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Expansive soil movement due to atmospheric boundary interaction: a field study in a semi-arid climate area

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ABSTRACT: Expansive soils are characterised by their ability to swell and shrink significantly due to variations in moisture content, primarily because of the presence of different clay minerals. These volume changes can lead to substantial ground movement, imposing additional stresses on structures built on or within such soils. To study this phenomenon, a research site was established near Adelaide, Australia, where extensive instrumentation was employed to monitor key parameters. Monitored parameters included weather conditions, ground movement, and moisture content at depths of up to 6 meters. The monitoring was conducted for nearly five years at multiple points across the site. This paper analyses a subset of the observations. Notable variations in ground movement were observed across the site. Correlations were explored to understand the underlying reasons for the disparities. The findings highlight the complexity of expansive soil behaviour and emphasise the importance of considering localised environmental and subsurface conditions when designing and constructing on such problematic soils.

KEYWORDS: Expansive soils, ground movement, field study, moisture movement, atmospheric boundary interaction, vegetation.

1 INTRODUCTION

Expansive soils are sensitive to changes in moisture and can undergo significant volume change. They are common in various parts of the world, including Australia, South Africa, the USA, Canada, and India (Nelson et al., 2015). Nearly 30% cent of Australian surface soils can be classified as expansive (Karim et al., 2021, Devkota et al., 2024, Richards et al., 1983). The design and construction of lightweight structures (residential footings and linear structures such as water mains or pavements) on/in expansive soils have been challenging due to the significant stresses induced by ground movement. Expansive soil was treated as the most damaging geohazard, and damage cost was estimated to exceed £3 billion in the UK for the decade of 2000 to 2010. Expansive soil-related damage exceeds $15 billion/year in the USA (Jones & Ian, 2012). The ground movement-related damages contributed ~80% of insurance claims annually in Australia in the housing sector (Considine, 1984). The combination of the presence of expansive soils and arid or semi-arid climate for places such as South Australia (SA) can amplify the severity of the problems, which are expected to worsen due to climate change (Karim et al., 2024, Devkota et al., 2023).

Several past studies focused on accounting for ground movement in geotechnical design since the 1960s (Cameron & Walsh, 1984, Building Research Advisory Board, 1968, Walsh, 1978, Mitchell, 1981, 1984, Aitchison & Holmes, 1961). Empirical methods are commonly used to estimate ground movement for design (Mitchell, 1981). More recent works (Devkota et al., 2023, Karim et al., 2024, Mitchell, 2008, 2013, Karim et al., 2021, Jewell & Mitchell, 2009) have emphasised accounting for climate change on the behaviour of expansive soil in design. The depth of suction change (H_s) has been used in several past studies to correlate the effect of various climate scenarios for different Australian regions (Karim et al., 2024, Devkota et al., 2023, Karim et al., 2021, Mitchell, 2013, Sun et al., 2024, Hu et al., 2016, Fityus et al., 1998, Davenport, 2007, Jackson, 2022). Fernandes et al. (2015) investigated the association between ground movement and changes in climatic conditions in France. Despite the importance, field studies have been limited on ground movement and correlations with the soil-vegetation-atmosphere (SVA) boundary. Numerical studies require good-quality field or laboratory data for validation. Lack of good-quality field studies has contributed to limited progress in the numerical front as well.

Among the limited number of studies that can be found in the literature, Li and Guo (2017) monitored the relative movement of a house footing in Melbourne, Australia, for four months (November 2010 to February 2011) and correlated it to seasonal weather variations and tree root water uptake. They showed that the tree could uptake water from below H_s and increase ground movement. Cheng et al. (2017) monitored ground movement at a site in Nairobi, Kenya, over 14 months for two small footings. Up to 47 mm of settlement and 28 mm of heave were observed over the seasons. Karunarathne (2016) monitored an open ground with reactive soil for nearly two years in three nearby locations and observed 29 mm to 54 mm total seasonal movement over the study period.

Some numerical studies have been conducted to incorporate the soil-atmospheric interaction at reactive sites (Karunarathne et al., 2018, Teodosio et al., 2020, Shams et al., 2018, Devkota et al., 2024). Despite such efforts and widespread distribution of expansive soils globally, the detrimental effects of expansive soils have been generally overlooked, as a longer duration of distress exposure is required before damage is visible (Richards et al., 1983).

This study presents a field study conducted in a semi-arid region of Australia. The site was instrumented and monitored for over five years. Observations from a selected period of two years are discussed here. SVA boundary interactions were evaluated based on the differences in the ground movement among several grid points of the research site.

2 RESEARCH SITE

The research site is located within a natural reserve ~7.5 km south of Adelaide. The study area is ~4000 m^2 in size and is surrounded by 5 m to 19 m tall trees. Figure 1 shows the location and surroundings of the research site. Red points in the figure denote the near-surface deformation monitoring pads installed in a 8 m square grid. The deformation pads are named 1 to 8 in the west-to-east direction and A to H in the south-to-north direction. Eight access holes (AH-A to AH-H) of 6 m depth were installed for neutron moisture meter (NMM) readings. The vegetation on open ground included Kikuyu grass and some weeds. The ground has a gentle slope towards the centre of the park. Shrinkage cracks are observed extensively during the summer and autumn seasons.

The subsoil profiles of the research site vary across the field, as evident from Table 1 for two boreholes at North (N) and South (S) (Figure 1). The subsoil was mostly clay with variation in colour and plasticity with depth, as shown in Table 1. The plasticity of clay varied between intermediate to high, except for the soil near the surface of the south side, which was less plastic (low plasticity clay, CL). Intermediate plastic (CI) clays below high plastic (CH) clay layers often consisted of sand and/or silt with occasional gravels and patches of $CaCO_3$. Sheard and Bowman (1996) classified the soil in an adjacent reserve at the top 3 m as red-brown clay (Pooraka formation) with occasional gravels, and the soil was calcareous. Below the Pooraka formation, a transitional gley clay layer of high plasticity clay/silt (CH-MH) was examined extending nearly up to 10 m depth as shown in Table 1. Although the expansion potential of the soils is controlled by clay minerals such as Kaolinite, Illite and Montmorillonite (Devkota et al., 2022, Devkota et al., 2024, Nelson et al., 2015), the soil's mineralogy was not explored in this study. Instead, the reactivity of soil was determined to assess the shrink-swell potential. The shrink-swell index (I_{ss}) was used. I_{ss} varied from 2.6%/pF to 4.7 %/pF depending on the soil types. Based on AS2870 (2011), the site was categorised as a highly reactive site with deep-seated movement (H2-D). The vertical hydraulic conductivity determined using laboratory Rowe cell tests varied from 2×10^{-10} m/s to 3×10^{-9} m/s.

Figure 1. The study area (Google Earth Pro, 2024) showing access holes (AH), bore holes (BH), and ground movement monitoring points (A1 to A8).

Table 1. Soil profile at the site.

Depth	Colour	USCS	Liquid Limit, %	Plastic Limit, %
North borehole				
0.33	Tan/yellow brown	CI	47	26
0.85	Tan/yellow- brown	CH	60	29
1.15	Red-brown	CH	52	24
2.1	Reddish-brown to yellow-brown	CI	43	21
3.1	Grey-brown and mottled-yellow	CI	46.5	22.5
3.3	Grey-brown and mottled yellow	CI	47.5	23
South borehole				
0.4	Black earth	CL	23	13
0.8	Tan	CI	47	24
1.3	Red-brown	CH	55	24
2.1	Red-brown	CI	42.5	20
3.1	Brown/yellow-brown	CI	45	24
Borehole near the site from Sheard and Bowman (1996)				
4	Light olive brown mottles	CI	45	20
6	Dark orange yellow	CH-MH	55	28
9	Strong yellowish brown Stiff plastic clay transitional gley	CH-MH	56	30

3 SOIL MOISTURE

An NMM device was used to monitor the seasonal variation of moisture content up to 6 m depth at half-meter intervals. The installation of the access tube and the test device is shown in Figure 2. Four additional AHs were established ~1 m east of the main AHs for calibration. Standard U50 samples were extracted. NMM readings were taken at additional AHs immediately before the sampling. A relationship between neutron count ratio (NCR) and volumetric water content (VMC) was developed for the different soil types. Figure 4 presents the calibration for the clay (TRANS) transitional between the red-brown (RB) and grey-brown mottled orange clay (GBMOC).

Figure 2. Set-up for NMM monitoring (a) access tube installation, (b) reading taken.

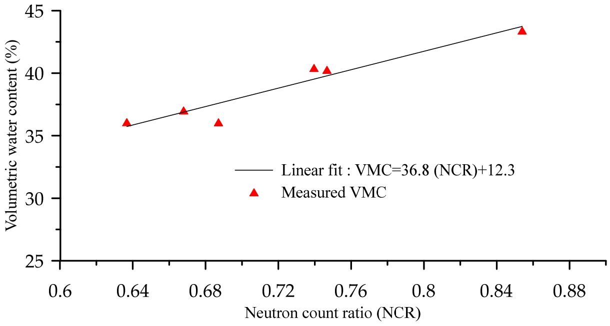

Figure 3. NMM calibration for red-brown transitional clay.

Selected water content profiles measured between October 2022 and October 2024 are presented in Figure 4. Significant differences in moisture content were observed among the AHs. The changes in near-surface moisture profiles were generally greater towards the centre of the site (Figure 4c and d) compared to those closer to the tree canopy line (Figure 4a and b). The depth up to which the seasonal moisture variations were observed also increased towards the centre of the field (AH-E and AH-G). This is the opposite of observations made by Cameron (2001), who stated that trees can increase the level of desiccation. The lower changes in water content could be due to the presence of mulch near the treeline, which may have slowed down the moisture ingress and evapotranspiration by creating a barrier. However, trees are expected to extract water from a significant depth, and their effect was not apparent in the relatively short-term observations in this study. Indeed, total suction profiles (not shown here) confirmed the consistent high levels of desiccation to 6 m depth that had been established near the trees compared to those away from the trees.

4 LOCAL WEATHER

Local meteorological parameters need monitoring when accounting for the SVA boundary interactions. A weather station was established approximately 1 km south-west of the study area, and recording began on August 1, 2021. Monitored parameters are shown in Figure 5. Persistent and heavy rainfall was experienced from June to November (during winter and spring) except for the spring of 2023. Whereas the rainfall events were less frequent in summer. The average yearly rainfall at the weather station location was 649 mm over the monitoring period, which was wetter than the long-term average for the area. Average maximum and minimum daily temperatures were 21.2 and 11.9°C.

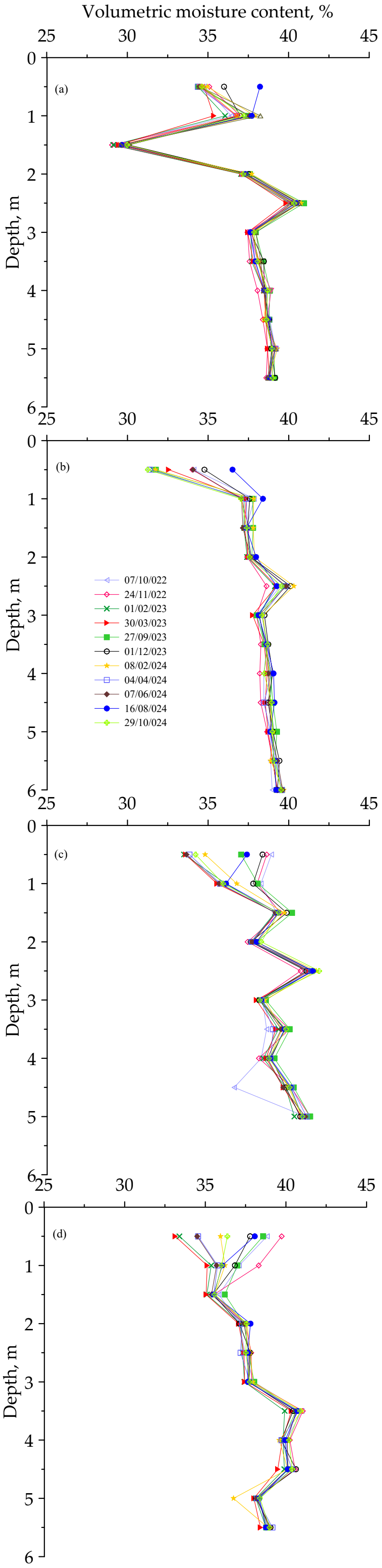

Figure 4. VMC profiles for access holes (a) AH-A, (b) AH-B, (c) AH-E, and (d) AH-G.

5 GROUND MOVEMENT

Near-surface movements were monitored at 2 to 3-month intervals using level surveys. A 6 m deep benchmark was installed near the centre of the study area. Each measurement pad (Figure 1) consisted of 100 mm thick × 400 mm diameter concrete pads with a rod at the centre acting as the measurement point. The bottom of the pad was 400 mm below the ground surface and was covered by an irrigation valve box. To prevent water ingress, the boundary of the box and pad was sealed by water water-proofing compound. The concrete pads served to ensure a relatively stable location for the soil movement measurement, as the ground is an open area and is subjected to frequent mowing and other maintenance activities.

Figure 6 shows the measured maximum movements at various points across the site. The measured movements were highly variable across the study site. The measured maximum movement (with respect to the first measurement date) at different locations ranged from 5 mm at pads B6, D3 and F3 to 44 mm at E5 and E7. Movements ≥40 mm at 5 pads, mostly away from trees (E5, E7, D6, H6, and G6). The north-east quarter of the study site saw the maximum movement. The differences in movement are likely to be significantly contributed to by the variation in site geology and hydraulic boundary conditions (e.g., presence of a buried creek bed).

Near-surface movements along row H during the monitoring period relative to November 2022 are shown in Figure 7. As expected, shrinking of the ground was observed during summer and swelling was observed during winter and early spring. Some exceptions were observed, such as pads H1, H2, and H3 slightly heaved during the mid-summer of 2024. Temporal variation of total ground movement at B6, D3 and F3 (minimum variation 5 mm), and E5 and E7 (maximum variation 44 mm) is presented in Figure 8. The additional point closer to the higher concentration of crack, D6, is also shown in the same figure. It is likely that the presence of cracks contributed to the increased ground movement by affecting the moisture dynamics. Please note cracks of up to a depth >1 m were observed at the research site near the end of summer, and they concentrated near the centre and north-east side of the ground.

From the comparison of measurements between subsequent columns, Columns 1 and 2 (see Figure 6), the presence of trees contributed significantly towards the ground movement, which is understandable as trees are likely to increase the desiccation of soil during the dry season and can extract moisture from significant depth. A similar observation can be made when comparing observations from Row A (near the tree line) and Row B (away from the tree line).

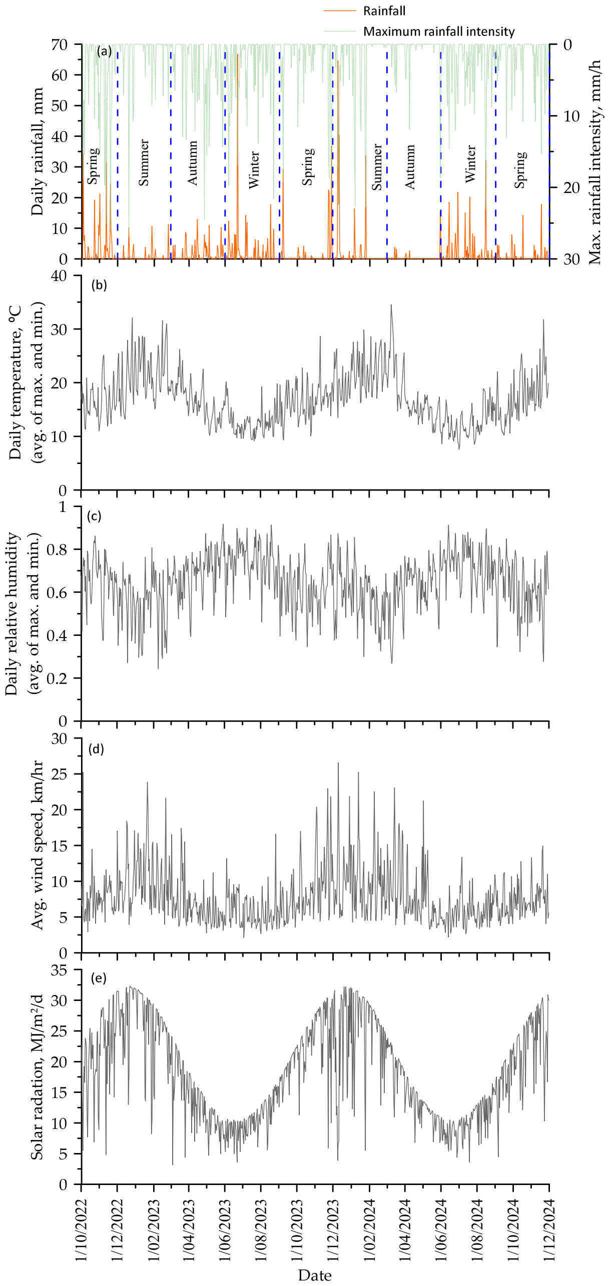

Figure 5. Climate data of the research site from newly established weather station (i) Rainfall, (ii) Temperature, (iii) Relative humidity, (iv) Wind speed, and (v) Solar radiation.

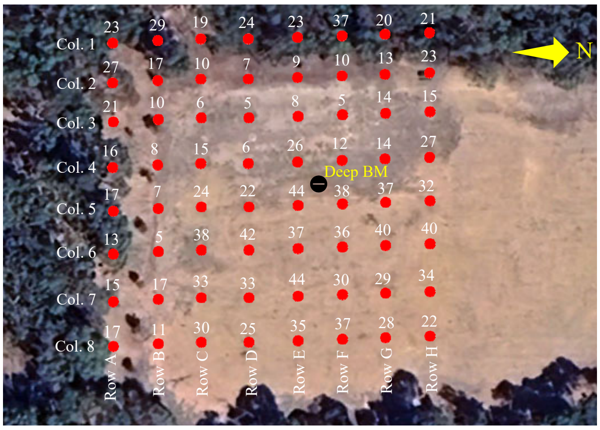

Figure 6. Maximum differences in mm of near-surface movements since November 2022 at various locations.

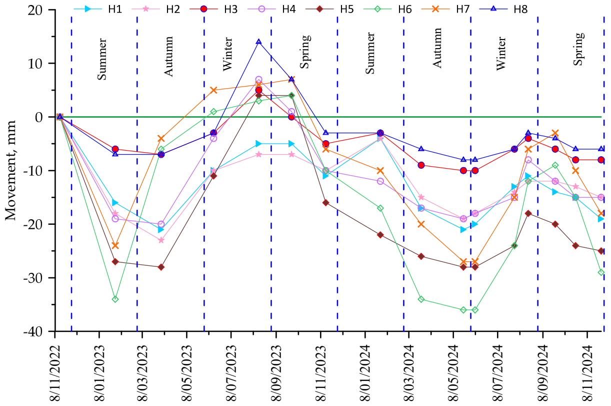

Figure 7. Observed seasonal ground movement (relative to 15/11/2022) on row H.

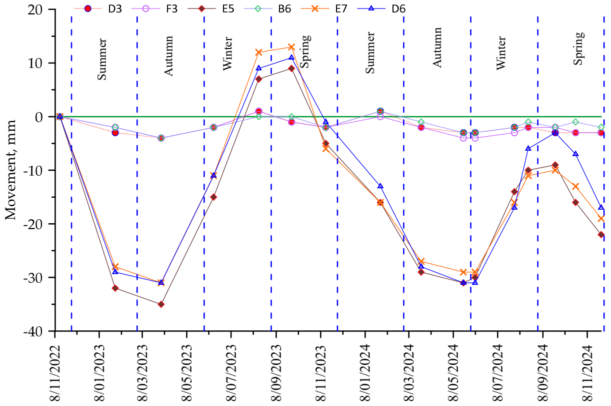

Figure 8. Seasonal ground movement of selected pads, least movement at B6, D3 and F3, largest at E5 and E7 and second largest at D6.

To analyse the correlation between meteorological variables and ground movement, a simple parameter, "available water", was defined as the difference between available rainfall for infiltration and potential evapotranspiration (PET). The monthly available water over the study period is shown in Figure 9. The average movement of pads near the centre of the study area (D5 to H5) was added to the same plot. The strong dependency between "available water" and near-surface movement was demonstrated in the figure. The ground movement pattern closely followed the available water plot. A time lag of nearly two months was observed between the available water and ground movement. Similar observations were made in other studies (Fityus et al., 2004, Karunarathne, 2016, Karim et al., 2019, Karim et al., 2016). This lag was expected due to the relatively lower hydraulic conductivity of the clay-rich soils.

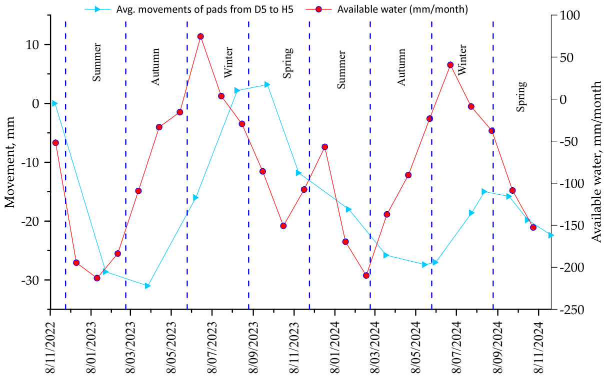

Figure 9. Monthly available water and ground movement over time

6 LIMITATIONS AND RECOMMENDATIONS

Shrinkage cracks of varying concentration/depth/width were observed during field monitoring. However, systematic observations were not carried out in this study. Future research is recommended to quantify crack volume and distribution across the field. Besides, this study showed a time lag of nearly 2 months between changes in available water and ground movement, attributed to the clay-rich soils of low hydraulic conductivity. The correlation of ground movement with only rainfall or available water data may not capture all physical processes involved in soil-atmosphere-vegetation boundary interaction. The use of advanced modelling supported by long-term monitoring of the site is recommended.

7 CONCLUSIONS

A well-instrumented research site with 64 grid deformation measurement points, 48 moisture content measurement points and differences in vegetation and soil geology was monitored for seasonal variation of moisture content and ground movement. The conclusions from this research are outlined below:

- The soil profile in the research site was highly variable, and measured soil moisture and movement varied significantly across the site.
- The changes in near-surface moisture profiles were greater towards the centre of the site compared to those closer to the tree canopy line. This could be due to the differences in soil mineralogy.
- Significant differences in ground movement were observed along the settlement pad line close to the trees and 8 m away from the trees, indicating that the presence of trees significantly increases the ground movement.
- The maximum differential ground movement at any monitoring point ranged from 5 mm to 44 mm across the research site.
- Movements were significantly higher towards the centre and northwest quarter of the ground, indicating significant variability in soil minerology.
- Wider and deeper cracks were observed towards the centre of the ground and may have contributed to the higher movements.
- Seasonal variations in ground movements were generally lower close to the canopy lines than away from these lines. This was likely because of the long-established drying effect of mature trees and the protection provided by the tree canopy against wetting and drying of extreme seasonal events.
- The ground movement correlated well with "available water". A time lag of nearly 2 months was observed between changes in "available moisture" and changes in ground movement.

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