Assessment of Soil Reactivity: Tahmoor/Thirlmere region

Prepared for

Subsidence Advisory NSW

Prepared by

Professor Stephen Fityus and Dr Glen Burton

The University of Newcastle

March 2019

Executive Summary

This report describes site investigations and classifications undertaken on a selection of sites of interest to Subsidence Advisory NSW. These were deemed to be representative of reactive clay soil conditions that occur across the three different geological domains that are found in the Tahmoor-Thirlmere area: the Bringelly Shale, the Ashfield Shale and the Hawkesbury Sandstone. The reliability of geological map data to predict the subsurface geological conditions was found to be poor.

The fieldwork in September 2018 involved sampling using a special-purpose sampling rig operated by Grace Coring, to push a heavy-walled sampling tube into the ground in one metre intervals, to recover an intact continuous core of the ground below. In all, 16 soil profiles were sampled to between 1 and 3m deep, with a total of 34 tubes of sample recovered. Subsequent laboratory testing of specimens from the extracted cores included 28 shrink swell tests; 28 Atterberg limit tests; 28 linear shrinkage tests and soil suction and water content profiles.

For the Bringelly Shale profiles, the plasticity indices are between 17 and 26% with a mean of 21.8% and the linear shrinkage values range from 7 to 14% with a mean of 10.3%. By contrast, the Ashfield Shale profiles display plasticity index values between 10 and 52% with a mean of 33.5%, and linear shrinkage values range from 5.5 to 20.7% with a mean of 13.1%. The majority of soils derived from the Hawkesbury Sandstone are low plasticity or non-plastic.

Shrink-swell testing showed that on average, the Ashfield Shale-derived soils were most reactive, with an average I_{ss} value of 2.1 %strain/pF unit, and a range of 0.7 to 3.0 %strain/pF unit, with one outlier of 3.9 %strain/pF unit. The Bringelly Shales had an average I_{ss} value of 1.3 %strain/pF unit, and a range of 1.1 to 2.3 %strain/pF unit. Hawkesbury Sandstone soils were, as expected, least reactive. Correlation of shrink-swell index to linear shrinkage was poor.

A surface suction range of 1.2 pF units was adopted for the study area. A depth of seasonal moisture change H_s of 2.2m is recommended for the Tahmoor-Picton area, based on TMI values calculated for Picton Council Depot, Campbelltown Swimming Centre and Camden Airport AWS, from available Bureau of Meteorology data. The depth of cracking was taken as 1.2m.

Following the approach of Section 2 in AS2870-2011, characteristic ground surface movements (y_s) of the deeper clay profiles (>~1.5m) were calculated to be around 30-35mm, and the characteristic ground movements of the shallower clay profiles are of the order of 15-20 mm. Overall, the sites assessed were dominantly class S (14 sites) with less common class M (3 sites) and one site which was borderline class S/class M. Only one site approached class H, and that site (SA Hawk 4) was borderline M/H. These values are lower than expected, but considered to be reasonable estimates.

If the values are compared with those based on identified soil profiles in the Sydney area, they are lower than suggested in Table D2 of AS2870, which indicated that many of the deeper clay sites in this area could be expected to be class H. Further, if the I_{ss} values are recalculated using a crack depth of only 0.5m, they are found to increase by 10-20mm, pushing some of the assigned classes into a higher category. However, there is no good basis for taking these values over those based on direct measurement and rigorous calculation of a y_s.

It is noted that this work was undertaken whilst the region was experiencing an especially dry period, and the sampled soils were tested from very dry initial conditions. Whilst this might have some influence on the shrink-swell index values determined, it is considered the measured I_{ss} values provide a good basis for the y_s calculations, and that these values are good estimates of the characteristic ground surface movement in accordance with AS2870-2011.

1.0 Agreed Scope

In accordance with your letter dated 5th September 2018, and in accordance with the scope of RFx123161, Professor Stephen Fityus and Dr Glen Burton from the University of Newcastle have undertaken an assessment of reactivity in the Tahmoor Picton region. According to our accepted proposal, the scope of the work was to:

- Sample 8-10 sites using a push tube rig, across the three different geological settings of the area to recover either 2 or 3 one metre long, 100mm diameter continuous, intact soil samples from each site, where possible.
- Undertake shrink swell testing of 2 or 3 sub-samples from the tubes recovered from each site (minimum 20 tests).
- Atterberg limit tests from three depths within each hole would also be completed.
- Undertake an analysis of available climate data to estimate the Thornthwaite Moisture Index (TMI) for the area, and from this, infer depths of seasonal moisture change.
- Perform calculations based on the logged soil profiles and the shrink swell test data to determine characteristic ground movement values that can be correlated to site classifications according to Section 2 of AS2870-2011.
- Provide a summary report of results containing borehole logs, test results, predicted characteristic ground movements, site classifications and a map showing borehole locations.

The area for assessment was identified as that bounded by the pink line in Figure 1.

Figure 1: Area indicated for assessment (email from J Johnston, 19/7/2018)

2.0 Work Completed

A meeting was held with Mr John Johnston of Subsidence Advisory NSW on 17 September to agree upon a selection of properties in the area to target for investigation. Twelve locations, comprising 6 properties owned by Subsidence Advisory and 6 areas currently designated as parks and public reserves were identified, in order to achieve some potential redundancy in achieving the intended investigations of 8-10 sites. They were also selected to be representative of the three different geological domains that are found in the area: the Bringelly Shale, the Ashfield Shale and the Hawkesbury Sandstone, according to the geological outcrop information available through the NSW Department of Minerals data sets. The identified sites are indicated in Figure 2.

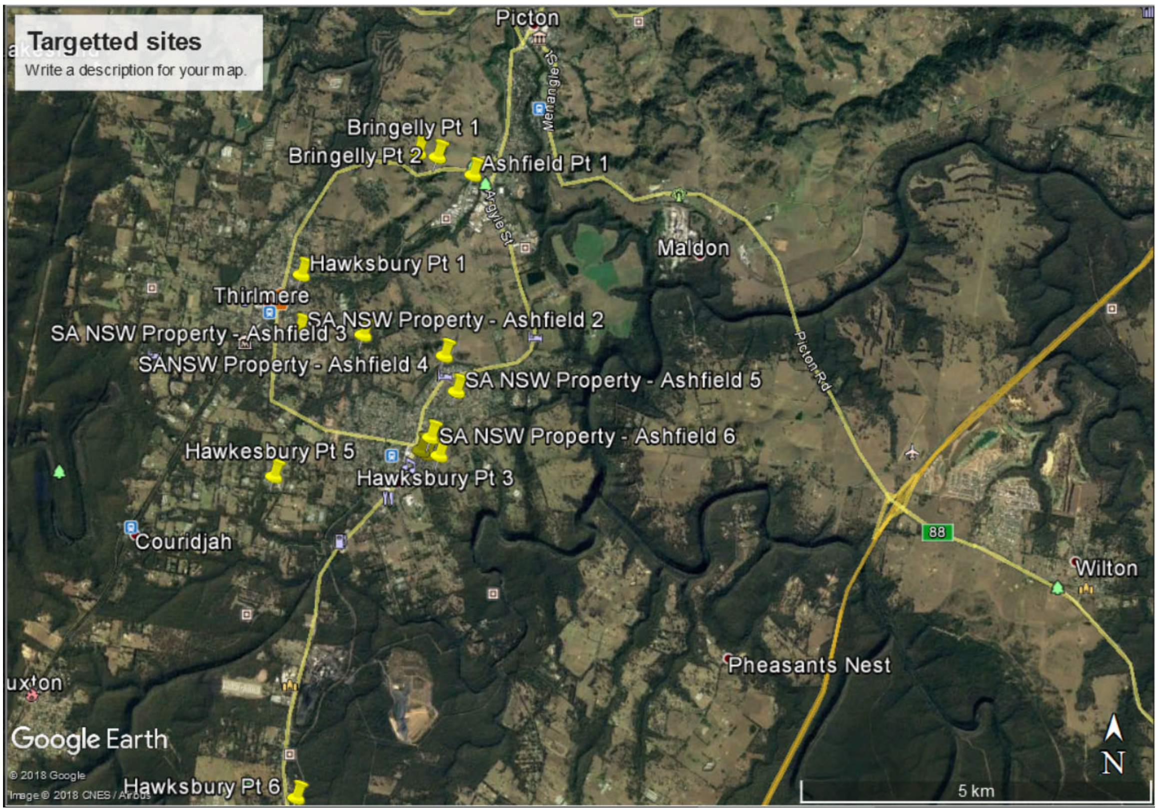

Figure 2: Sites targeted for assessment, as agreed with J Johnston, 17/9/2018. (Properties owned by SA are prefaced by SA; Ashfield, Bringelly and Hawkesbury denote the expected geological provenance.)

The fieldwork for this study was completed on 24-26 September. Sampling took place on 25-26 September after clearing the sites for services with assistance from a professional services locator, using *Dial before you dig* information.

Samples were taken using a special-purpose sampling rig operated by Grace Coring. This rig, shown in Figure 3, was able to push (by hammering) a heavy-walled sampling tube into the ground in one metre intervals, to recover an intact continuous core of the ground below.

In all, 16 soil profiles were sampled to between 1 and 3m deep, with a total of 34 tubes of sample recovered. The actual sites sampled are shown on Figure 4. Consistent with the labels in Figure 2, the prefaces "Ash", "Bring" and "Hawk" denote the expected geological provenance at the site. Logs of each sampled profile have been produced from the recovered samples.

Figure 3: Sampling operation using the Grace Coring rig.

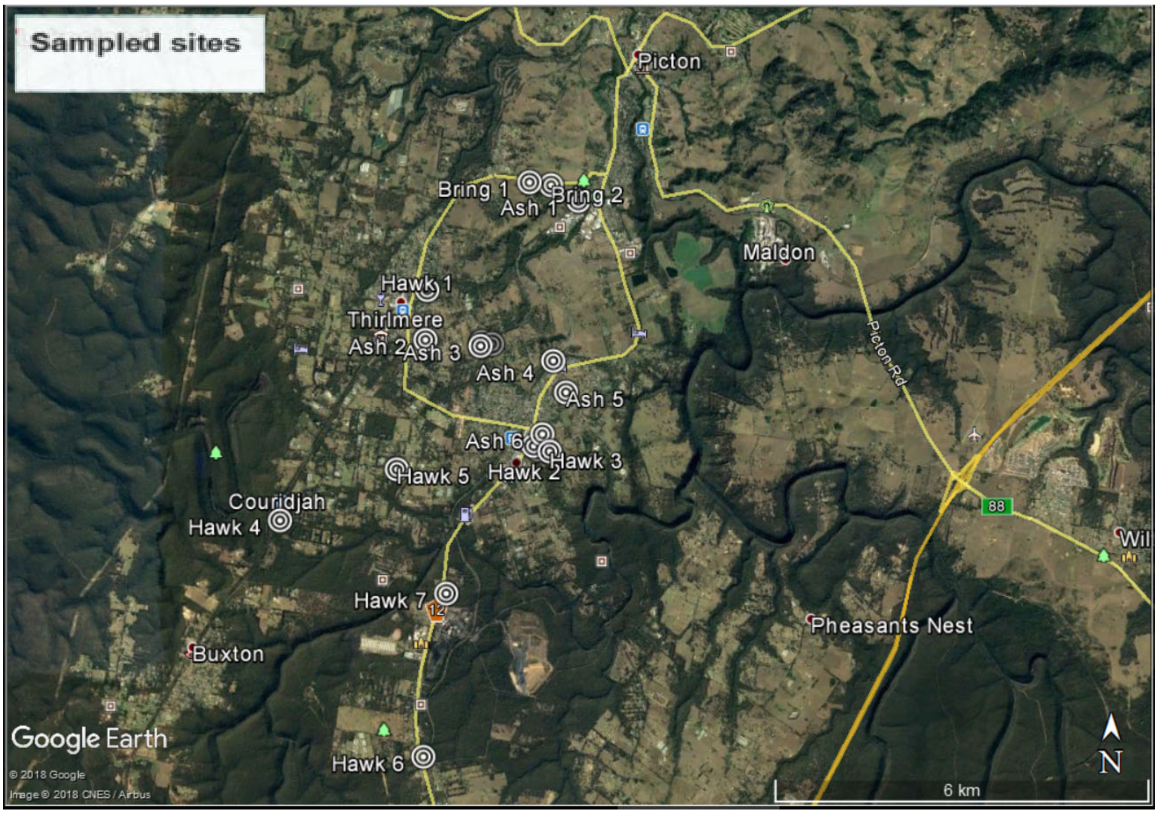

Figure 4: Sites sampled in this study, as agreed with J Johnston, 17/9/2018. (Ash, Bring and Hawk denote the expected geological provenance in the Ashfield, Bringelly and Hawkesbury, respectively.)

Laboratory testing of specimens taken from the extracted cores included:

- 28 shrink swell tests,
- 28 Atterberg limit tests (plastic limit and liquid limits by fall cone),
- 28 linear shrinkage tests,
- Soil suction and water content profiles.

Tests were generally carried out in accordance with the relevant parts of AS1289, except where noted.

Amongst the samples tested for Atterberg limits and linear shrinkage were two disturbed samples taken from a soil profile exposed in the Bringelly Shale, between Bring1 and Bring2. This profile, denoted Bring OC, was logged and sampled to augment the data on the Bringelly Shale, which was generally very poorly represented in the study area.

3.0 Observations and Test Results

Logs of all of the sampled profile are presented in Appendix A.

The first important observation of the soil profiles sampled is that the boundaries between Ashfield Shale and Hawkesbury Sandstone sub-crops are inaccurate as they are shown in the available geological data sets. It happened in the site selection that many of the sites of interest fell close to this geological boundary, with the expected geological conditions to be encountered being inferred from the geological data. However, for 6 of the sampled sites, the actual conditions encountered were not those anticipated. Specifically, for four of the sites that were expected to be underlain by Hawkesbury Sandstone, shale was encountered; and for two of the sites that were expected to be underlain by Ashfield Shale, sandstone was encountered. A summary of the expected and encountered conditions is presented in Table 1.

Sample site	Expected conditions	Actual Conditions	Depth Sampled (m)
Bring1	Bringelly Shale	shale	1.0
Bring2	Bringelly Shale	shale	1.8
Ash1	Ashfield Shale	shale	2.8
Ash2	Ashfield Shale	shale	2.0
Ash3	Ashfield Shale	shale	2.0
Ash4	Ashfield Shale	sandstone	1.0
Ash5	Ashfield Shale	shale	1.6
Ash6	Ashfield Shale	sandstone	2.0
Hawk1	Hawkesbury Sandstone	sandstone	1.0
Hawk2	Hawkesbury Sandstone	shale	2.9
Hawk3	Hawkesbury Sandstone	shale	2.9
Hawk4	Hawkesbury Sandstone	sandstone	1.0
SAHawk4	Hawkesbury Sandstone	shale	2.65
Hawk5	Hawkesbury Sandstone	shale	1.7
Hawk6	Hawkesbury Sandstone	sandstone	0.8
Hawk7	Hawkesbury Sandstone	sandstone	0.9

Table 1. Summary of sampled sites comparing expected and encountered conditions. Note that in the remainder of this report, profiles in weathered shale are shown purple (Bringelly) and blue (Ashfield) and profiles in weathered sandstone are shown in orange, irrespective of their name.

The locations of the sampled sites are shown in Figure 5. It is evident from Inset C in Figure 5, and the data in Table 1, that the geological boundaries are particularly unreliable in the Tahmoor area.

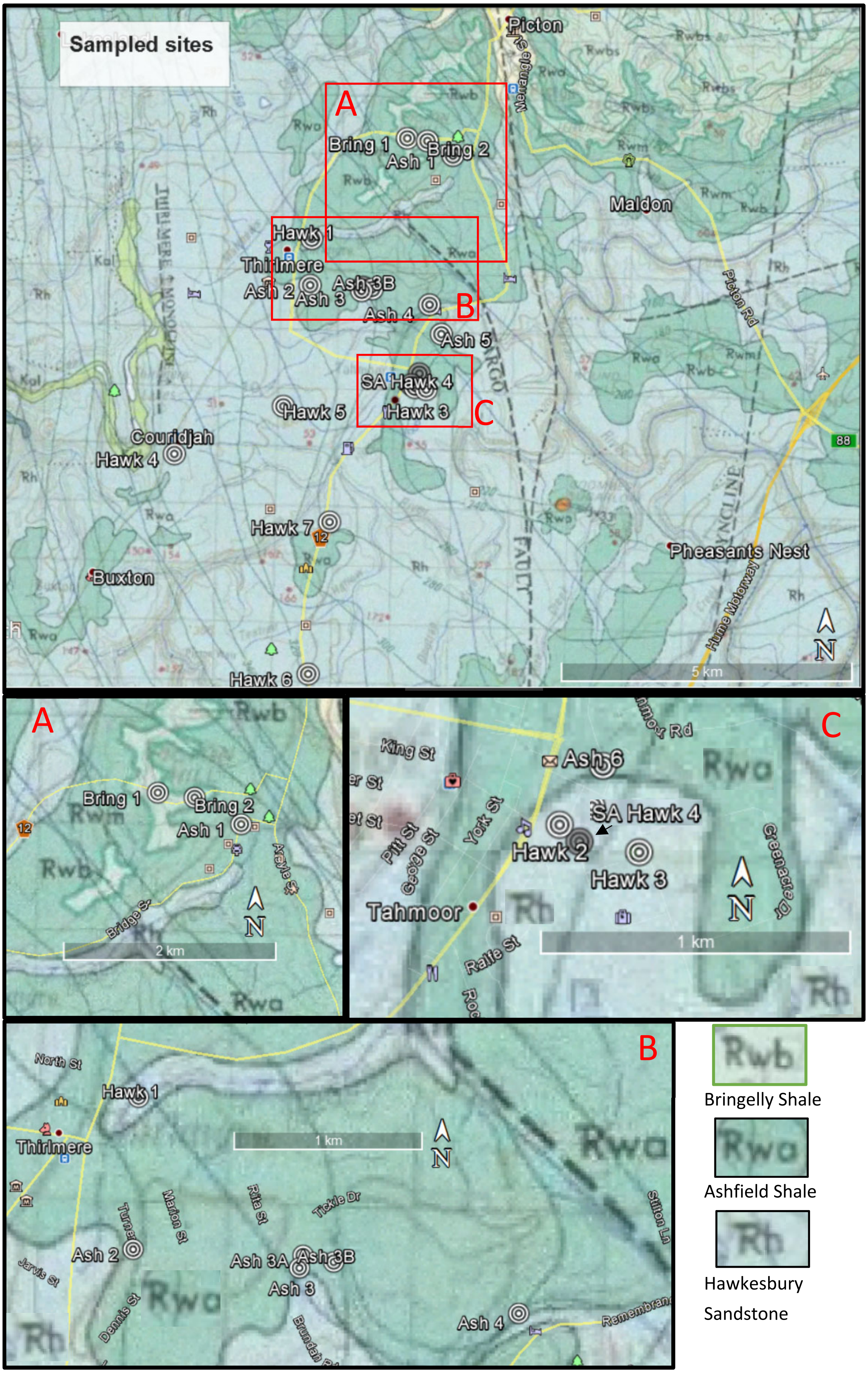

Figure 5: Locations of the sites sampled relative to the expected geological conditions according to the available geological data.

4.0 Soil moisture data

An overarching observation from the both the field testing and laboratory testing campaigns was that the soils were, with few exceptions, very dry and hard at the time of sampling. Despite being sampled at the very beginning of spring, the ground in the studied area was dry to an extent that might be expected at the end of a long, dry summer. This is considered unusual from a general seasonal perspective, but consistent with the anomalously dry conditions that had prevailed for most of the preceding 12 months.

Figure 6 presents the profiles of water content and suction in the samples at the time of sampling. Total suctions were measured using a WP4C dewpoint potentiometer from Decagon Devices.

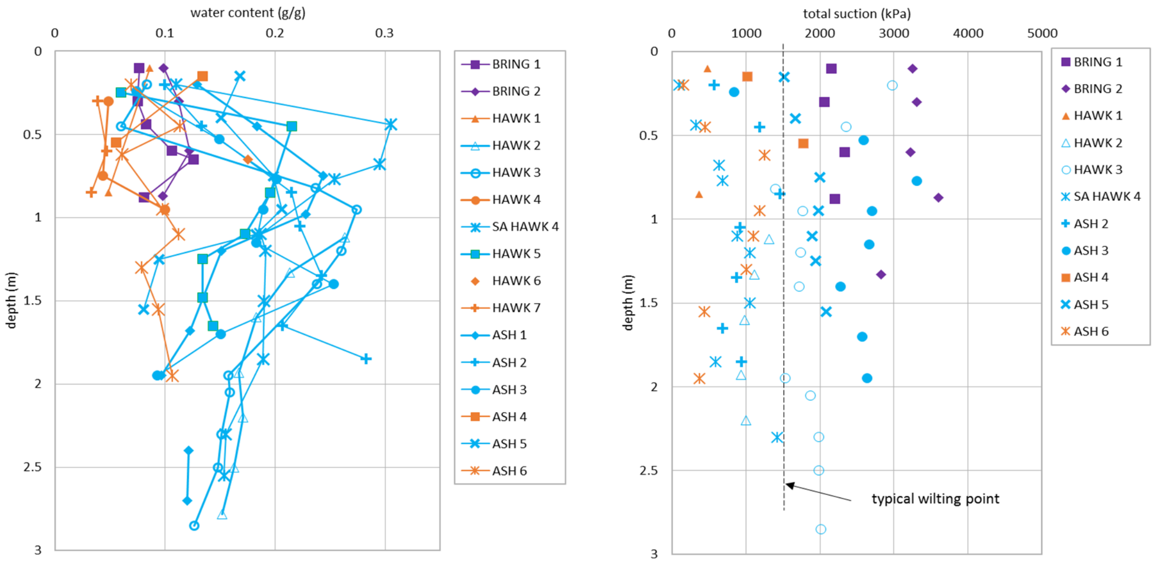

Figure 6: Water content (left) and total soil suction (right) profiles at the time of sampling. Note that profiles in weathered shale are shown purple (Bringelly) and blue (Ashfield) and profiles in weathered sandstone are shown in orange.

It is readily apparent that the sandstone and Bringelly Shale profiles were very dry, with water contents less than 10%, whereas profiles in the Ashfield Shale were somewhat wetter with water contents mostly between 10 and 25%, and wetter in the depth interval from 0.5 to 1.5m. Despite this, the suctions in the sandstone were generally lower, reflecting the substantially different water retention properties of the sandier materials. By contrast, the Bringelly profiles and the Hawk3 and Ash3 Ashfield Shale profiles were very dry, with suctions as much as twice the value generally considered to represent the wilting point of typical vegetation.

5.0 Soil plasticity data

Table 2 presents the results of the Atterberg limit tests and linear shrinkage tests. The last two lines have the average values of all samples derived from the Bringelly and Ashfield Shales, for comparison. For the Bringelly Shale profiles, the plastic limits consistently vary between 15 and 22% with a mean of 19.6%; the liquid limits consistent vary between around 35 and 47% with a mean of 41.3%; and the plasticity indices are between 17 and 26% with a mean of 21.8%. The linear shrinkage values range from 7 to 14% with a mean of 10.3%. The relatively strong consistency within these Bringelly Shale values may be because all three sampling sites fell within a distance of only 250m.

Profile	Sample depth (m)	Geological provenance	Liquid limit (%)	Plastic limit (%)	Plasticity Index (%)	Linear Shrinkage (%)
Outcrop C	0.5	Bringelly Shale	44	20	24	8.1
Outcrop C	1.2	Bringelly Shale	41	20	21	6.9
Bring 1	0.44-0.64	Bringelly Shale	33	15	18	9.8
Bring 1	0.65-0.85	Bringelly Shale	47	23	24	10.5
Bring 2	0.20-0.35	Bringelly Shale	40	19	21	11.5
Bring 2	0.37-0.52	Bringelly Shale	47	21	26	14.3
Bring 2	0.62-0.76	Bringelly Shale	43	20	23	13.8
Bring 2	1.4-1.5	Bringelly Shale	37	18	19	7.5
ASH 1	0.75-0.95	Ashfield Shale	91	38	53	19.6
ASH 1	1.00-1.20	Ashfield Shale	61	27	34	16.2
ASH 1	1.45-1.65	Ashfield Shale	47	25	22	7.1
ASH 2	0.50-0.68	Ashfield Shale	63	31	32	17.3
ASH 2	1.80-2.00	Ashfield Shale	78	33	45	20.7
ASH 3	0.55-0.75	Ashfield Shale	58	29	29	16.5
ASH 4	0.60-0.80	Hawkesbury Sast.	38	16	22	13.5
ASH 5	1.35-1.55	Ashfield Shale	27	16	11	6.7
ASH 6	0.75-0.90	Hawkesbury Sast.	34	14	20	9.1
ASH 6	1.70-1.85	Hawkesbury Sast.	42	14	28	4.4
HAWK 1		Hawkesbury Sast.	assessed to be everywhere non plastic			
HAWK 2	1.70-1.90	Ashfield Shale	58	25	33	15.0
HAWK 2	2.00-2.18	Ashfield Shale	51	23	28	12.2
HAWK 3	2.85-2.90	Ashfield Shale	52	21	31	5.7
HAWK 4		Hawkesbury Sast.	assessed to be everywhere non plastic			
SA HAWK 4	0.55-0.77	Ashfield Shale	81	34	47	16.9
SA HAWK 4	0.77-0.90	Ashfield Shale	76	29	47	17.6
SA HAWK 4	1.50-1.70	Ashfield Shale	50	21	29	12.0
SA HAWK 4	1.50-1.70B	Ashfield Shale	52	21	31	5.5
SA HAWK 4	2.00-2.24	Ashfield Shale	42	17	25	11.1
HAWK 5	0.6-0.8	Ashfield Shale	71	32	39	16.1
HAWK 5	1.25-1.45	Ashfield Shale	58	23	35	6.4
HAWK 6		Hawkesbury Sast.	assessed to be everywhere non plastic			
HAWK 7		Hawkesbury Sast.	assessed to be everywhere non plastic			
Averages						
Bringelly	average	Bringelly Shale	41	20	21	10.3
Ashfield	average	Ashfield Shale	60	26	34	13.1

Table 2. Summary of Atterberg limit values.

By contrast, the Ashfield Shale profiles display much wider variability with greater maximum values. The plastic limits vary between 17 and 38% with a mean of 26.2%; the liquid limits vary widely between around 27 and 90% with a mean of 59.7%; and the plasticity indices are between 10 and 52% with a mean of 33.5%. The linear shrinkage values range from 5.5 to 20.7% with a mean of 13.1%.

The Atterberg limit data is plotted on the Casagrande chart in Figure 7. According to this, the soils derived from Bringelly Shale classify as clays of medium plasticity whereas the soils derived from the Ashfield Shale classify as clays of medium but mostly high plasticity.

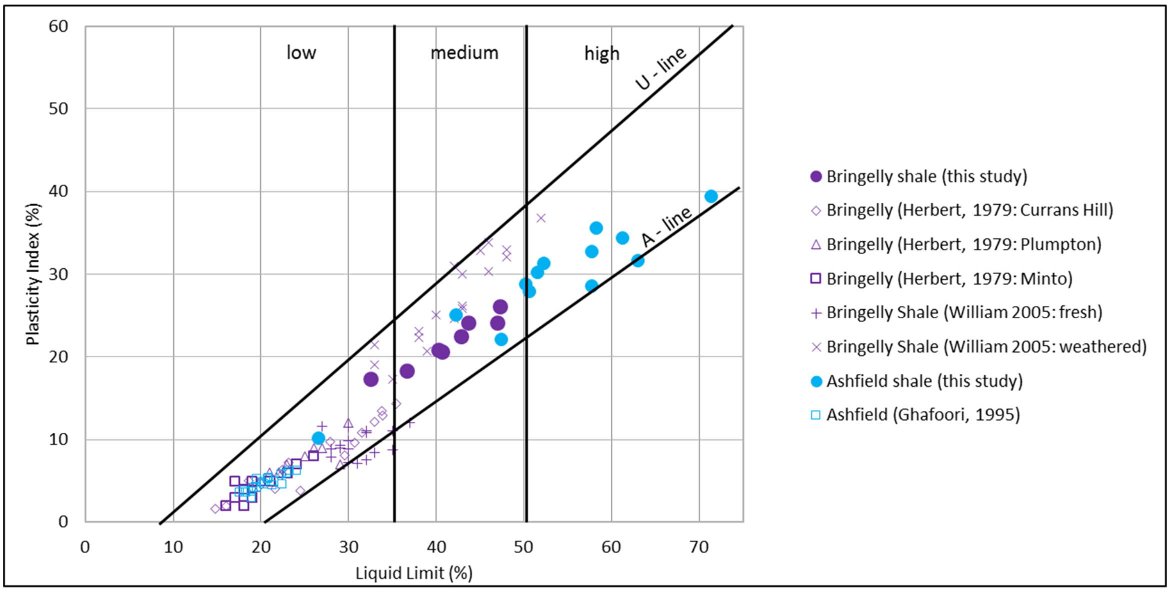

Figure 7: Atterberg limit test results compared with literature data for the Ashfield and Bringelly shales on the Casagrande chart.

Also plotted on this figure is Atterberg limit data from previous studies reported in the literature. For the majority of these, the materials tested were remoulded shales rather than residual soils, and the plasticities are not surprisingly, lower than that of the soils tested here. The exception to these are the weathered Bringelly Shales of William (2005) which like the Bringelly clay soils tested here, also plot as clays of medium plasticity.

6.0 Shrink-swell Index data.

28 shrink-swell tests were carried out on samples taken during this study. The method of AS1289-2003 was generally followed except that the extreme dryness of the samples meant that sample preparation by conventional push tube and wire-saw trimming was not possible. Instead, ~50mm diameter shrinkage cores were cut from the larger 100mm diameter sample cores using a diamond saw, and swell specimens were formed by pushing oedometer rings into trimmed blocks of soil using a 5 tonne load frame, before being ground using an electric sanding disc, to achieve flat, parallel surfaces. Examples of typical shrinkage cores are shown in Figure 8. In this way, even brittle dry soils containing ironstone gravels could be trimmed and prepared to give appropriate specimens for the shrink-swell test

Where cores proved sufficiently coherent, at least one sample was prepared from each location. Locations where no tests were performed, the cores over their entire length proved too friable for samples to be prepared, and these mostly corresponded to sandy rather than clayey materials. Samples were targeted from the upper 2.2 m (H_s) of the cores, however, two samples from below 2.2m were also tested for HAWK 2 and HAWK 3 where a thickness of fill was identified and the samples fell within the upper 2.2m of the original ground surface. In total, 5 samples were tested from the two profiles within the Bringelly Shale; 20 samples were tested from the eight profiles that were judged as deriving from the Ashfield Shale; and 3 samples were tested (all clayey sands) from within the six profiles derived from Hawkesbury Sandstone.

Figure 8: Typical shrinkage cores after cutting and shaping with a diamond saw

The shrink-swell test results are presented in Table 3. Note again, that the results are colour coded so that samples judged to be derived from Hawkesbury Sandstone are in orange text; samples derived from Ashfield Shale are in blue text; and samples derived from the Bringelly Shale are in purple text. On average, the Ashfield Shale-derived soils were most reactive, with an average I_{ss} value of 2.1 %strain/pF unit, and a range of 0.7 to 3.0 %strain/pF unit, with one outlier of 3.9 %strain/pF unit. The Bringelly Shales had an average I_{ss} value of 1.3 %strain/pF unit, and a range of 1.1 to 2.3 %strain/pF unit, with one outlier of 0.1 %strain/pF unit. Hawkesbury Sandstone soils were, as expected, least reactive. In most places they were non-plastic, but even where they were clayey, the average I_{ss} value was 0.8 %strain/pF unit, and a range of 0.7 to 1.3 %strain/pF unit, with one tested sample actually proving to be totally unreactive (I_{ss} =0).

Sample reference	Swelling strain	Shrinkage strain	I_{ss} (%strain/pF)	Liquid limit (%)	Linear shrinkage (%)
Bring 1 0.44-0.64	-0.002	0.000	0.1	32.5	9.8
Bring 1 0.65-0.85	-0.069	0.000	1.9	47.0	10.5
Bring 2 0.37-0.52	-0.038	0.005	1.3	47.3	14.3
Bring 2 0.62-0.76	-0.074	0.004	2.3	42.8	13.8
Bring 2 1.33-1.40	-0.038	0.000	1.1		
ASH 1 1.00-1.20	-0.057	0.005	1.8	61.3	16.2
ASH 1 1.45-1.65	-0.062	0.005	2.0	47.4	7.1
ASH 2 0.50-0.68	-0.018	0.010	1.1	63.1	17.3
ASH 2 1.10-1.25	-0.029	0.001	0.9		
ASH 2 1.80-2.00	-0.038	0.010	1.6	78.0	20.7
ASH 3 0.55-0.75	-0.019	0.035	2.5	57.7	16.5
ASH 4 0.60-0.80	-0.041	0.003	1.3	38.1	13.5
ASH 5 0.50-0.70	-0.024	0.000	0.7		
ASH 6 0.75-0.90	-0.031	0.004	1.1	34.1	9.1
ASH 6 1.70-1.85	0.005	-0.001	0.0	41.6	4.4
SA HAWK 4 0.55-0.77	-0.015	0.040	2.7		
SA HAWK 4 1.50-1.70	-0.051	0.027	2.9	50.2	12.0
SA HAWK 4 2.00-2.24	-0.043	0.027	2.7	42.3	11.1
HAWK 2 1.35-1.55	-0.050	0.014	2.2		
HAWK 2 1.70-1.90	-0.040	0.015	2.0	57.8	15.0
HAWK 2 2.00-2.18	-0.072	0.017	3.0	50.7	12.2
HAWK 2 2.55-2.75	-0.024	0.018	1.7		
HAWK 3 1.50-1.70	-0.070	0.006	2.3		
HAWK 3 1.70-1.95	-0.060	0.015	2.5		
HAWK 3 2.00-2.20	-0.141	-0.002	3.9		
HAWK 3 2.85-2.90	-0.082	0.009	2.8	51.5	5.7
HAWK 5 0.6-0.8	-0.039	0.016	2.0	71.4	16.1
HAWK 5 1.25-1.45	-0.044	-0.001	1.2	58.3	6.4
Bringelly average			1.3		
Ashfield average			2.1		
Hawkesbury average			0.8		

Table 3. Summary of Shrink-swell instability index values.

Figure 9 shows the shrink swell index values plotted against linear shrinkage (left), where both were determined for the same sample. The correlation is surprisingly poor. The same data is overlaid onto the figure from Johnston and Fityus (2016) where a much larger data set was tested, and it is evident that whilst the data falls within the scatter of that diagram, it does nothing to better define its trend.

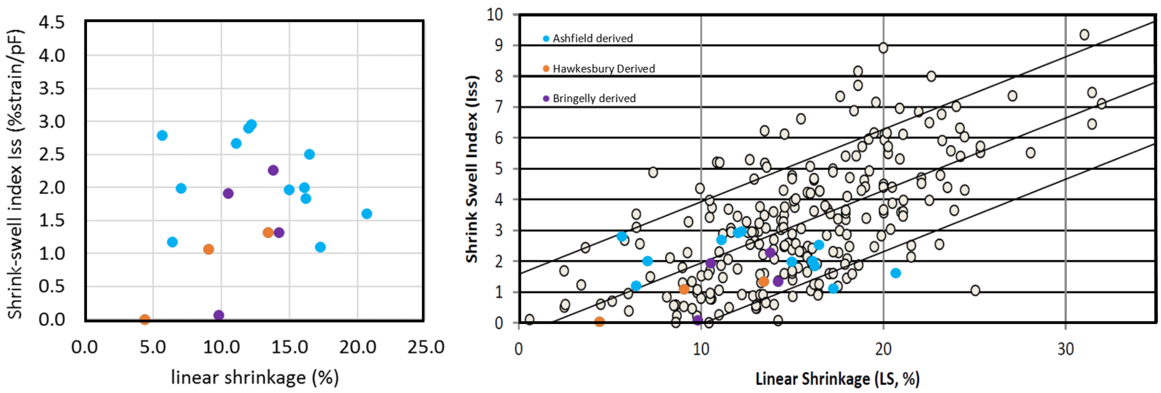

Figure 9. Shrink-swell index values plotted against linear shrinkage: data from this study (left); overlaid onto data from Johnston and Fityus (2016) (right).

7.0 Determination of site classification parameters.

In order to perform a site classification in accordance with AS2870-2011, it is necessary to nominate values of soil reactivity (shrink-swell index – I_{ss}), depth of seasonal moisture change (H_s), crack depth (Z_{cr}) and suction change at the soil surface (Δu). The necessary I_{ss} values have been mostly determined by direct measurement (see above). Some guidance on the selection of H_s, Z_{cr} and Δu is given by Section 2 of AS2870-2011, though the applicability of any values in AS2870-2011 is limited.

AS2870-2011 recommends the use of 1.2 pF units for surface suction range Δu in all parts of Australia (table 2.4), and so there is no basis for adopting anything different for the study area.

Limited values of H_s are given for “Sydney” (1.5-1.8), “Newcastle” (1.5-1.8) and “Hunter Valley” (1.8-3.0), however AS2870-2011 acknowledges that H_s depends upon climatic conditions, and none of the locations for which values are provided are considered to have a suitably similar climate to the study area.

It is now reasonably well accepted (e.g. Fityus et al, 1998) that H_s can be estimated on the basis of a crude climate index, the Thornthwaite Moisture Index or TMI, that can be calculated from locally-specific climate data (where available). Mean temperatures and rainfall data are needed, with a longer data record generally giving a better statistical inference. From the data available from the Bureau of Meteorology, the three nearest weather recording sites with suitable data available were 68052 Picton Council Depot (6km away; 61 years of continuous data); 68081 Campbelltown Swimming Centre (24km away; 22 years of data) and 68192 Camden Airport AWS (22km away; 42 years of data). Using this data, the approach of Fityus et al (1998) was used to calculate the average TMI values for the three sites. These are shown in Table 4.

BOM station	Location	Distance from Tahmoor	Years of data	TMI
68052	Picton Council Depot	6km	61	-0.8
68081	Campbelltown Swimming Centre	24km	22	-0.3
68192	Camden Airport AWS	22km	42	-9.6

Table 4 Calculated TMI values for nearest neighbouring sites with suitable climate data.

The values in Table 3 are consistent with the work of Barnett and Kingsland (1997) who produced a TMI map of NSW. An excerpt of this map, reproduced as Figure 10, indicates a TMI value for Picton somewhere less than 10 but greater than -5.

According to Fityus et al (1998), the TMI range of +10 to -5 can be correlated to a range of H_s from 1.8m to 2.3m. This would suggest that TMI values of around zero would correspond to an H_s of 2.1-2.2m; a TMI of -10 would correspond to an H_s of 2.4-2.5m. On the basis of these values, a depth of seasonal moisture change H_s value of 2.2m is recommended for the Tahmoor-Picton area, and this value has been adopted for this study. In evaluating the reasonableness of the 2.2m value, it is noted that the H_s values for Kurri Kurri and Cessnock in the Hunter Valley (Fityus et al 1998) are estimated to be similar, and geomorphically, (distance from the coast, general topography, west of a ridge escarpment, annual rainfall, mean temperature etc.) the areas are also very similar.

The final parameter required is the depth of cracking Z_{cr}, which is not easily measured or inferred. AS2870-2011 suggests that Z_{cr} should generally be taken as 0.5 H_s, although it does allow for values of between 0.5 H_s and H_s for the areas it provides H_s values for. This report recommends and has used a value of 1.2m, which is slightly greater than 0.5 H_s, but consistent with the values found from research in the Hunter Valley (Fityus et al 2005), and observations of desiccation in the profiles sampled for this study.

Figure 10. Excerpt from TMI map of Barnett and Kingsland (1999), showing a TMI for Picton of less than +10, and greater than -5.

8.0 Typical Site classifications for the Tahmoor/Thirlmere area.

By combining the shrink-swell test results with the parameters discussed above, site classifications were determined for each of the sampled locations, in general accordance with Section 2 of AS2870-2011. The general principles were followed:

- Soils that were too sandy to be coherent enough to test (including most topsoils) were deemed non-reactive and assigned an I_{ss} value of 0 %strain/pF.

- Weathered rock was deemed non-reactive, noting that for most shale sites, weathered rock was mostly only encountered below the H_s value of 2.2m, and for the sandstone sites, the weathered rock was sandstone, which is unlikely to be significantly reactive under any circumstances.
- Where I_{ss} values were measured at some depth in a soil profile, their values were extended to include the soil interval for which photographs and logs would justify that the soil conditions remained consistent.
- Where clay soil intervals occurred which were not tested, these often corresponded to intervals where the clay soils were insufficiently cohesive to allow a sample to be tested. Where possible, the I_{ss} for an interval of similar soil was adopted, or else, if the soils were judged to be non-plastic, they were assumed to also be non-reactive.

In two profiles, Hawk 2 and Hawk 3, the profiles were judged to contain a significant thickness of sandy fill within the upper metre. Since this fill would cause the site classification to be reduced in those specific situations, additional consideration was given to how the sites would classify more generally, if the fill were not present.

The calculated values of y_s and the consequent site classifications are presented in Table 5.

Profile	Depth to rock (m)	Geological provenance	Depth of clay (m)	Calculated y_s (mm)	Site Classification
Outcrop C	>2.4	Bringelly Shale	2.1	16.5	S
Bring 1	0.9	Bringelly Shale	0.7	4.7	S
Bring 2	0.85	Bringelly Shale	0.4	10.6	S
ASH 1	1.9	Ashfield Shale	1.9	18.8	S
ASH 2	>2.0	Ashfield Shale	1.6	19.6	S/M
ASH 3	>2.0	Ashfield Shale	1.55	29.0	M
ASH 4	0.80	Hawkesbury Sast.	0	3.3	S
ASH 5	1.3	Ashfield Shale	1.25	7.6	S
ASH 6	1.95	Hawkesbury Sast.	0	7.8	S
HAWK 1	0.85	Hawkesbury Sast.	0	0	S
HAWK 2 (with fill)	>2.9	Ashfield Shale	1.3	14.6	S
HAWK 2 (fill ignored)	>2.1	Ashfield Shale	2.1	31.7	M
HAWK 3 (with fill)	>2.0	Ashfield Shale	1.4	17.3	S
HAWK 3 (fill ignored)	>2.1	Ashfield Shale	2.1	33.1	M
HAWK 4	0.75	Hawkesbury Sast.	0	0	S
SA HAWK 4	>2.65	Ashfield Shale	2.1	39.5	M/H
HAWK 5	1.65	Ashfield Shale	1.3	14.9	S
HAWK 6	0.72	Hawkesbury Sast.	0.15	0	S
HAWK 7	0.8	Hawkesbury Sast.	0	0	S
Summary					
Bringelly Shale profiles	0.9->2.4	Bringelly Shale	0.4-2.0	<14mm	S (3)
Ashfield Shale profiles	1.3->2.9	Ashfield Shale	1.3-2.1	11 - 40	S(5) S/M(1) M(3) M/H(1)
Hawkesbury Sast profiles	0.7-0.9 (mostly)	Hawkesbury Sast.	0		S(6)
Overall					S(14) S/M(1) M(3) M/H(1)

Table 5 Calculated y_s values for the sites in this study.

Overall, the sites assessed were dominantly class S (14 sites) with less common class M (3 sites) and one site which was borderline class S/class M. Only one site approached class H, and that site (SA Hawk 4) was borderline M/H.

9.0 Discussion

The persistent outcome of class S for the Hawkesbury-derived sites is consistent with expectation. In most cases, these sites comprised sandy soils overlying bedrock at less than 1m. The exception to this was ASH 6, which comprised almost 2m of deeply weathered sandstone occurring as clayey sand. However despite being able to be tested, it returned low shrink-swell values with less than 10mm of predicted ground movement.

The predicted y_s values for the shales, and their corresponding classifications, are lower than expected. Anecdotally, the deep, deeply-weathered shales of the Sydney region are widely believed to be typically H (H1 and H2). However, only one of the predictions, based on a best-estimate of characteristic ground movement guided by Section 2 of AS2870-2011, came close to indicating a class H site. The y_s estimates for the studies sites suggest that the deeper clay profiles have characteristic ground movements of around 30-35mm, and the characteristic ground movements of the shallower clay profiles are of the order of 15-20 mm.

Lower than expected y_s values partly reflect the relatively low shrink-swell index values. It has been suggested anecdotally that the measured shrink-swell index is affected by the starting sample moisture, and that values measured in very dry samples may be systematically biased. However, as yet, the published experimental evidence to support this hypothesis is lacking, and there is no justification to do anything other than accept the measured I_{ss} values in this study as valid data.

The low y_s values determined for this region are inconsistent with the advice in appendix D2 of AS2870-2011, as reproduced in Figure 11, which suggests that for clay soil profiles in the Sydney region, where the depth of clay exceeds 0.6m, the classification should be M or H.

TABLE D2

CLASSIFICATION OF ALL SYDNEY CLAY SOILS

Depth of clay in profile m	Classification
<0.6	S
≤0.6 to ≤1.8	M
>1.8	H1 to H2

NOTE: The H1 to H2 classification arises from the possibility of moisture changes at depths in excess of 1.8 m because of changing groundwater regimes, and hence the depth of design suction change of Section 2 is inappropriate. Some less reactive soils do occur and, if a check is desired, the methods of Section 2 may be used, but with a depth of design suction change equal either to a maximum depth of 2 m or to the depth from the surface to extremely to highly weathered rock. In addition, the crack depth should be taken as 0.5 m.

Figure 11: Excerpt from AS2870-2011 for site classification by soil profile identification for Sydney.

In accordance with Table D2 in Figure 11, only one of the Bringelly Shale profiles should have classified as class S, while eight of the shale profiles should have classified as class M, and five of the shale profiles should have classified as class H.

The footnote to D2 in Figure 11 is interesting, suggesting that when site classifications for Sydney shales are carried out according to Section 2 of AS2870-2011, a crack depth of 0.5m should be adopted. This represents 0.3-0.33 of the recommended H_s value of 1.5-1.8m recommended for "Sydney" in table 2.4 of AS2870-2011, and it is inconsistent with the advice in section 2.3.2 that the crack depth should be 0.5 H_s to H_s.

Reducing the crack depth from 1.2m used in this study to the value of 0.5m in the footnote of Table D2 of AS2870-2011, would cause the predicted ground movements to increase, and possibly, the classification to increase. As a sensitivity exercise, the y_s calculations were repeated using a crack depth of 0.5m, and the outcomes are shown in Table 6 below

Profile	Depth to rock (m)	Geological provenance	Depth of clay (m)	Calculated y_s (mm)	Site Classification
Outcrop C	>2.4	Bringelly Shale	2.1	23.6	**M**
Bring 1	0.9	Bringelly Shale	0.7	8.5	S
Bring 2	0.85	Bringelly Shale	0.4	16.2	S
ASH 1	1.9	Ashfield Shale	1.9	27.2	**M**
ASH 2	>2.0	Ashfield Shale	1.6	24.0	M
ASH 3	>2.0	Ashfield Shale	1.55	39.5	**M/H**
ASH 4	0.80	Hawkesbury Sast.	0	6.2	S
ASH 5	1.3	Ashfield Shale	1.25	7.6	S
ASH 6	1.95	Hawkesbury Sast.	0	12.8	S
HAWK 1	0.85	Hawkesbury Sast.	0	0	S
HAWK 2 (with fill)	>2.9	Ashfield Shale	1.3	17.6	S
HAWK 2 (fill ignored)	>2.1	Ashfield Shale	2.1	41.1	**H1**
HAWK 3 (with fill)	>2.0	Ashfield Shale	1.4	21.9	**M**
HAWK 3 (fill ignored)	>2.1	Ashfield Shale	2.1	43.5	**H1**
HAWK 4	0.75	Hawkesbury Sast.	0	0	S
SA HAWK 4	>2.65	Ashfield Shale	2.1	51.9	H1
HAWK 5	1.65	Ashfield Shale	1.3	23.3	**M**
HAWK 6	0.72	Hawkesbury Sast.	0.15	0	S
HAWK 7	0.8	Hawkesbury Sast.	0	0	S
		Summary			
Bringelly shale profiles	0.9->2.4	Bringelly Shale	0.4-2.0	<14mm	S (2) M (1)
Ashfield shale profiles	1.3->2.9	Ashfield Shale	1.3-2.1	11 - 40	S(2) M(4) M/H(1) H1(3)
Hawkesbury Sast profiles	0.7-0.9 (mostly)	Hawkesbury Sast.	0		S(6)
Overall					S(10) M(5) M/H(1) H1(3)

Table 6 Recalculated Ys values and corresponding site classifications using a crack depth of 0.5m. (the bold classifications denote those which have increased from the values listed in Table 5)

The classifications in Table 6 are more consistent with the suggested site classifications from Table D2 in AS2870-2011, suggesting that shale-derived profiles that contain less than 1.3m of clay will be class S; profiles which contain from 1.3 to 2.1m of clay will be class M; and those which contain more than 2.1m of clay will be class H. Whilst this is more consistent with Table D2, there is no justification as to why these classifications should be more valid than those calculated directly and explicitly using the approach of Section 2 in AS2870-2011, and it is recommended that the values calculated in accordance with Section 2 of AS2870-2011 (in Table 5) should be regarded as more appropriate.

In considering if it is reasonable that the y_s values for the Tahmoor-Thirlmere area should be lower than those anecdotally associated with reactive soil sites in the Bringelly and Ashfield Shales in other areas to the north, and west of Sydney, it should be considered that these shales outcrop over a very broad area, and although they are stratigraphically recognised as being persistent shale units, it is not unreasonable that there may be some spatial differences in the content and nature of inherited clays that were entering the Sydney basin at the time of deposition, from spatially disparate sources. That is, it is feasible that the Ashfield and Bringelly Shales in this area could weather to produce less reactive clays in this area than they do in areas further to the north and west.

One of the most important outcomes of this work is the demonstrated poor reliability of the geological boundaries as given by the available geological data sets. The outcrop patterns of the region are somewhat complex, particularly in the more densely populated areas around Tahmoor and Thirlmere. The available geological data (maps and GIS) should not be relied upon to infer the geological conditions for a given site. Verification by site investigation is needed unless a site is well away from a geological boundary. It was noted that there are many areas where active and past developments have disturbed ground in the area, and it may be possible to achieve some refinement of the geological data from detailed surface mapping, though it is unlikely that the sub-crop could be fully resolved without more extensive subsurface investigation.

References

AS1289 (2003). “Australian Standard AS 1289.7.1.1-2003: Methods for testing soils for engineering purposes: Method 7.1.1: Determination of the shrinkage index of a soil - Shrink-swell index.” SAI Ltd, Sydney, 8 pp.

AS2870 (2011). “Australian standard AS 2870-2011: Residential slabs and footings.” SAI Ltd, Sydney, 176 pp.

Barnett, I. and Kingsland, R. (1999) “Assignment of AS2870 soil suction change profile parameters to TMI derived climate zones for NSW.” *Proceedings 8th Australia New Zealand Conference on Geomechanics*. Hobart, Vol.1, 149-155

Fityus, S. G., Walsh, P. F., and Kleeman, P. W., (1998) “The influence of climate as expressed by the Thornthwaite index on the design depth of moisture change of clay soils in the Hunter Valley.” *Conference on Geotechnical Engineering and Engineering Geology in the Hunter Valley*, Conference Publications, Springwood, Australia: 251–265.

Fityus, S.G., Smith, D.W. and Allman, M.A. (2004) An expansive soil test site near Newcastle, *ASCE Journal of Geotechnical and Geoenvironmental Engineering* Vol. 130, No. 7,686-695.

Ghafoori, M. (1995). Engineering behaviour of Ashfield Shale. PhD Thesis, Univ. of Sydney. 306pp.

Herbert, C., (1979), "The geology and resource potential of the Wianamatta group", New South Wales Geological Survey, Bulletin 25, 203 p.

Johnston J. A. and Fityus S. G. (2015). The use of engineering index correlations with the shrink-swell test *Proceedings of 11YGPC, The 11th ANZ Young Geotechnical Professional’s Conference.* Queenstown, New Zealand. 6 pages

William, E. (2005) "Engineering performance of Bringelly Shale." PhD Thesis University of Sydney.

Appendix A

Logs for the sampled sites

Appendix B

Ys Calculations