determine whether the surface soil suction (Δus) of 1.2pF was adequate for 'Normal' climatic conditions and also for the predicted chaotic atmospheric changes. The CCS test (Lopes[1] 2017) was designed as a practical and commercial method for measuring soil instability indices. The data for this research project consisted of (a) the interpretation of 267 near-surface moistures of samples collected around the houses being investigated, (b) the performance of 84 newly built houses (<7 years old) and the development and validating the soil index properties in 36 test sites using CCS and SWCC tests.

1 INTRODUCTION

The latest Australian Bureau of Statistics (ABS, June 2017), show that Melbourne is a city of approximately 4.5 million and growing at about 150,000/year. Approximately 700,000 dwellings were built during the research period on highly expansive clay. The aim of this research was to establish whether the AS2870 'Normal' surface suction model of Δus = 1.2 pF was adequate for the recent extreme climate and if this design value was adequate for future climatic conditions.

During an Australia-wide severe drought climate period (1997 to 2016) the authors carried out field, fofrensic and laboratory investigations separately but have recently combined part of their results for this paper. At this time there was an Australia-wide residential building and mining boom which led to a shortage of skilled contractors and many engineering and geotechnical practitioners became concerned by the amount of slab edge-heave found in houses constructed during the drought and investigated after the wet period. Since most of the damage was caused by excessive ground movement the site characterization in Australian Standard AS2870 drew the greatest attention in this paper.

Author[3] provided 887 moisture results from forensic investigations carried out between 2005 and 2015. Author[1] tested 84 houses and developed a 'Conditioned Core Shrinkage' test (CCS) for new Site Classification models as part of his PhD. Author[2] investigated three unoccupied house sites to measure seasonal soil moisture changes as part of an ARC/Swinburne University research project in Braybrook, Victoria, Australia. The aim of this project was to model long term soil suction variations. Author[3] has investigated soil conditions and the performance of numerous houses during this time and contributed most of the soil moisture results presented in this paper. In this paper only those results collected near the surface and in 'normal' conditions were used (267 samples) to determine the near-surface soil suction, shrink and moisture changes.

Conditioned core shrinkage graphs were plotted to estimate the suction and moisture variations which occurred in the extreme climate period. These measurements were conducted on samples 'conditioned' to a suction range of 3 - 3.5 pF, 3.5 -

4.5 pF and 4.5 - 5.5 pF and 7 pF and tested for suction in a WP4C psychrometer. The 7 pF suction was plotted as the oven-dry suction. Moisture, shrink and suction were measured at each of the above points allowing the core shrink/suction characteristic curve (CCS) and the soil-water characteristic curve (SWCC) to be determined. These tests in combination solved some of the problems with the shrink/swell test and forensic investigations.

2 RESEARCH SETTING AND GEOLOGY

The research quoted in this paper has been carried out only on the basaltic clays in the Melbourne area which are Smectites with a mixture of Montmorillonites, Halloysites and Kaolinites but often contain small amounts of alluvial or aeolian sand, silt and carbonate inclusions. The test area is collectively known as the Werribee plains which is covered almost exclusively by the weathered products of Quaternary age basalts, locally known as 'Newer Volcanics'

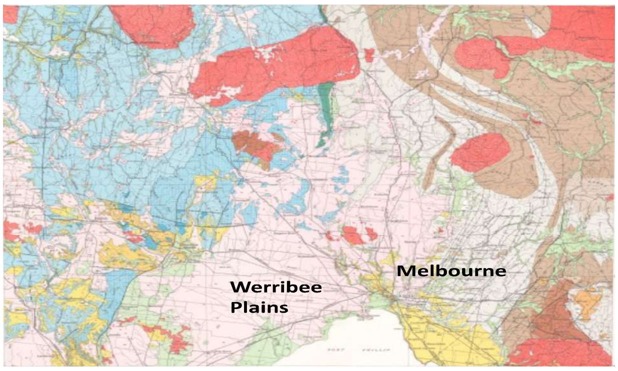

Figure 1: - Location of research area in Werribee Plains, Melbourne (after AGS Map, 2017).

After developing a new test method to measure shrink and suction (using a WP4C psychrometer) CCS and SWCC curves were drawn from 84 samples collected from damage-affected houses. From figure 2a the *I*ccs (≡ *I*ps) can be calculated and from 2b the moisture/suction state of the foundation soil can be estimated from simple moisture tests. This is a great help in forensic work. Example Pt. Cook B.H. 1 at 0.5m

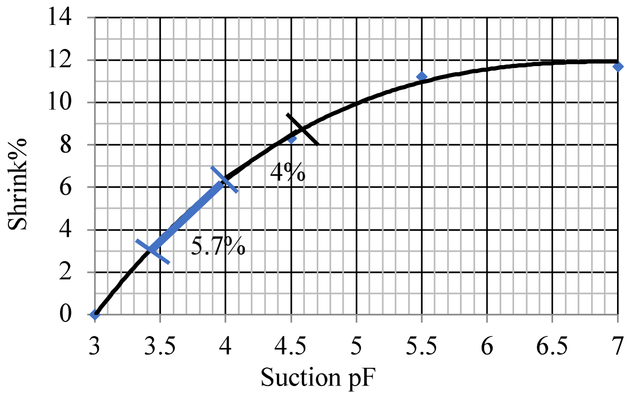

Figure 2: - CCS graph from a typical Point Cook house site.

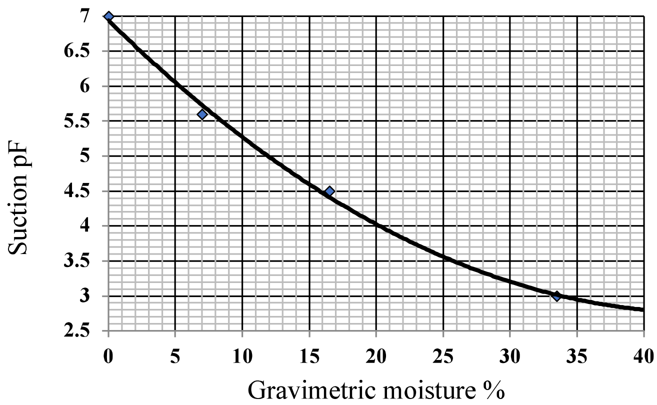

Figure 3: - SWCC from same site and tube sample in figure 2.

In figure 2 the curve can be simplified to two straight lines giving I_{ccs} values of 5.7% at 3.1–4.0 pF and 4.0% at 4.0–4.6 pF. In figure 3 suctions can be estimated and compared with 'Normal' conditions. These graphs can also be used to approximate the amount of ground movement that may occur in various climatic conditions. Allowing for the α factor as outlined in AS2870 this site would be at least a H2 site.

3 SOIL MOISTURES, CCS & SWCC RESULTS

887 samples were collected by 'R. I. Brown', 'USL Group' and 'J.M. Fieldwork' and tested for gravimetric moisture. After discarding the results from sites with the following conditions 267 remained.

1) If the ground had been heavily watered near test area.
2) Where free surface water was noted near test hole(s).
3) A water or sewer pipe leak detected nearby.
4) Samples taken at depths <300 mm and >700mm.
5) Samples with substantial calcrete content.
6) Recent heavy rain.
7) Poor drainage around sample point.
8) Re-developed older building sites.
9) Soil fill or with multiple roots.
10) Samples from non-basaltic environments.

This selection was designed to exclude 'Abnormal' moisture conditions as described in AS2870.

The sampling dates of the 267 samples were compared with the rainfall records and grouped accordingly as 'drought', 'wet' and 'transitional. ('Transitional' describes the short period between 'La Nina' and 'El Nino' in 2012-2014). The results and time lines are shown in tables 2 and 3.

Table 1: 90 percentile moisture and suctions 1997-2016. (Refer Figure 3)

Climate period	Moisture range	Suction interval
Drought	11.0% - 22.0%	5.3 - 4.1pF = 1.2pF
Wet	30.0% - 41.0%	3.4 - 3 0pF = 0.4pF
Transitional	22.0% - 30.0%	4.1– 3.4pF = 0.7pF
Total Δus during test period = 2.3 pF.		

Table 1 indicates that building during a severe drought period exposes the edge of slabs to a maximum suction variation of up to 2.3 pF if a very wet period were to follow immediately (such as in 2011). In this case the 'Natural" surface soil moisture could rise from 11% to 41%.

If a severe drought were to follow a wet period the moisture variation could be similar however droughts are much slower to change the ground moisture than a heavy downpour therefore the home owner would have time to reduce the ground desiccation (provided there are no severe water restriction!).

Building in a 'transitional' period the maximum surface soil moisture variation would be 22% to 41% = 19% ≡ 1.1 pF or 30% to 11% = 19% ≡ 1.9 pF. However this latter change from transitional to severe drought gives the home owner time to prevent the worst drying which only occurs around the edges.

It is important to note however that the suction to shrink/swell is not linear (refer figure 2) i.e. 4% in the dry soil and 5.7% in moist soil therefore (as most practitioners have found) wet periods after severe droughts are the worst-case scenario and cause more damage than during the drought alone.

Table 2: Dates and climatic conditions

Sampling period	Climate	Comment
1997 - 2009	Drought	'Millennium' drought
2010 - 2011	Wet	Record wet La Nina
2012 - 2014	Transitional	Short El-Nino/La Nina
2014 – mid-2016	Drought	Dry El Nino

Table 3: 90 percentile moistures and suctions from CCS & SWCC, 2014-2017. (Refer Figure 4).

Climate period	Moisture range	Suction interval
'Drought'	10.5% - 17.0%	5.3 - 4.5 pF = 0.8pF
'Wet'	31.0% - 40.0%	3.4 - 3 0 pF = 0.4pF
'Normal'	17.0% - 31.0%	4.5 – 3.4 pF = 1.1pF
Total maximum Δus during test period = 2.3 pF		

The data in table 3 gives similar results.

The data in figure 4 was derived from CCS and SWCC tests (Lopes) and only the 90 percentile were plotted whereas in figure 4 the moistures were derived from (Brown) and all of the results were plotted. The suctions were calculated by comparing Brown's moistures with the suctions in figure 3 at the corresponding moistures.

In figure 4 the 90 percentile Δus was 11% - 40% = 29% which is equivalent to 2.3 pF. In Figure 4 the total moisture range was 8% - 40% and the Δus was ≡ to 2.6 pF. Considering the large area involved, it is not realistic to use the full range of moistures and suctions for any ground movement calculations for any discrete site. The authors are more inclined to recommend a higher Δus in the triangular design model in AS2870 where the site warrants it.

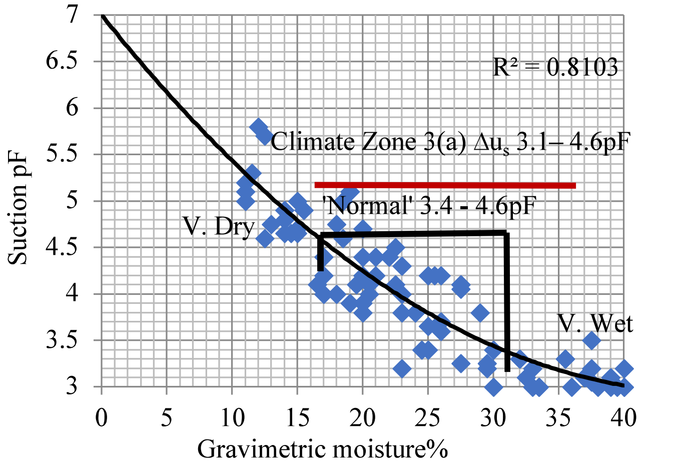

Figure 4 – 90 percentile grouped SWCC results (Lopes)

This figure also shows an estimate of the increased Δus due to site inundation or poor drainage (an increase from 1.2 to 1.5 pF). It was also observed that the greatest house damage occurred in 2011 as a result of swelling of the very severe drought which affected the foundation clay; hence the authors suggest that allowance should be made for these conditions in these and similar dry sites in designing footings.

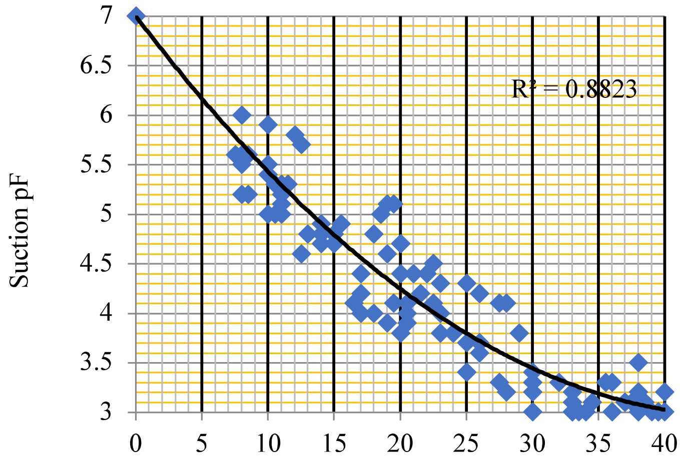

Figure 5 – All gravimetric moistures/suctions (Brown)

4 EXAMPLE OF MOISTURES AND SUCTIONS

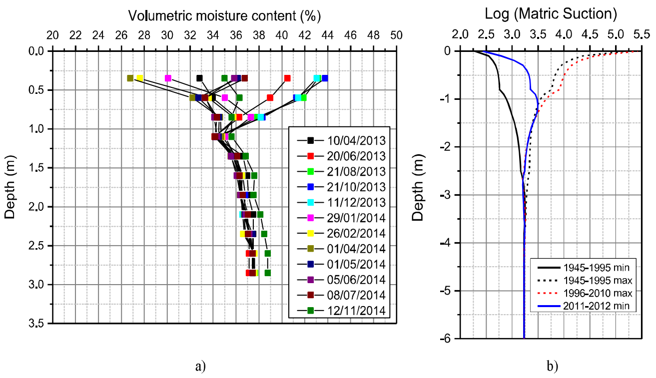

Figure 6: Monitored data and modelled results. (Karunarathna).

Author[2] measured seasonal soil moisture and suction since 2012 Braybrook, Victoria, Australia. These figures highlight the effects of recent extreme climate events. The results indicate that the surface suction changes are greater than 1.2 pF and are in line with the conclusions of this study, (Karunarathne, 2016). e.g.: Δu_s = 2.3 – 5.3 pF = 3 pF and maximum ΔGm% (at 300 mm depth) ~27 – 43% = 16%.

5 CCS IN OTHER SOIL TYPES

It is expected that the younger marine sedimentary clays will have significant osmotic suction due to salt content. This has added a new dimension to the importance of more field testing due to the salt and other chemical variations in addition to the variation of marine sand content. Marine Limestone clays in Southern Victoria have high plasticity and, in places, have been eroded and deposited in lakes with a great variety of terrestrial inclusions.

In the South East of Melbourne such as in and around the Berwick, Clyde and Cranbourne suburbs there are volcanic mixtures such as Basalt lava flows, Pyroclastics and Tuff that are also highly water-reactive and sometimes mixed with alluvial soils. In these areas the soil variation extremely variable due to a variety of volcanic, granitic, and sedimentary outcrops and lake deposits containing many soil mixtures.

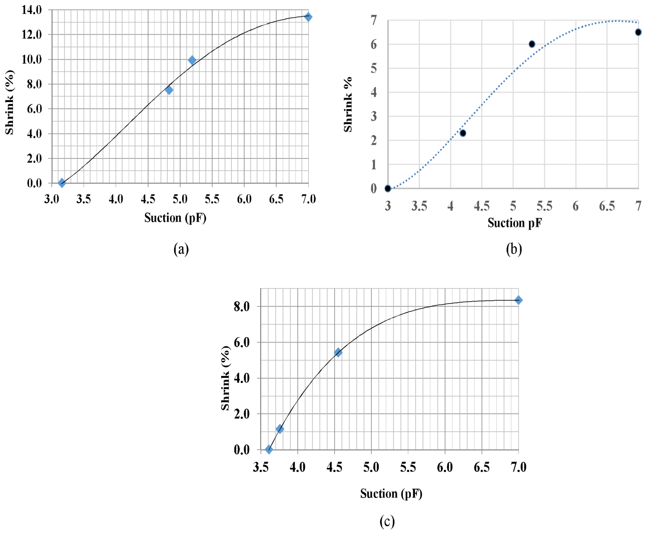

Figure 7 a),b),c) - CCS results in other areas;

7a) Tertiary age pyroclastic clay- Clyde North;
7b) Silurian sediment- Clyde North;
7c) Tertiary age basaltic clay- Cranbourne West.

Recently this research has been extended to testing samples from other soil types in Melbourne

6 CONCLUSIONS & RECOMMENDATIONS

This paper includes field and laboratory data obtained during an extreme climate period (1997-2016) and has concentrated on two ground movement parameters, namely the range of surface suction/moistures and soil instability indices.

The recent extreme climate conditions pushed the limits of 'normal' surface suction changes and has caused an increase in ground and footing movements and subsequent house damage. Whether these values occur in any one particular site is doubtful and has not been evidenced by measured slab movements; however Δus >1.2 pF have been measured and will continue to occur in areas where these basaltic clays are exposed to severe droughts followed by heavy drought-breaking rains or are subject to inundation conditions hence Engineers should consider using a minimum Δus of 1.5 pF in their ground movement calculations.

This study also shows that in numerous sites the design surface suction change specified in the standard AS2870 has been exceeded by significant margin from 1.2 pF to ≥1.5 pF, therefore causing underestimation of characteristic ground movement.

The review of the research produced has indicated that there are more questions to be answered. Australian Codes require amplification for both Limit State and when data is less than 50-100 years old (i.e. AS1170 series and AS3500 series). Testing has shown that the 'Normal' conditions are not always achievable in many building sites. The authors suggest that some flat land which is inundation-prone and has a large percentage of highly expansive soils requires a larger design surface suction (Δus 1.5 pF). A similar or larger value should also be considered in the driest climate zones.

It is generally agreed that the causes of inundations around houses built on highly expansive soils is critical. Thornthwaite Moisture Index (TMI) information is helpful but not singularly successful in a site classification. Soil moisture investigation at least 0.75 *H*s (other than in rock or permanently shallow water table areas) is suggested to establish the true building platform moisture conditions prior to slab construction. This places difficulties on the designer and builder, however, its importance cannot be understated, the maintenance of the as-built moisture conditions should be conveyed to the owners and subsequent owners in writing.

Much of the suction variation measured could be attributed to very poor natural drainage and other man-made causes which could be avoided or greatly reduced. The more extreme soil moisture conditions could be avoided with better garden care, re-usable water systems and avoiding garden water restrictions.

The research to date does not answer all the questions but demonstrates that changes to the AS2870 site classification model is required. Authors[1 & 2] are working on new site classification models and author[3] on a simplified version of free swell test each of which are expected to be published in the near future. In addition, testing for causations of flooding of building service trenches is expected to also require further research.

Although basalts and their products cover large areas in the eastern states of Australia there are significant variations in other soil types (particularly in soils derived from limestone or clayey marls) which require more rigorous field and laboratory testing that is presently undertaken. The calculation of ground movement (y_s) is a very complex issue and requires many other considerations not able to be discussed in this paper.

NOTATIONS:

CCS: Conditioned Core Shrinkage Test.
Δu: Soil suction change.
Δu_s: Soil surface suction change.
Gw: Gravimetric water.
α: Lateral and vertical restraint factor.
I_{ps}: Shrinkage or instability index without lateral or loading restraint.
I_{ccs}: Conditioned shrink index.
SWCC: Soil-water Characteristic Curve
y_s : Characteristic surface movement.

APPENDIX: BRIEF DESCRIPTION OF CCS & SWCC TESTS

This test is performed using two intact and near-identical soil cores sampled with thin-walled Shelby tubes. The sample tubes are 38 mm in diameter and are preferred over 50 mm diameter tubes due to a much shorter conditioning time and being much easier to collect. In southern summers and autumns it is very difficult to drive the larger tubes in very stiff clays with one-man drill rigs. For these reasons the authors consider the sample disturbance to be similar for either tube sizes.

The conditioning process is to achieve similar initial suction values ranging from 3 - 3.5 pF. Conditioning samples to this range of suctions avoids the error in measuring soil indices at different initial moistures such as in some other tests. A 'Dew-point mirror' psychrometer is used to measure suctions, shrink and moisture values in each sample at 3 different moistures. These readings are taken from near-identical samples cut from the same tube. The test method allows one technician to carry out multiple tests simultaneously with only one psychrometer and complete numerous tests within 4 - 7 days. The CCS test measures the core shrinkage and suction during each test interval and the SWCC values are also read at the same test suction intervals. This allows the plot of 3 parameters: moisture, suction and shrink.

The soil cores are extruded and trimmed as two near-identical samples (A and B) each to 90 mm length. They are then wrapped in thin and wet kitchen sponges and secured in de-ionised water in small container and allowed to condition for 3 - 4 days (depending on soil plasticity and field moisture). In some cases the samples arrived at the laboratory at the correct suction range and required no conditioning. At the completion of the conditioning they are unwrapped and each trimmed to a length of 60 mm. Sample A is used for shrinkage testing and weighing and B for suction testing. Each of these processes are carried out quickly and simultaneously. Both samples are kept wrapped in dry kitchen sponges until ready for each subsequent test. Suction and shrink is measured at 3 - 3.5 pF, 4.0 - 4.5 pF, 4.5 - 5.0 pF and estimated for 7 pF at oven-dry. Once the sample is oven dried the moisture for each testing stage can also be calculated to plot the SWCC.

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