FIELD MONITORING OF EXPANSIVE SOIL BEHAVIOUR IN THE NEWCASTLE-HUNTER REGION

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ABSTRACT

As part of a long term research project on the behaviour of expansive soils, twenty open-ground field sites which cover a range of soil, geological and geographic conditions were set up in the Newcastle-Hunter region. The sites were selected to provide detailed information on the distribution and nature of expansive soils and soil behaviours in the region. Seasonal ground movements, at various levels relative to the ground surface, were measured to a precision of 0.1 mm on a regular basis. *In situ* soil moisture content variation profiles were monitored by a neutron probe. This paper presents the results of the field monitoring over periods of up to 7 years. The site selection, instrumentation and laboratory testing results are discussed. A comparison of predicted design ground movement based on the method of AS2870 with the measured movements is also presented.

1 INTRODUCTION

Expansive or reactive soil is any soil composed predominantly of clay, which undergoes appreciable volume change in response to changes in soil moisture content. This volume change occurs as swelling upon wetting and shrinkage upon drying. Buildings constructed on expansive soils are frequently subjected to severe movement arising from non-uniform soil moisture changes, with consequent cracking and damage due to distortion. These moisture changes may be induced by rainfall and evaporation, garden watering, leaking water pipes or tree root activity.

Damage to lightly loaded structures founded on expansive soils has been widely reported throughout the world. The problems are particularly significant in Australia as approximately 20% of the total land area is covered by expansive soils (Richards et al., 1983; Cameron et al., 1987). In fact, the expansive soil problems are present in most capital cities and regional centres of Australia (Walsh and Cameron, 1997). Although research into expansive soil behaviour has been carried out in Australia since the late 1950's, the majority of research has focussed on Melbourne and Adelaide regions, while a significant report relevant to the Sydney region was compiled during the 1980's (Coffey and Partners, 1985).

In 1993, a research study into the behaviour of expansive soils in the Newcastle-Hunter Valley region was commenced at the University of Newcastle. This mostly experimental research was focussed on two major projects: a detailed study of a major field site at Maryland and a regional study based on a network of nineteen minor field sites located throughout the Newcastle and Hunter regions. The primary objectives of this research were to:

- Provide information on the nature and distribution of expansive soils in the region,
- Record data on *in situ* expansive soil ground movements and moisture changes and
- Acquire regionally specific data, with which the design recommendations of AS 2870 could be assessed.

The outcomes for the major field site at Maryland are now mostly complete and have been described in a number of publications (Allman et al., 1994; Fityus, Smith and Allman, 2004). The present paper is focussed on the minor site study. Selected preliminary results from the minor site study have been published by Delaney et al. (1996) and Fityus, Delaney and Smith (2004). This paper presents the final outcomes of the minor site study. The site selection, instrumentation and laboratory testing results are discussed. A comparison of predicted design site surface movement, y_s, (based on the method of AS2870) with the measured movements is also presented. The value of y_s is determined using soil shrinkage indices appropriate to the soil profile of the site and design soil suction change profiles for different climatic regions of Australia

2 MINOR SITE STUDY

2.1 SITE SELECTION AND DETAILS

Details of the nineteen minor sites established in the Newcastle-Hunter region are shown on the regional map in Figure 1 and in Table 1. The sites were specifically targeted to:

- Be representative of and distributed throughout the regional geological sequence,

- Provide a broad geographical coverage (Figure 1, Table 1),
- Cover a range of residual soil profiles developed on conglomerate, sandstone, shale, coal and tuffaceous rock types of variable depth,
- Include alluvial and colluvial (gully infill) soil deposits,
- Include a range of terrain, vegetation and site development conditions and
- Cover areas designated for future residential development.

Sites were located on land owned or administered by The Hunter Water Corporation, Landcom, Lake Macquarie City Council, Newcastle City Council, Wyong Shire Council, Mount Thorley Coal Loading Ltd and Liddell Coal.

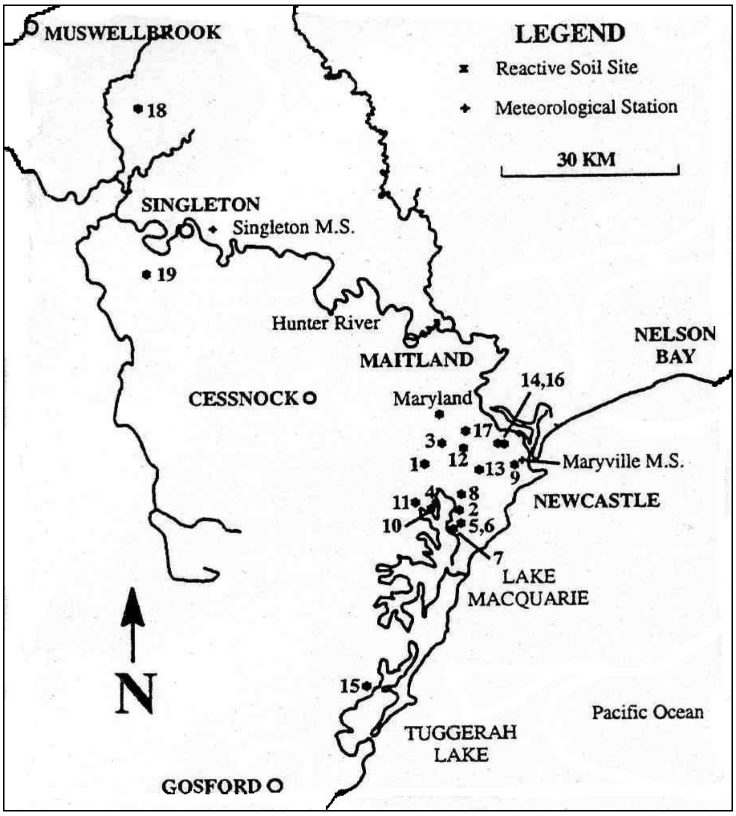


Figure 1: Regional map showing site locations (after Delaney et al., 1996).

The details of all field sites are provided in Table 1, which include the site location, the depth of benchmark (against which level measurements were referenced), the depth of bedrock, the site features and the brief description of soil profile and rock type. From Table 1, it can be seen that the depth of bedrock is highly variable from 0.9 m to greater than 4.5 m. Generally, bedrock depths in excess of about 3 m are limited to alluvial soil areas. The soil profiles are generally shallow, including 0.1 m to 0.35 m of non-expansive topsoil and mixtures of silt, sand and clay. The boundary between soil and weathered rock is often indistinct and occurs as a gradational change.

2.2 SITE INSTRUMENTATION AND MONITORING

Sites 1 to 17 were set up during June to September 1994 and sites 18 and 19 in September 1995. The site features are briefly described in Table 1.

A typical layout of each site, showing the arrangement of soil movement probes and location of the neutron probe access tube is given in Figure 2. Generally each minor site occupies an area of about 2 m by 2 m and consists of:

- Two surface movement probes, consisting of galvanised steel rods grouted into 150 mm wide by 150 mm deep holes,
- Sub-surface movement probes installed in 100 mm diameter bores to depths of 0.5 m, 1.0 m, 1.5 m, 2.0 m and 3.0 m, depending on the depth to rock. The probe comprises a 19 mm diameter galvanised steel rod with a 45

mm diameter base plate enclosed within a 50 mm diameter PVC tube. The annulus between the soil and pipe is backfilled with a 10% bentonite and sand mixture,

Table 1: Details of minor sites.

Site number and Suburb	Depth of benchmark (m)	Depth of rock (m)	Site Features	Soil Profile Description and Rock Type
1. Edgeworth	4	2.6	Level area, mown lawn eucalypts about 8m away	Sandy topsoil and slopewash to 0.25 m over clay and silty clay of medium to high plasticity over tuffaceous siltstone rock
2. Eleebana	4	2.5	Eucalypts adjacent to and surrounding site, level area	0.2 m clay topsoil over residual clay and silty clay of high plasticity, relatively dry and friable over tuffaceous claystone rock
3. South Wallsend	3	1.7	Row of eucalypts within 5m, slight slope	0.2 m silty clay topsoil over clay and gravelly clay of high plasticity over tuffaceous claystone and coal
4. Marmong Point	4	2.8	Slight slope, surrounded by eucalypts	Sandy topsoil and slopewash to 0.3 m over residual and gravelly clay of medium plasticity over conglomerate rock
5. Tingira Heights	1.35	0.9	Moderate slope, open grassed area	0.15 m of sandy silt topsoil underlain by medium plasticity sandy gravelly clay over conglomerate
6. Tingira Heights	4	2.8	Slight slope, open grassed area	0.1 m silt topsoil over high plasticity clay, becoming sandy clay and clayey sand below 1.5 m over tuffaceous sandstone and claystone rock
7. Valentine	3	2	Grass cover, eucalypts ~10m away, slight slope	0.25 m gravelly topsoil overlying high plasticity clay to 0.5 m and then high plasticity silty clay to 2 m over sandstone and tuffaceous sandstone rock
8. Warners Bay	3.8	3.4	Patchy grass cover, mature eucalypts at each corner of the site	0.35 m silty topsoil overlying medium plasticity alluvial clay to 2.7m and then medium plasticity sandy clay to 3.4m over siltstone rock
9. Hamilton	4.5	>4.5	Flat, mown lawn, at rear of existing residence	0.45 m sandy fill overlying high plasticity alluvial clay to 2.4 m and then dense sand to depth > 4.45m
10. Booragul	4	1.5	Slight slope, eucalypts approx. 10m away	0.65 m high plasticity clay overlying medium plasticity silty clay to 1.25 m over oxidised coal and tuffaceous claystone rock
11. Fennell Bay	1.35	0.9	Slight slope, eucalypts nearby	0.1 m sandy topsoil overlying gravelly sandy clay of medium plasticity to 0.9 m over conglomerate
12. Elermore Vale	4.15	3.8	Slight slope, shrub to 3m adjacent, no trees	0.25 m clayey sand topsoil over high plasticity clay to 2.4 m, becoming gravelly clay over sandstone rock
13. New Lambton	3	2.7	Gentle to moderate slope, grassed, eucalypts ~10m away	Sandy topsoil and slopewash to 0.7 m over gravelly sandy clay of medium plasticity over conglomerate
14. Waratah	3.7	3.3	Slight slope, open grassed area. Adjacent to road and old quarry cuttings	0.25 m clayey fill overlying high plasticity silty clay to 1.1 m over residual coal comprising high plasticity clay over sandstone rock
15. Charmhaven	4	3.2	Slight slope, eucalypts approx. 5m away	0.2 m clayey fill overlying sandy topsoil to 0.6 m and sandy clay to 1.1 m, then high plasticity clay over silty sandstone rock
16. Waratah West	2	1.5	Slight slope, open grassed area	0.2 m clayey topsoil overlying high plasticity clay to 1 m and then medium plasticity silty clay over shale
17. Wallsend	4.3	>4.5	Pine and palm tress approx. 10m away, mown lawn	0.6 m fill over high plasticity alluvial clay to 2.2 m and then clayey sandy gravel to depth >4 m
18. Liddell	3	2.2	Slight slope, open grassed area	0.2 m clayey sand topsoil over gravely clay slopewash to 0.7 m over medium plasticity silty clay to 2.2 m over silty sandstone rock.
19. Mount Thorley	5	3.5	Slight slope, open grassed foot slope area	0.15 m silty clay topsoil overlying high plasticity clay slopewash to 0.65 m over medium plasticity silty clay to 3.5 m over siltstone rock
Maryland	>5	1.7	Slight slope, open grassed area, one mature eucalypt	0.25 m silty clay topsoil underlain by high plasticity clay to 1.2 m, then medium plastic silty clay over siltstone rock

- A deep survey datum (bench mark), similar in form to the movement probes noted above, except grouted into bedrock or deep non-reactive layers where depth to rock exceeds 4.5 m. The depth of the deep survey datum for each site is listed in Table 1,
- An aluminium neutron probe access tube installed to depths up to 3 m to allow soil volumetric moisture content determination at specific depths using a Campbell Pacific Nuclear Model 503 Hydroprobe,
- A 50 mm diameter standpipe piezometer with groundwater level indicators (in alluvial soil areas) and
- Vandal deterrent, 100 mm diameter, galvanised pipe housings to protect each of the above installations, concreted to 150 mm depth and secured by threaded cap.

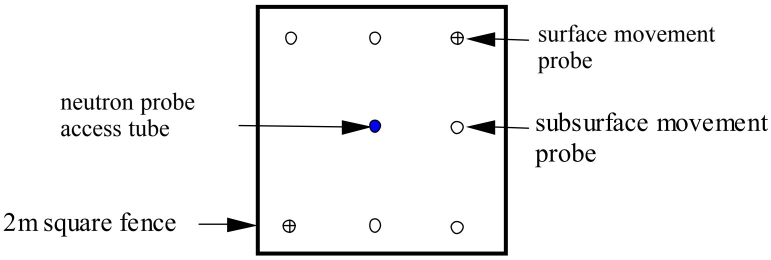


Figure 2: A typical instrumentation layout for minor sites.

Sites were initially monitored on a monthly basis, but at a reduced frequency with ongoing time, as warranted by specific weather conditions. A full set of readings from all sites took a total of three days. The seasonal soil movements with depths were determined to an accuracy of 0.1 mm by using a high precision electronic level. *In situ* soil moisture content variations were monitored at specific depths using the neutron probe.

2.3 LABORATORY TESTING AND SOIL PROPERTIES

The disturbed and undisturbed soil samples obtained during site installation were subjected to various laboratory tests to provide information on the nature of the soil at each site. The laboratory tests were carried out in accordance with AS1289 (1992), and included 85 shrink-swell index tests, 78 Atterberg limits tests, 78 linear shrinkage, 78 particle size distributions by hydrometer analysis and 82 cation exchange capacity determinations.

The soils were generally inorganic, low to high plasticity clay, as demonstrated by their position on the plasticity chart of Figure 3. The samples plotting below the A-line comprise topsoils and weathered rock. The description of soil profile for each site is presented in Table 1.

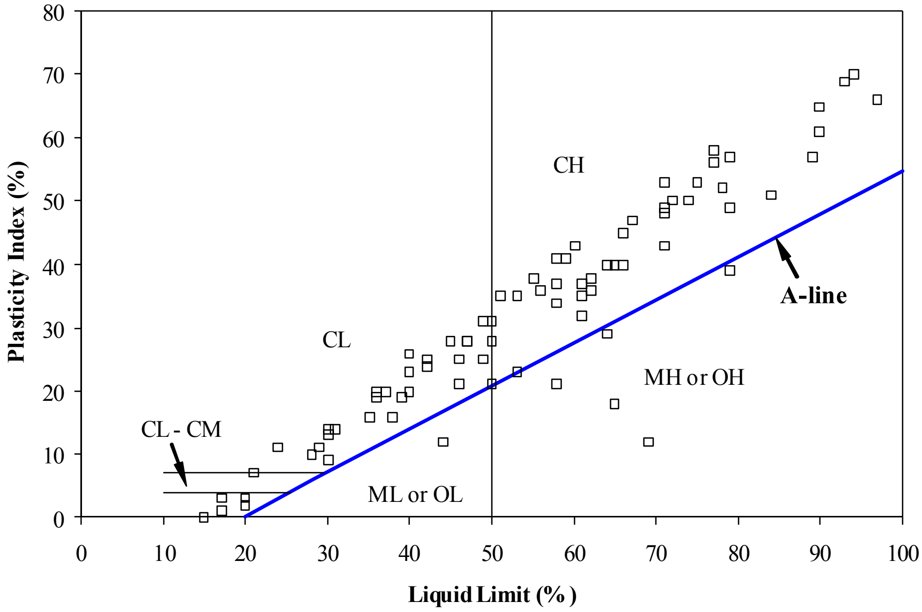


Figure 3: Plasticity chart showing soils studied.

The soil reactivity at each site has been assessed by 3 to 7 laboratory shrink-swell tests over the full soil depth range with some tests having been carried out in extremely weathered rock material. The range of shrink-swell indices for each site is given in Table 2. The results of 85 shrink-swell index tests show:

1) Instability indices (I_{ss}) ranging from 0.1%/pF to 8.5 %/pF with an average value of 3 %/pF.
2) Instability indices are related to soil type. Alluvial clay soils and those weathered from coal seams are typically of high reactivity with soils weathered from tuffaceous claystones and siltstone typically of medium to high reactivity. Low reactivity soils typically comprise those weathered from conglomerate and coarse sandstone.
3) Some extremely weathered rock, in particular shale and tuffaceous claystone/siltstone, exhibit reactive swell strains ranging from 0.3% to 2.5% on inundation. This suggests that where these rock types occur within 1.5 m of the surface, it may be appropriate to treat them as soils and assume a full depth of influence (instead of assuming non-reactivity at the depth that rock structure becomes evident).

The results of shrink-swell index tests were also used to assess the values of I_{ss} estimated on a visual-tactile basis by a senior geotechnical practioner with ten-years experience in site classification in the Newcastle-Hunter region. It was found that the visual-tactile method was highly inaccurate because of the diversity and abruptness of the local geological conditions and large variability in the colours and textures observed in local clays either weathered from the same parent rock unit or a different lithotype. This result, which is consistent with that of Fityus and Delaney (1995), suggests that the methods of site classification by soil profile identification and visual assessment are inappropriate for the Newcastle-Hunter region.

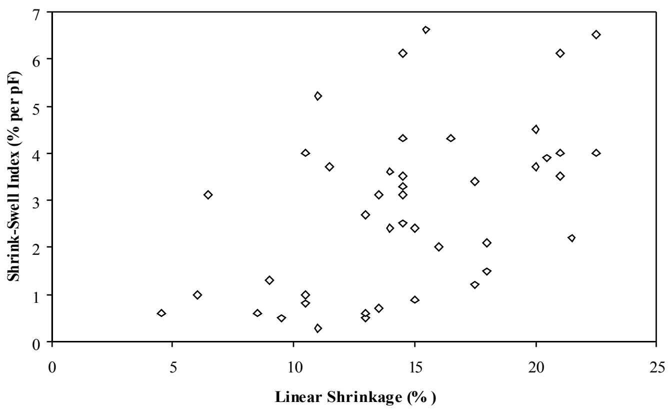


Figure 4: Relationship between the shrink-swell index and linear shrinkage.

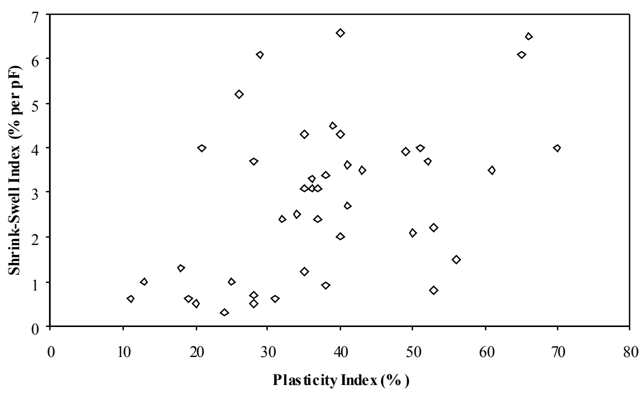


Figure 5: Relationship between the shrink-swell index and plasticity index.

For most engineering purposes, the properties of soil can be defined by index tests such as plastic index, linear shrinkage or liquid limit. The correlations between the instability indices and traditional soil indices have been presented by Mitchell and Avalle (1984) and Cameron (1989), who found linear shrinkage to be a reasonable indicator of soil reactivity. A number of correlations were attempted in this research between the shrink-swell test and other soil tests including linear shrinkage, plastic index and liquid limit, and the results are plotted in Figures 4 to 6. It can be seen that considerable scatter exists in the relationship between the shrink-swell index and other soil indices, so that an unambiguous, reliable relationship does not appear to exist. The results obtained from the minor site study indicated that traditional index tests are of little general value in assessing the reactivity of expansive soil unless the correlation is confined to a particular soil type, a conclusion also reached by Cameron (1989).

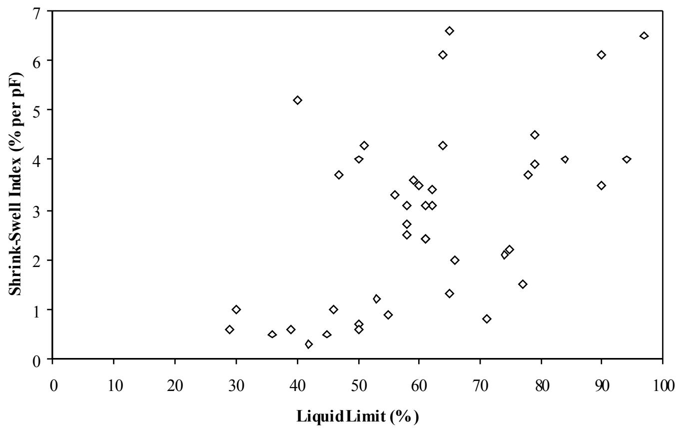


Figure 6: Relationship between the shrink-swell index and liquid limit.

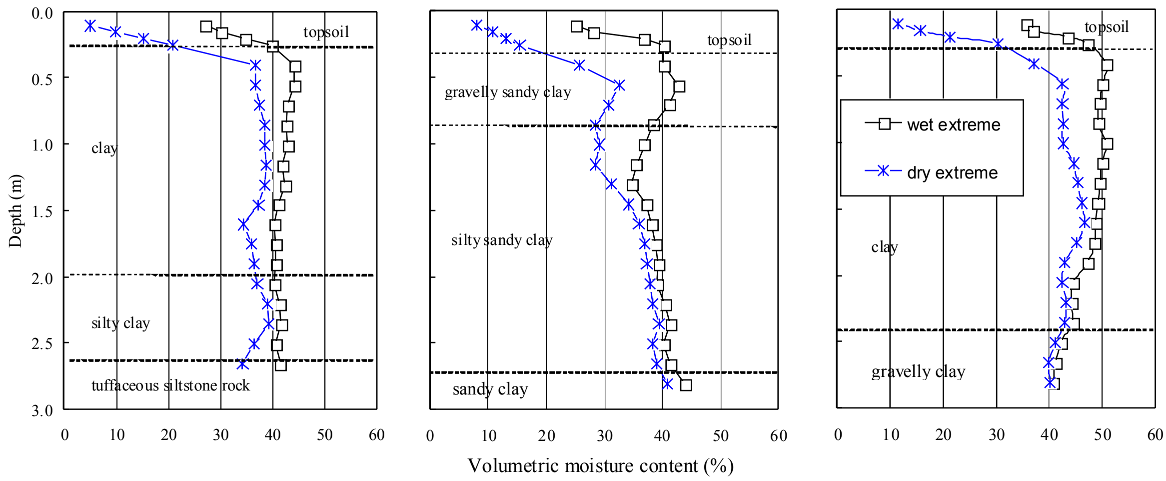
3 MEASUREMENTS AND RESULTS

3.1 SOIL MOISTURE CONTENT

The soil moisture content profiles were monitored by using a CPN 503 Hydroprobe (neutron probe), which effectively quantifies the concentration of hydrogen (mostly present as water) in an inorganic soil. Soil moisture content is determined by lowering the instrument into the ground through an access tube and measuring the localised amount of hydrogen at selected depths. The neutron probe has proven to be an effective means for monitoring relative, long-term *in situ* soil moisture variations, although the extraction of absolute moisture content data from neutron probe counts has proved to be problematic (Li et al., 2003).

The soil moisture content at minor sites was measured on a monthly base, at 0.05 m intervals for the top 0.25 m of soil and at 0.15 m intervals over the remaining depth up to 3 m. The complete presentation of the neutron probe soil moisture profiles for all minor sites is beyond scope of this paper due to the space limitation. Figure 7 shows the extremes of moisture content measured with the neutron probe at sites 1, 8 and 12. The profiles shown represent the upper and lower envelopes of all readings taken at each depth during the project. Intermediate values were omitted for clarity. A number of observations can be made. These include:

- The maximum moisture content change at Site 12 (open grassed area, no trees) becomes very small at about 1.5 m. There is essentially no change below 2 m.
- The maximum moisture content change at Site 8 (eucalypts presented at each corner of the site) becomes also very small at 1.5 m, but then appears to remain at a consistent value to a depth of 2.8 m. This is consistent with the expectation that large trees are able to extend the active depth, beyond the depth of seasonally induced moisture change.
- The effect of trees is evident at Site 1 where large eucalypt trees are located about 8m away as the active depth is extended below 2.6 m and just into the weathered rock.
- Comparing with Site 12, the values at the extremes of moisture content range at Sites 1 and 8 are relatively smaller. This is due to the stand of trees extracting water all year round and depleting the soil moisture.
- For all three envelopes, the values of observed moisture content are much lower above a depth of about 0.35 m. There are two reasons for this. First the neutron probe measures the average moisture content in a ‘sphere’ of soil of variable radius between 0.1 m and 0.3 m (decreasing with increasing moisture content) (Li et al., 2003). For readings taken at depths of less than 0.35 m, some of this volume extends above the ground surface where there is only air and, hence, the values will be low. Second, due to weathering and soil formation processes, the topsoils contain less clay than the deeper clay soil (Fityus and Smith, 2004), so their moisture holding potential is lower (see Table 1).



(a) Site 1-Edgeworth(trees about 8m away) (b) Site 8-Warners Bay(trees at site corners) (c) Site 12-Elermore Vale(open grassed area)

Figure 7: Typical volumetric moisture content change profiles.

3.2 GROUND MOVEMENTS

The preliminary results presented by Delaney et al. (1996) were derived on only 2 years of data. Consequently, the climatic record on which they were based could not be considered as broadly representative. In the present paper, the observation period is increased to between 4.6 and 7.7 years for most sites. Whilst still short in climatic terms, this period is likely to be considerably more representative of the longer term trends.

Generally, the surface and sub-surface movement probes for minor sites provided reliable, trouble-free data on soil movement profile since the field sites were established.

The maximum recorded seasonal movement profiles throughout the monitoring period for all field sites are plotted in Figure 8, relative to soil origin. Figure 8 shows a wide regional variability in observed surface movements, with a range from 7 mm to 58 mm. This variability also occurs between sites weathered from the same rock type. The range of maximum surface movements recorded for soil profiles weathered from conglomerates (4 sites) are 7 mm to 18 mm, tuffaceous rock types (6 sites) 10 mm to 52 mm and coal sequences (2 sites) 23 mm to 49 mm. The results indicate that the distribution of expansive soils in the Newcastle-Hunter region is likely to be erratic and locally unpredictable. This result, which is consistent with that of Fityus and Delaney (1995), means that the compilation of a reactive soil zoning map for the Newcastle-Hunter area would be an exhaustive, if not impossible task and that design and construction on reactive soil sites must be generally guided by specific site investigation and engineering principles.

At most sites, the majority of soil movement takes place above a depth somewhere between 1 m and 2 m. This behaviour is consistent with the larger changes in moisture content occurring at shallower levels (Figure 7). Deeper movements beyond 2 m depth are mostly limited to sites in close proximity to mature eucalypt trees.

The active depth is the depth below which no significant moisture changes, and hence no significant soil movement, occur. Where climate is the only significant influence on moisture change, then the active depth may also be described by the more specific term, “depth of seasonal moisture change”. The depth of seasonal influence (away from trees) or active depth (affected by trees) at a particular site can be estimated based on the neutron probe moisture content measurements and the ground movement measurements, as shown for each minor site in Table 2. For sites situated in open grassed areas with no trees present, the depths of seasonal moisture change range from 1.5 m to 2 m, consistent with the recommendations of Fityus et al. (1998). The results of the minor site study suggest that the active depth recommended by AS2870 (1996) for the Newcastle area should be deeper. The implications of this were considered in Fityus, Delaney and Smith (2004).

The vertical seasonal ground movement at a particular site is not only dependent on the clay type and the soil profile, but also dependent on the ground watertable. This is demonstrated by the movement profile at Waratah (see Figure 8(d)) which shows minimal ground movement below 1 m depth in clay soils (I_{ss} = 6.6 %/pF) weathered from coal. Groundwater seepage in the coal seam maintains relatively constant, wet, moisture content and so limits the amount of ground movement in the highly reactive soils.

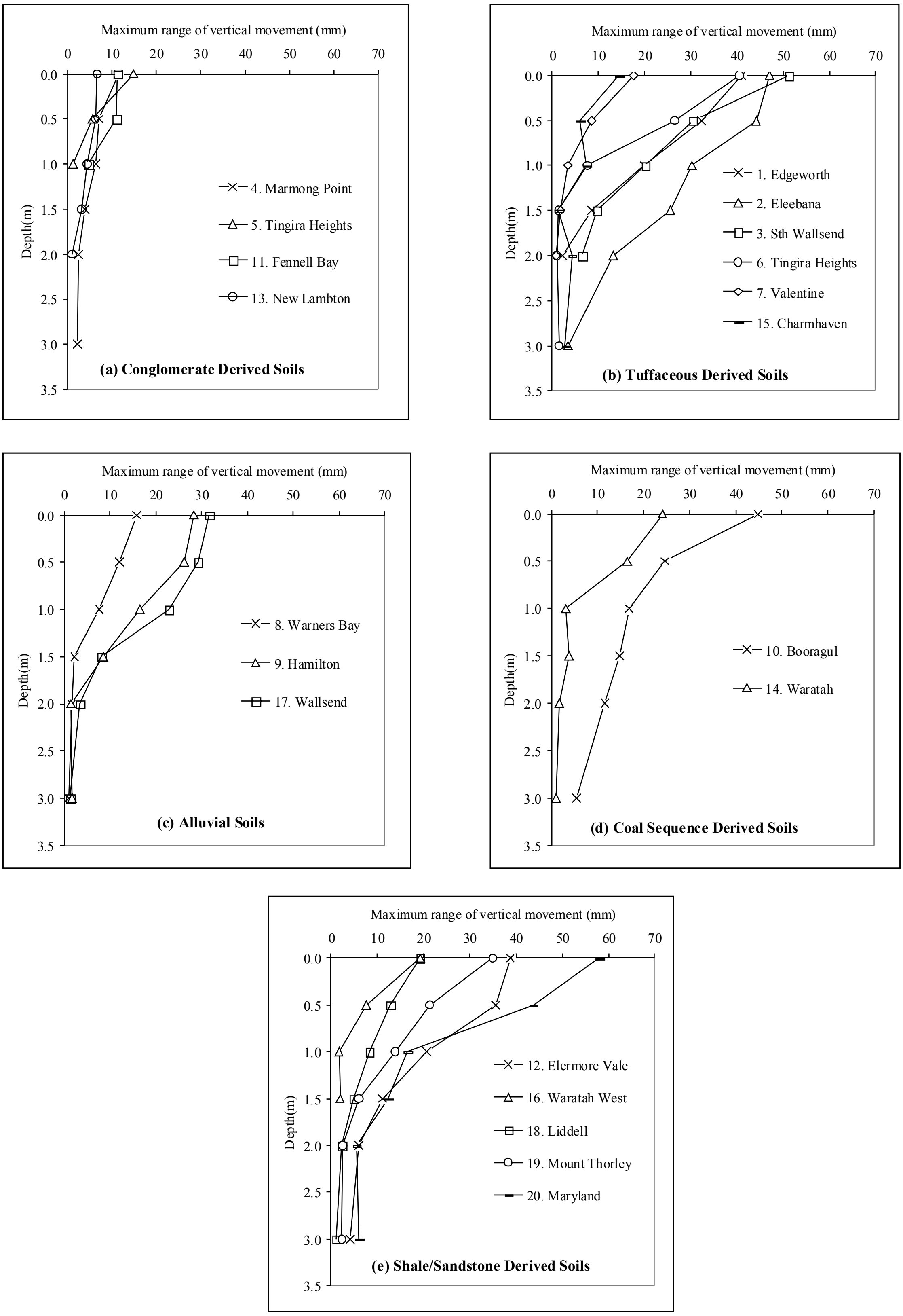


Figure 8: Total range of vertical movements with respect to depth for all field sites

One of the primary objectives of this research is to enable the predicted design ground movements, based on the approach of AS2870 to be assessed by comparing them against the measured movements. In making such a comparison it must be clearly understood that the predictions are intended to be representative of a long period (of the order of the lifetime of a structure) and that the measurements represent only a small fraction of this. Hence, the measured movements should represent lower bounds to accurate ground movement predictions and accurate predictions should not fall below measured values.

Using laboratory shrink-swell results, predictions of design site surface movement, y_s, were made according to the recommendations of AS2870 (1996). A summary of the results is presented in Table 2. The following observations can be made.

- Based on AS2870 (1996), 7 sites are classified as Class H (i.e. highly reactive), 5 sites as Class M (i.e. moderately reactive) and 7 sites as Class S (i.e. slightly reactive).
- Based on measurements, *at least* 6 sites are classified as Class H (i.e. highly reactive), 5 sites as Class M (i.e. moderately reactive) and 9 sites as Class S (i.e. slightly reactive). This suggests that, on average, the measurements are lower-bounds to the predicted movements and so the predictions are not significantly underestimating actual ground movements.
- Predicted ground movements according to AS2870 (1996) are 4.1 mm to 61.6 mm with an average of 30.4 mm, while the measured ground movements ranged between 6.7 mm and 58 mm with an average of 28.6 mm. This also suggests that, on average, the predictions are not significantly underestimating the actual ground movements.
- The predictions do underestimate the measured movements in 10 cases, and overestimate them in 9 cases. It is interesting to note that the preliminary results based on the first two years of observation indicated that, in all cases but one, the predicted movements overestimated the measured movement values (Delaney et al., 1996). This suggests that the period of field monitoring should be as long as possible so that a truly representative envelope of extreme ground movements and moisture contents is obtained.
- The ratio of predicted to observed ground movements ranged from 0.37 to 2.25, with an average value of 1.1. This result suggests that in extreme cases (say, where the current predictions are still more than 50% greater than the measured values), that predictions can over-estimate movements. In considering this result, however, the significance of cases such as sites 11 and 13 must be noted. In these cases, the predicted movements were less than 10 mm, and so discrepancies of only 3-5mm represent errors of as much as 70%.
- The difference between predicted and observed ground movements ranged from -29.6 mm to 30 mm, with an average absolute difference value of 11 mm. The average actual difference is 1.3 mm (prediction exceeding measurement). Assuming that over a longer period the measured values are likely to increase by some amount, this suggests that the average error in a ground movement estimate is likely to approach zero. It is noted that the greatest error occurred at Site 14 (Waratah) where the predicted ground movement is 30 mm larger than the measured value. As discussed previously, this can be attributed to a presence of a coal seam at shallow depth which is water-charged, acts as a local aquifer and significantly reduces the seasonal ground movement below a depth of 1m.
- A wide variability in observed surface movements not only occurs between sites with similar soils of comparable depth that have weathered from the same rock type, but also occurs between the two surface movement probes, which are located on one site and generally less than 2 m apart. The ratio of the observed movements of the two surface probes ranged from 1.0 to 1.9 with an average of 1.2. This result suggests that site classification based on a single borehole may be insufficient.
- The average movement for the 4 conglomerate sites was only 11.1 mm, yet the errors ranged from 30 to 60%. This suggests that ground movement estimates on conglomerate sites are proportionately less reliable than of other sites. This is because the gravelly residual soils are inherently difficult to sample and their reactivity is otherwise difficult to judge. Also, they are inherently more variable, as is evident in the 50% or more difference between the two surface movement measurements made at 3 of the 4 conglomerate sites.

In most cases, underestimation of the measured movements occurs at sites with the observed active depth deeper than the assumed depth of seasonal moisture change of 1.5 m, due to the presence of trees.

It is interesting to reconsider the data of Figure 8 to consider where the movement is occurring within the soil profiles of the Newcastle-Hunter region. If the recorded surface movement is taken to be the total movement in the profile, then movement in specific depth intervals (say, 0 to 0.5 m, 0.5 m to 1.0 m etc.) can be calculated and expressed as a proportion of the total movement, giving an idea of how much movement is occurring at different depths. This has been done for all of the minor sites and the results are summarised in Figure 9, as the average proportion of movement occurring in particular depth intervals (for all sites) and the maximum proportion of movement recorded in each depth interval (for any of the sites).

Table 2: Summary of minor site results.

Site number and Suburb	AS2870-1996		Observed surface movement				Predicted/Observed	Predicted/Observed	Observed. depth of seasonal movement	Rock Type	Range of Shrink-Swell test indices
	Site classification	Predicted surface movement y_s	surface probe 1	surface probe 2	average movement	Length of observation					
		mm	mm	mm	mm	yrs		mm	m		%/pF
1. Edgeworth	M	29.5	40.9	41.1	41.0	5.0	0.72	-11.5	2	Tuffaceous	2.1-3.5
2. Eleebana	S	17.5	47.1	36.9	47.1	7.5	0.37	-29.6	3	Tuffaceous	1.2-3.1
3. South Wallsend	H	36.6	50.0	52.3	51.2	5.0	0.71	-14.6	2	Tuffaceous	1.3-4.6
4. Marmong Point	S	20.0	8.1	14.8	11.5	6.1	1.74	8.5	2	Conglomerate	1.5-3.0
5. Tingira Heights	M	21.3	12.0	17.7	14.9	6.5	1.43	6.4	0.9	Conglomerate	2.1-3.4
6. Tingira Heights	H	60.4	43.2	37.9	40.6	6.5	1.49	19.8	1.5	Tuffaceous	0.1-6.1
7. Valentine	S	16.7	17.9	17.2	17.6	6.5	0.95	-0.9	1.5	Tuffaceous	0.2-3.7
8. Warners Bay	S	12.2	17.4	14.1	15.8	6.5	0.77	-3.6	1.5	Alluvium	0.6-1.8
9. Hamilton	H	44.2	30.0	26.8	28.4	3.6	1.56	15.8	1.7	Alluvium	5.4-8.5
10. Booragul	H	61.6	48.9	40.1	44.9	6.5	1.37	16.7	3	Coal	0.5-6.5
11. Fennell Bay	S	7.5	13.0	9.5	11.3	6.1	0.66	-3.8	0.9	Conglomerate	0.6-1.0
12. Elermore Vale	M	33.6	36.9	40.7	38.8	7.4	0.87	-5.2	2	Sandstone	0.8-4.3
13. New Lambton	S	4.1	6.7	6.7	6.7	2.4	0.61	-2.6	1.5	Conglomerate	0.5-1.1
14. Waratah	H	54.2	24.8	23.3	24.1	7.4	2.25	30.1	1.5	Coal	1.0-6.6
15. Charmhaven	S	18.9	10.1	18.9	14.5	3.1	1.30	4.4	3	Tuffaceous	2.7-4.4
16. Waratah West	M	21.3	17.1	21.6	19.4	7.4	1.10	1.9	1.5	Shale	0.6-3.3
17. Wallsend	M	26.4	32.2	31.1	31.7	7.4	0.83	-5.3	2	Alluvium	1.1-5.4
18. Liddell	results missing		17.6	20.8	19.2	4.6			1.6	Sandstone	
19. Mount Thorley	H	50.7	34.7	35.3	35.0	4.6	1.45	15.7	1.8	Shale	2.7-3.7
Maryland	H	41.0			58.0	7.7	0.71	-17	1.7	Shale	1.8-6.1
mean					28.6	5.9	1.1	1.3	1.9		3

Figure 9 suggests that, on average, around 30% of the total movement occurs in the upper half metre of the profile, although this might be as much as 62% in some cases. Similarly, on average, almost 30% of the total movement occurs in the 0.5-1.0 m interval of the profile, although this might be as much as 55% in some cases. On average, around 20% of the total movement occurs in the interval 1.0-1.5 m, and a further 20% below 1.5 m. In some sites, however, more than 50% of the total movement occurs below a depth of 1.5 m. Significant aspects of these observations include:

- A significant proportion of the movement is likely to occur in the upper 0.5 m, which typically contains a substantial thickness of topsoil.
- The significant movement in the upper 0.5 m has important implications for the style of the foundations adopted. Foundation systems that excavate soil to embed footings are likely to significantly reduce the likely movements that would occur beneath the embedded elements. Footing systems, such as waffle slabs, that are constructed on-grade, do not benefit from this removal of soil and hence the potential for movement directly beneath stiffening beams is greater.
- Significant movement occur below the typically adopted active depth of 1.5 m, suggesting that the active depth may be deeper in some cases and/or the effects of adjacent trees are having a significant effect on the results of this study.

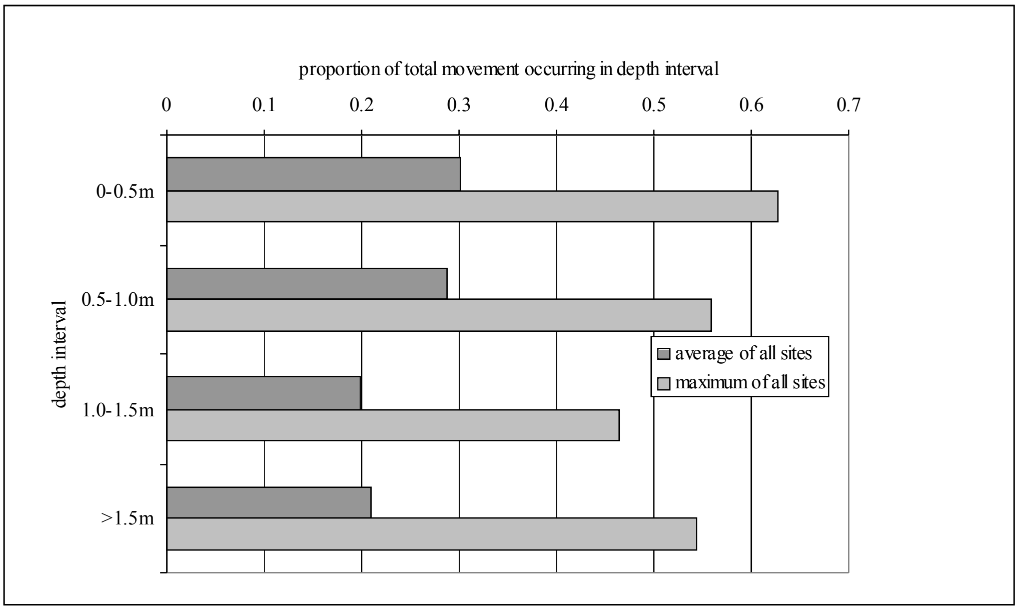


Figure 9: Average and maximum contributions to total movement by different intervals of the soil profile.

It is noted that most of the minor sites have been monitored for a period of between 5 and 7 years. Whilst the data recorded to date is considered appropriate to evaluate the current ground movement predictive methods recommended by AS 2870 (1996), it may not reflect extreme ground movements and moisture contents as the observation period is still likely to be short in climate terms. It is worth noting that for site classification from established data, at least 10 years of monitoring is required by the Australian Standard for Residential Slabs and Footings (AS2870 1996).

4 CONCLUSIONS

A network of field sites comprising a major site and nineteen minor sites has been successfully established and monitored for the purpose of investigating expansive soil behaviours in the Newcastle-Hunter region. The long-term, high quality field data collected to date has provided valuable information on the nature and distribution of expansive soils in the region. Based on the results of the field monitoring and laboratory testing, the following conclusions may be drawn:

1) Traditional index tests are of little general value in assessing the reactivity of expansive soil.
2) The visual-tactile approach to reactivity estimation is highly unreliable because of large variability in the colours and textures observed in local clays, either weathered from the same parent rock unit or a different lithotype.
3) The presence of trees results in an increase in the active depth.
4) The observed reactive soil ground surface movements in open ground areas across the region range between 7 mm and 58 mm with an average of 29 mm. Using the approach suggested by AS2870, on average these movements can be reasonably reliably predicted, although the average error between predictions and observations is up to 11 mm and in individual cases the errors may be as large as 30 mm.
5) The differences between predictions and observations may be attributed to the following reasons:
    - The presence of trees affecting the assumed depth of soil moisture variation,
    - difficulties in testing and quantifying reactivity trends in gravelly conglomeratic soils and
    - the presence of water tables in alluvial soils and layers such as coal.
6) The variability in observed ground movements on a small scale suggests that one swell-shrink test is insufficient to determine the site reactivity in the Newcastle–Hunter region.

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