An Investigation into the Displacement of Permanent Survey Marks in the Hillcrest Area Resulting from Reactive Soils

M. Filmer

G. Sandford

ABSTRACT

Reactive soils in the Adelaide suburb of Hillcrest (South Australia) have resulted in concrete Permanent Survey Marks (PSMs) being horizontally displaced. This has been identified by different surveys over the past 50 years showing differences in relative measurement between PSMs. It has been assumed that this movement relates directly to the seasonal wetting and drying of reactive soils found in the area. A monitoring project was established, which found that minimal movement occurred within the 10 month study period. The results suggest that any substantial horizontal displacement previously identified is a gradual movement occurring over a number of years rather than seasonally.

M. Filmer

University of South Australia

GPO Box 2471

Adelaide, South Australia 5001

Australia

(now at Curtin University of Technology)

M.Filmer@curtin.edu.au

G. Sandford

Supervising Surveyor

Geodetic Services Section

Land Services Group

Department for Transport, Energy and Infrastructure

GPO Box 1354

Adelaide, South Australia 5001

Australia

email: sandford.geoff@saugov.sa.gov.au

INTRODUCTION

Problems arising from reactive soil movements in certain areas of Adelaide (South Australia) have been known for many years (Sheard and Bowman, 1994). Reactive soil problems (ie. reaction to changes in soil moisture due to seasonal conditions or human activity) of this nature are generally reflected in vertical movement ie. localised settlement or heave, which damage infrastructure such as housing, roads, pavement and pipes.

These areas containing reactive soils also present a problem for the local cadastral surveying community in that survey data over the past 50 years suggest that the local Permanent Survey Marks (PSMs) of the tertiary network are horizontally unstable.

This paper will investigate the horizontal stability of PSMs within a localised area using historical data and the results of a monitoring project (five surveys at 2 month intervals) carried out over a 10 month period from December 2002 to October 2003. The objectives of the project are to determine whether PSM displacement over the study period is:

- Of the magnitude indicated by historical data, ie. substantial relative linear movement of 0.03 m - 0.09 m, and
- Dependent on seasonal change ie. the displacement occuring at the change of season as soil moisture content changes and the soil shrinks-swells or more gradually over the course of the year (or over a number of years).

This study has particular interest in this problem with regard to the impact on boundary re-definition, with the north eastern suburb of Hillcrest selected as the study area. Historical survey data, which has been used to identify the problem will be presented, with relative linear discrepancies between PSMs in different surveys of 0.03 m to 0.09 m being referred to as substantial for the purpose of this paper.

REACTIVE SOILS AND TERTIARY NETWORK PSMS IN THE HILLCREST AREA

Reactive soils

Suburbs such as Hillcrest, Northfield, Gilles Plains, Windsor Gardens and Greenacres in the north eastern Adelaide (South Australia) metropolitan area are situated on soils that are highly reactive to seasonal conditions and changes resulting from human activity. A surface soil known as Black Earth (BE) soil overlays heavy clay that has been formally defined by Sheard and Bowman (1987) as Keswick Clay and is particularly susceptible to these types of movements.

Sheard and Bowman (1994) carried out a comprehensive study of the soils and geology of the Adelaide Plains that included the soil profiles from 129 boreholes across the Adelaide area, one of which is within the study area for this project. This soil profile confirms the presence of BE soils to a depth of 0.45 m, with a transitional clay at 0.85 m and Keswick Clay at 2.05 m.

BE soils typically feature large cracks appearing during the dry months, with a highly plastic mass resulting as the soil becomes wet during winter, closing up the cracks. These seasonal conditions cause moderate to extreme shrink-swell movement during the year which can result in significant infrastructure damage. Sheard and Bowman (1994) cite previous work by the same authors (Sheard and Bowman, 1984) and state that *the properties of black earth soils cause some of the worst geomechanical problems in the Adelaide area*.

The Keswick Clay that underlays the BE soils in the Hillcrest area as described above, appears to be an even worse soil type in regard to causing infrastructure damage. The study by Sheard and Bowman (1994) found that *Keswick Clay has demonstrated to be the most geomechanically unstable unit in the Adelaide area* and that *BE soils are only half as reactive as the substrate Keswick Clay*.

As indicated above, soil volume change (shrink-swell) results in vertical settlement or heave of the soil surface, but uneven vertical movement (particularly gilgai formations), are considered the most likely cause of horizontal displacement of the measuring point on the top of a PSM as described and illustrated later in this paper. Gilgai features (Figures 1 and 2) are common where the upper surface of the Keswick Clay is within 1 to 2 metres of the present ground surface (Sheard and Bowman 1987; 1994) and can be described as a type of structural irregularity. The term gilgai refers to the undulating soil surfaces that are common in certain areas of metropolitan Adelaide (also found in other areas of Australia and overseas). These all seem to be the result of underlying reactive clays (Figure 1) pushing upward through the soil on the surface as the underlying clay expands, usually as a result of changes to the soil moisture.

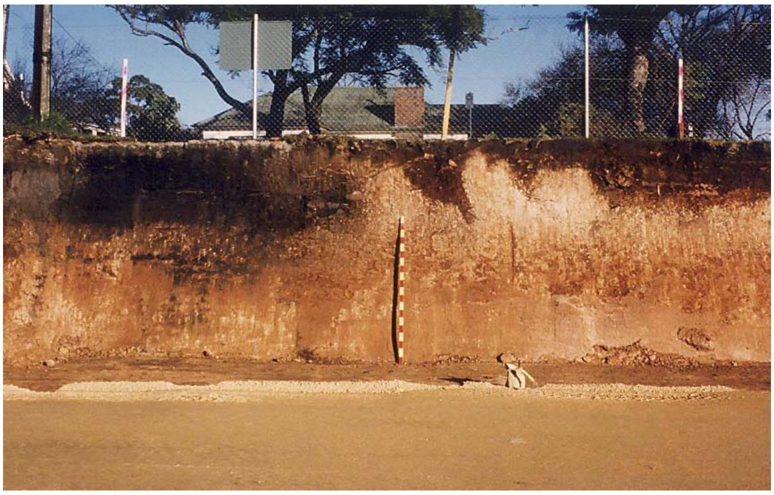

Figure 1. *Cross-section of excavation in Adelaide metropolitan area revealing light coloured Keswick Clay pushing up through the surface soil to form gilgai (from Sheard and Bowman, 1994).*

Figure 2. *Undulating surface resulting from gilgai formations. This example is from western Victoria. (from http://www.dpi.vic.gov.au/dpi/vro/vrosite.nsf/pages/gloss_DG)*

Gilgai structures are not always active, with triggers that alter soil moisture artificially able to reactivate inactive gilgai. Sheard and Bowman (1994) identify the practice of construction companies and underground service installers using porous materials such as sand or gravel as backfill being a major cause for promoting the channelling of surface or soil water into reactive soils. In addition, any excess water from leaking pipes is effectively collected and channelled through these service trenches and into the reactive underlying Keswick Clay.

Tertiary Network PSMs

The PSMs that are the subject of this investigation form a part of the tertiary network which *represents the national and State geodetic network at a localised level* (MSPV2, 1992). Objectives of the tertiary network (and thus the published MGA coordinate values) include providing the foundation for the South Australian coordinated cadastre, enabling redefinition of land parcels, irrespective of loss or destruction of survey marks and simplifying cadastral survey examination (MSPV2, 1992). The tertiary network is allocated levels of precision, known as Class and Order (ICSM, 2002). All PSMs included in the study area have published MGA coordinates of Class C, Order 3. Equation 1 can be used to assess the relative fit of two stations to the existing data set (ICSM, 2002):

$$r = c(d+0.2) \tag{1}$$

where c = 30 for 3rd Order and is an empirically derived factor represented by historically accepted precision for a particular standard of survey, *d* is the distance to any station in km, and *r* is the length of the maximum allowable semi major axis in mm (one standard deviation) of the error ellipse for one station relative to the other. Equation 1 can also be used to allocate Class to a survey, which is generally related to the survey observations (ICSM 2002).

The Surveyor General's Direction No. 2 (1992) states that the construction of PSMs (eg Figure 3) must be below ground, with a brass plaque or steel rod measuring at least 300 mm in length and 10 mm in diameter set in a concrete block measuring at least 150 mm square on the top, 250 mm square at the base and 300 mm in depth. The PSMs in the Hillcrest study area were constructed in the original 1954 subdivision survey and may not conform exactly to these specifications. The published MGA coordinates for this marks result from a Government control survey in 1981 using terrestrial survey equipment.

Figure 3. *Pre-cast PSM with plaque glued to the top. The plaque will be situated just below the surface after the PSM is installed in the ground, with the raised centre of the plaque the measuring point.*

Cadastral surveys in tertiary network areas are required to connect to at least three PSMs that are part of the tertiary network (or two network marks and one non-network mark of similar construction). For urban surveys these connections must be within a positional tolerance of 0.05 m or a linear tolerance of 0.03 m plus one part in 10 000, of the published MGA coordinates as set out in Surveyor General's Direction No.1 (1992).

Recent cadastral surveys in the study area have been unable to connect to the required PSMs within cadastral tolerances as outlined above. The problems in Hillcrest have been appearing since the mid-1990s when this area began to be re-developed, with allotments being divided and new housing constructed.

The impact of this problem is that:

- It costs private sector surveyors time and money to re-check their work when discrepancies to MGA coordinates and previous surveys arise and also for the government to investigate these problems, generally finding no problem with the work of the most recent surveyor.

- Distortion of the cadastre. The PSMs in this area are marks placed in original subdivisions (mid 1950s) and are used to re-establish boundaries in this area.

- Serious problems will arise if a legalised coordinated cadastre is introduced in an area where the listed coordinates do not agree with unstable PSMs.

- All of the PSMs in the study area have published MGA coordinates stated to be of Class C, 3rd Order standard, but the movement identified is often larger than 3rd Order tolerance.

MONITORING PROJECT AT HILLCREST

Network design and field surveys

The monitoring project established in the Hillcrest area (Figure 4) was designed to monitor a localised sample of PSMs that had shown discrepancies between previous surveys, dating back to the original sub-division plan in 1954, when most of these PSMs were originally placed. While there appears to be limited published material on monitoring surveys of this size and nature (200 by 300 metre extent), there exist numerous examples of horizontal monitoring of crustal movement using GPS (eg Clarke *et al* 1998; Featherstone *et al* 2004). Crustal monitoring is generally conducted over a much larger area and longer timeframe, requiring geodetic considerations not required for this study, but the principles of determining significant horizontal displacement remain similar.

Coleman and Lambeck (1983) assert that repeatability is the important factor, not necessarily accuracy, to identify crustal displacement. Repeat surveys carried out at different epochs, under as near a set of identical conditions as possible, should thus result in any significant deformation identified as being largely independent of the choice of deflection, geoid heights and datum parameters. While this assertion is in the context of geophysical work over larger areas, it can be applied for this study, as any significant PSM displacement identified from repeat surveys under similar conditions with identical instrumentation should be largely independent of systematic errors associated with each survey. Any monitoring survey should take care to avoid interpreting observational uncertainty as displacement (crustal or resulting from soil movement) as highlighted by Coleman and Lambeck (1983), particularly when making comparisons to historical survey data.

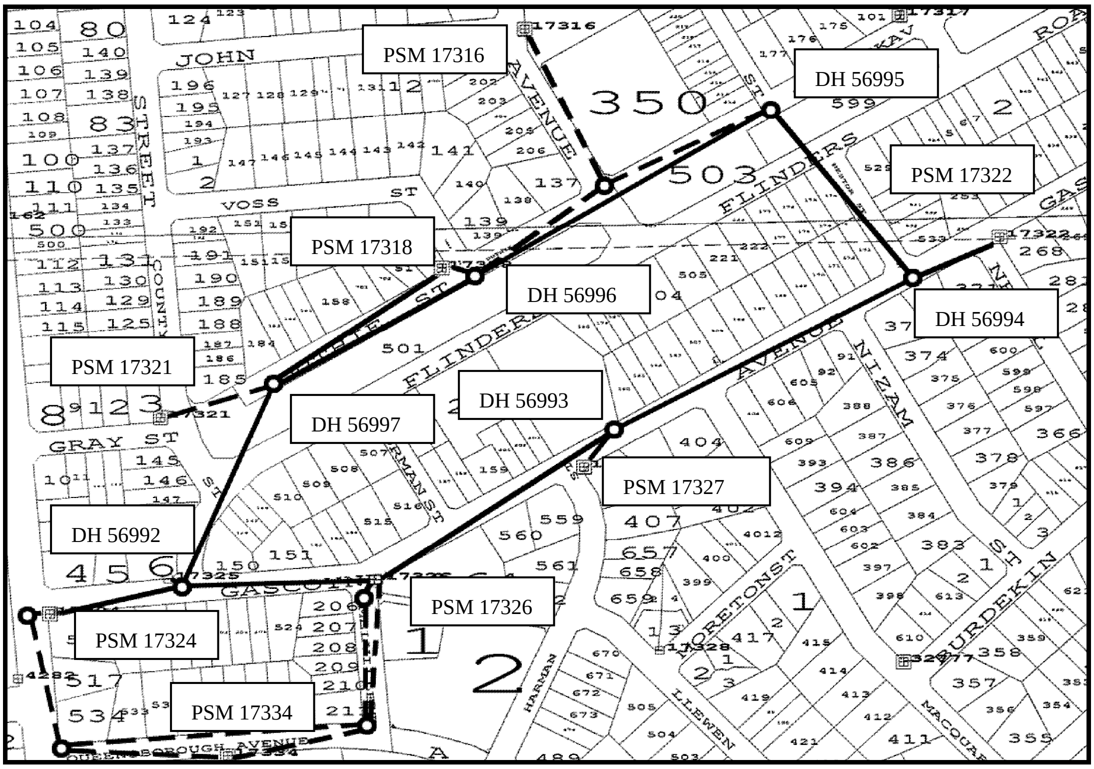

Figure 4. *Location of traverse points and PSMs connected during monitoring surveys. Original traverse lines are solid black lines (connecting five PSMs; 17324, 17326, 17327, 17322, 17318), while subsequent connections (additional three PSMs; 17316,17321, 17334) in dashed black lines (Map data are subject to Crown copyright and supplied by Department of Environment and Heritage).*

For the purpose of this study, five PSMs (17318, 17322, 17324, 17326, 17327) were monitored for 10 months, with the project widened to include an additional three PSMs (17316, 17321, 17334) towards the end of the study period for comparison to previous surveys. Five terrestrial monitoring surveys were conducted from December 2002, with a survey in March, June, August and October 2003 designed to identify when movement (if any) took place throughout the year and could be related to seasonal conditions at that epoch.

The total study area was small, only about 200 m by 300 m, with numerous trees and urban obstructions, which made conventional terrestrial survey methods more suitable than GPS. The small area allows a plane to be assumed with any geodetic considerations (eg deflection of the vertical, skew corrections, etc) considered negligible. A total station with 5 second digital theodolite was used to read angles (one set for each angle comprising one round per set, with the range within each round to be no more than 5 seconds) and EDM measurement of each distance twice. Each traverse was closed, providing an indication of the achieved precision. While this does not fully comply with ICSM (2002) standards for Class C surveys (eg. rounds per set of horizontal angles), it is expected that the relatively short traverse legs (maximum 200 m) using the above methods will be sufficient for these surveys to conform with Class C standards (Table 2).

The built up nature of the area made optimum traverse design difficult. This is a problem which regularly confronts cadastral surveyors in urban areas, where restricted lines of sight mean that traverse shapes generally must conform to the urban design. The resultant traverse (Figure 4) is therefore the best geometry that could be achieved. All measurements were captured digitally by data recorder, with calculations carried out within the recorder up to the adjustment stage. This eliminated the possibility of incorrectly booking angles or distances.

The traverse points established to measure to the PSMs (DHs 56992 - 56997) were constructed by simply drilling 3 mm holes in the top of the concrete kerb. It was expected that although these structures could be susceptible to vertical movement resulting from reactive soils, their continuous horizontal nature would ensure short term horizontal stability.

Network quality and adjustment of networks

The reliability of the terrestrial monitoring surveys carried out in December 2002 and March, June, August and October 2003 should first be assessed. The closures of each traverse loop will provide an indication of the precision attained by each survey, using Equation 1

Thus, for the project traverse where d = 1.08 and c = 30, to achieve Class C precision, the traverse must have a misclosure of no more than 38.4 mm. While this is considered a general guide only, it demonstrates the level of precision achieved by each traverse. Table 1 lists the precision with which each traverse was closed and indicates that the precision of each traverse conformed to Class C standard.

Survey	Hor. Misclose (metres)
1	0.008
2	0.004
3	0.003
4	0.027
5	0.004

Table 1. *Traverse misclosure for each monitoring survey.*

It was intended to use the traverse points as local control for the adjustment of each individual monitoring survey. As stated, these points were drill holes in concrete kerbing and were expected to be stable during the study period (Table 2). Each survey was adjusted separately by Land Services Group (LSG) using the NEWGAN adjustment software, with point 56994 held fixed and a fixed orientation on the line 56994 to 56997. Approximate MGA coordinates for 56994 and 56997 were derived from the local tertiary network for this purpose. It is not critical which set of coordinates was used to fix the terrestrial data, as the interest was in the relative measurements between the local PSMs. The resulting least squares adjustments provided five terrestrial surveys all fixed on the common point of 56994 and oriented to 56997, with the coordinates produced for each PSM in each terrestrial survey being compared and analysed for horizontal differences that could be attributed to displacement due to soil movement. It was therefore of importance to establish the stability of 56994 and 56997 throughout the study period.

The evidence for the horizontal stability of the traverse points used as control can be seen in Table 2. Table 2 shows the calculated ground distance (scaled from adjusted MGA coordinates) between traverse points for survey 1 and a comparison to these distances for each subsequent survey. A maximum difference is shown, which is the difference between the shortest and longest distance between the two points concerned. The Class C tolerance for each of these distances is shown as a guide to the uncertainty of each distance, although the error ellipses from the adjustment of these data (table3) suggest positional precisions of around 0.008 to 0.011 m.

Mark	To	S1 Dist	S2 Diff	S3 Diff	S4 Diff	S5 Diff	Max Diff	Class C Tolerance
56994	56992	466.451	-0.002	-0.002	-0.005	-0.004	0.005	0.020
56994	56993	204.339	0.000	-0.001	0.002	0.005	0.006	0.012
56994	56995	137.320	0.003	0.003	0.004	0.009	0.009	0.010
56994	56996	256.332	0.003	0.000	0.002	0.002	0.003	0.014
56994	56997	376.117	0.003	0.001	0.001	0.004	0.004	0.017
56992	56993	263.194	-0.003	-0.002	-0.008	-0.010	0.010	0.014
56992	56995	446.502	-0.006	-0.008	-0.001	-0.003	0.008	0.019
56992	56996	253.668	-0.003	-0.003	-0.002	-0.003	0.003	0.014
56992	56997	134.283	-0.001	-0.003	0.000	-0.002	0.003	0.010
56993	56995	220.375	-0.007	-0.005	0.004	0.006	0.013	0.013
56993	56996	122.833	-0.004	-0.002	0.001	0.000	0.005	0.010
56993	56997	192.538	-0.001	0.001	-0.002	-0.001	0.003	0.012
56995	56996	196.996	-0.003	-0.006	0.001	-0.001	0.007	0.012
56995	56997	328.607	-0.003	-0.005	0.002	0.001	0.007	0.016
56996	56997	131.656	0.000	0.001	0.001	0.002	0.002	0.010

Table 2. *Calculated ground distances for each survey between traverse points compared to survey 1. All distances shown in metres.*

The maximum variation in each distance is generally well inside Class C tolerance, which indicates that these points are stable relative to each other, certainly within measurement uncertainty. The comparisons between 56994 and 56997 support the use of these points as control for the adjustment.

Comparisons between monitoring surveys

Table 3 displays the positional differences (vector magnitude) for each PSM relative to its position in survey 1(S1). Survey 1 took place in December 2002 and survey 5 (S5) in October 2003. Despite not running the full 12 months, a representative range of seasonal conditions was experienced. It was very dry for the initial survey, as expected in Adelaide in December and by October 2003, had experienced rain and damp soil conditions during the winter. It must be stated that these results may be unique for this particular year, but it suggests that these PSMs did not experience substantial displacement of 0.03m or more as indicated by previous surveys during the study period.

Table 3 also displays the precision estimate (semi-major axis of the error ellipse at 95% confidence) from the adjustment of each terrestrial survey for each positional observation. It can be seen that all PSMs except 17326 have demonstrated movement greater than the estimated precision (shown in bold), but none could be considered substantial as has been historically suggested. The largest vector difference is for PSM 17324 which is only 0.004m outside of the precision estimate in survey 5.

Point	Vec Diff S2	Precision	Vec Diff S3	Precision	Vec Diff S4	Precision	Vec Diff S5	Precision
56994	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
17318	0.005	0.007	**0.010**	0.009	**0.011**	0.007	**0.008**	0.007
17322	0.004	0.006	0.002	0.006	**0.013**	0.006	**0.013**	0.006
17324	0.003	0.010	0.007	0.010	**0.011**	0.009	**0.014**	0.010
17326	0.005	0.008	0.006	0.008	0.005	0.008	0.007	0.007
17327	**0.011**	0.008	0.007	0.008	0.008	0.008	**0.009**	0.008
56992	0.004	0.008	0.002	0.008	**0.008**	0.007	0.007	0.007
56993	0.005	0.006	0.001	0.006	0.003	0.006	0.005	0.006
56995	0.005	0.006	0.006	0.006	0.004	0.006	**0.008**	0.006
56996	0.003	0.006	0.001	0.006	0.003	0.006	0.002	0.006
56997	0.003	0.007	0.001	0.007	0.001	0.007	0.004	0.006

Table 3. *Vector differences of each mark relative to survey 1 and their associated precision estimate. All distances are in metres.*

A direct comparison of relative distances between PSMs for each survey as carried out for the traverse points in Table 2 would provide further evidence of possible PSM displacement during the monitoring period. These comparisons are presented in Table 4, where ground distances between all PSMs in the study area are presented for each survey. This comparison is independent of any biases that may be present in the coordinate comparisons in Table 3 as a result of ignoring any random observational errors associated with the points 56994 and 56997 which were held fixed in the adjustment. Table 3 also makes a comparison to the maximum allowable error ellipse for these marks (using Equation 1) to remain within 3rd Order tolerance. The column showing maximum difference in metres is the difference between the longest and shortest calculated distances, not a comparison to the initial distance. Once again it can be seen that no substantial differences exist, although there are several that slightly exceed 3rd Order tolerance. The measurement uncertainty of the calculated distances could be considered to be similar to the 3rd Order tolerance shown, which are slightly larger than those suggested by the adjustment, but suitable for the purpose of this comparison. Any differences outside of 3rd Order tolerance are highlighted in bold.

Mark From	To	Survey 1 Distance	Survey 2 Distance	Survey 3 Distance	Survey 4 Distance	Survey 5 Distance	3rd Order Tolerance	max. diff. metres
17318	17322	320.865	320.863	320.857	320.845	320.849	0.016	**0.020**
17318	17324	309.090	309.083	309.082	309.093	309.093	0.015	0.011
17318	17326	194.497	194.486	194.487	194.496	194.499	0.012	**0.013**
17318	17327	146.570	146.555	146.553	146.554	146.554	0.010	**0.017**
17322	17324	592.188	592.184	592.180	592.177	592.179	0.024	0.011
17322	17326	413.715	413.709	413.707	413.708	413.714	0.018	0.008
17322	17327	276.631	276.629	276.629	276.619	276.629	0.014	0.012
17324	17326	190.071	190.071	190.071	190.068	190.063	0.012	0.008
17324	17327	320.051	320.046	320.043	320.050	320.041	0.016	0.010
17326	17327	137.084	137.080	137.078	137.089	137.084	0.010	**0.011**

Table 4. *Comparison of ground distances between PSMs for all five monitoring surveys. All distances in metres.*

Comparisons with existing survey data

The above data indicates that substantial relative horizontal movement of the PSMs in the study area of 0.03 m or more does not occur every year. It is thus of interest to make some comparisons between the survey data from this project and previous data from the other surveys conducted in previous years. As there were no substantial differences between the monitoring surveys, all five surveys carried out in 2003 were adjusted together to produce one coordinate for each PSM during the study period. Comparisons between these adjusted data and the listed MGA coordinates (1981 survey data) for each PSM are made in Table 5.

Table 5 is a relative distance comparison, shown in ground distance as in Table 4. It confirms that the calculated distance between many of these PSMs using the published MGA coordinates differ substantially to subsequent (2003) survey measurement between these same PSMs. The quality of both data sets are well represented by the calculated 3rd Order precision, with the relative fit of the 2003 survey data to the published MGA coordinates generally not conforming to 3rd Order standard. There are several examples where the comparisons are greater than linear cadastral tolerance which is simply 0.03m + one part in 10,000 of the distance. It confirms the situation where tertiary network PSMs (and their published MGA coordinates) in this area that are stated to be of 3rd Order quality, do not currently conform to the tolerance required for a 3rd Order network.

Distance comparisons between a 1995 cadastral survey and the 2003 survey data between the PSMs in the study area over the past 8 years, are illustrated in Table 6. While most of these distances show good agreement, there are differences of up to 0.05 m between these surveys. A precision of 0.02 m for these calculated distances is considered realistic based on previous estimates. This comparison thus indicates that over 8 years, five relative PSM distances have changed by 3-5 cm, which are greater than the precision estimates.

Differences in distance between MGA and 2003 monitoring surveys

PSM From	To	1981 MGA Distance	2003 Distance	3rd Order Tolerance	Linear Cadastral Tolerance	Difference
17324	17326	190.047	190.069	0.012	0.049	0.022
17324	17327	320.001	320.046	0.016	0.062	0.045
17324	17322	592.168	592.182	0.024	0.089	0.014
17324	17318	309.113	309.088	0.015	0.061	-0.025
17324	17316	449.938	449.935	0.020	0.075	-0.003
17324	17334	133.658	133.571	0.010	0.043	**-0.087**
17324	17325	71.672	71.642	0.008	0.037	-0.030
17324	17321	136.743	136.756	0.010	0.044	0.013
17326	17327	137.057	137.083	0.010	0.044	0.026
17326	17322	413.716	413.711	0.018	0.071	-0.005
17326	17318	194.528	194.493	0.012	0.049	-0.035
17326	17316	347.526	347.516	0.016	0.065	-0.010
17326	17334	137.286	137.295	0.010	0.044	0.009
17326	17325	120.434	120.499	0.010	0.042	**0.065**
17326	17321	160.454	160.477	0.011	0.046	0.023
17327	17322	276.659	276.628	0.014	0.058	-0.031
17327	17318	146.570	146.557	0.010	0.045	-0.013
17327	17316	269.966	269.949	0.014	0.057	-0.017
17327	17334	269.993	270.046	0.014	0.057	0.053
17327	17325	248.338	248.413	0.013	0.055	**0.075**
17327	17321	245.258	245.295	0.013	0.055	0.037
17322	17318	320.834	320.856	0.016	0.062	0.022
17322	17316	301.146	301.157	0.015	0.060	0.011
17322	17334	544.473	544.504	0.022	0.084	0.031
17322	17325	520.909	520.946	0.022	0.082	0.037
17322	17321	494.039	494.048	0.021	0.079	0.009
17318	17316	153.682	153.709	0.011	0.045	0.027
17318	17334	322.026	321.965	0.016	0.062	-0.061
17318	17325	246.775	246.744	0.013	0.055	-0.031
17318	17321	185.231	185.202	0.012	0.049	-0.029
17316	17334	475.396	475.360	0.020	0.078	-0.036
17316	17325	393.851	393.835	0.018	0.069	-0.016
17316	17321	315.890	315.874	0.015	0.062	-0.016
17334	17325	112.282	112.258	0.009	0.041	-0.024
17334	17321	210.497	210.441	0.012	0.051	**-0.056**
17325	17321	99.985	99.956	0.009	0.040	-0.029

Bold differences are outside cadastral tolerance

Underlined differences are outside 3rd Order tol.

Table 5. *Ground distance comparison between MGA coordinates (1981 data) and adjusted coordinates for all 5 terrestrial monitoring surveys. All distances in metres.*

From	To	1995 Distance	2003 Distance	Differences Distance
17327	17318	146.59	146.56	-0.03
17327	17322	276.63	276.63	0.00
17327	17326	137.08	137.08	0.00
17326	17325	120.50	120.50	0.00
17326	17324	190.08	190.07	-0.01
17326	17318	194.48	194.49	0.01
17326	17321	160.50	160.48	-0.03
17325	17324	71.65	71.64	-0.01
17318	17321	185.17	185.20	+0.03
17318	17316	153.76	153.71	-0.05
17321	17316	315.90	315.87	-0.03
17321	17324	136.76	136.76	0.00

Table 6. *Distance comparisons between a 1995 cadastral survey and the 2003 monitoring surveys. All distances in metres.*

Comparisons between the 2003 monitoring surveys and the original 1954 subdivision survey which placed these PSMs are not shown here, but differences in distance between the same PSMs ranged up to 0.09 m.

CONCLUSION AND RECOMMENDATIONS

The magnitude of horizontal PSM displacement across the study area during the study period was minimal, with maximum differences on or just over the estimated measurement uncertainty. This suggests that the substantial displacement due to reactive soils as indicated by comparisons between previous surveys occur over a longer period of time and not seasonally as previously believed. It should be noted however, that different seasonal and local conditions (ie. significant infrastructure work) may produce different results within a 12 month period. It would appear that these longer term movements are the result of moisture changes within the deeper lying Keswick Clay, which result in the gilgai formations that produce an undulating soil surface most likely to be the cause of any horizontal PSM displacement. The published MGA coordinates for the PSMs in the study area do not generally conform to the 3rd Order tolerance required by the tertiary network, which is a result of the horizontal displacement of the PSMs in the period since the 1981 survey which collected the raw data.

Considering the minimal movement identified within the study period, re-observation and re-adjustment of the network within this local area to reflect current PSM positions may be a short to medium term solution. An increase in the number of deep PSMs (anchored in bedrock and isolated from the moving soil) as already exist in the area may be the best long term solution for maintaining a tertiary network with published coordinates of 3rd Order precision or better, although the cost may be prohibitive. The use of concrete house footings, brick fences, or masonry nails in concrete footpaths (which would be more horizontally stable than the existing PSMs) for cadastral reference marks in preference to the unstable PSMs is an inexpensive option which should not be overlooked. The use of alternative cadastral reference marks as described would however, be contrary to the policy that the cadastre in tertiary network areas be defined solely by PSMs. Continued monitoring of this localised study area over an extended period such as 10 years would assist in identifying longer term trends.

ACKNOWLEDGEMENTS

The authors would like to thank Brenton Christie, Ashley Window and Rob Couzner for assistance with fieldwork and Steed & Pohl Licensed Surveyors and the University of South Australia for providing survey instruments. Steve Latham (Geodetic Services Section) for his considerable assistance with survey adjustments, Kevin Arthur for his help preparing the map in Figure 4 and Professor John Gilliland for his initial review and comments on the manuscript. We also thank Dr Graeme

Wright and the anonymous reviewer who reviewed this manuscript for their constructive comments.

REFERENCES

Clarke, P. J. Davies, R. R., England, P.C., Parsons, B., Billiris, H., Paradissis, D., Veis, G., Cross, P.A., Denys, P.H., Ashkenazi, V., Bingley, R., Kahle, H.-G., Muller, M.-V. and Briole, P. (1998) Crustal strain in Central Greece from repeated GPS measurements in the interval 1989-1997, *Geophysical Journal International*, 135:pp 195-214.

Coleman, R. and Lambeck, K. (1983) Crustal Motion in South Eastern Australia: Is there Geodetic Evidence for it? *Australian Journal of Geodesy, Photogrammetry and Surveying*, No. 39, pp 1-26.

Featherstone, W.E., Penna, N.T., Leonard, M., Clark, D., Dawson, J., Dentith, M.C., Darby, D., and McCarthy, R. (2004) GPS-geodetic deformation monitoring of the south-west seismic zone of Western Australia: epoch-one, *Journal of the Royal Society of Western Australia*, 87(1): 1-9.

ICSM (2002) *Standards and Practices for Control Surveys*, Version 1.5, Inter – governmental Committee on Surveying and Mapping, www.icsm.gov.au/icsm/publications/sp1/SP1v1-5.pdf

MSVP2 (1992) *Manual of Survey Practice*, Volume 2 (SA), (regularly updated), www.landservices.sa.gov/1Professional_Access/Manual_of_Survey_Practice/Volume_2/

Sheard, M. J. and Bowman, G. M. (1987) *Definition of the Keswick Clay, Adelaide/Golden Grove Embayment, Para and Eden Blocks, South Australia*, [CD-ROM, Nos. 1-129], South Australia Geological Survey, Quarterly Geological Notes, No. 103, pp. 4-9.

Sheard, M. J. and Bowman, G. M. (1994) *Soils, stratigraphy and engineering geology of near surface materials of the Adelaide Plains*, [CD-ROM], Primary Industries and Resources South Australia, Report Book 94/9, Vols.1, 2 & 3.