Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-1011

Modelling the movement of expansive soils due to moisture dynamics under current and future climate: a study in a semi-arid climate area

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ABSTRACT: Seasonal changes in weather conditions cause changes in soil moisture and can lead to significant ground movements in expansive soils, as such soils are very sensitive to moisture-induced suction changes. The lightweight structures, such as residential footings, road pavements, and pipelines, can be vulnerable due to suction-induced volume change and related additional stresses. To ensure the serviceability of geo-structures over their design life, possible future changes in ground movement due to changes in climate need to be accounted for in the design. This research provides insight into ground movements related to seasonal moisture dynamics in an area with a semi-arid climate. The ground movement was modelled using a computer program, Abaqus/CAE. Field monitoring data from a research site near Adelaide, Australia, were used to validate the model. In addition, the ground movement under possible future extreme climate scenarios was evaluated to capture the possible future worst-case scenarios. Ground movement was observed to be significantly higher under the possible future climate scenarios considered here. This study will support understanding the importance of incorporating ground movement associated with seasonal weather change and the effect of climate change to improve climate resilience of the built environment.

KEYWORDS: Expansive soil, ground movement, seasonal weather data, climate extremes, modelling.

1 INTRODUCTION

Anthropogenic activities have let to climate change around the world, and its effects are projected to worsen in the future (IPCC, 2023). Changes in rainfall amount and intensity, and increased temperature, have been experienced around the globe (Karim et al., 2021, Devkota et al., 2022, IPCC, 2013, Karim et al., 2024, IPCC, 2014). Australia has experienced increased temperatures in all states and reduced rainfall in the southern regions, while some increase in rainfall in the northern regions was observed (BOM, 2021). This pattern is expected to continue in future (CSIRO, 2020). An increase in frequency and/or intensity of various climate extremes, such as droughts, heatwaves, and storms, has been observed globally (South West Climate Change Portal, 2023). Many human casualties, along with large socio-economic losses, resulted from climate-induced disasters such as floods and landslides in Nepal in 2024 (DHM, 2024) and other parts of the world e.g., the USA and Australia (Gillett et al., 2023).

Expansive soils are highly sensitive to moisture changes and can undergo significant volume change. The shrink-swell induced ground movement is affected by two major factors: the soil's potential to shrink or swell (reactivity) and the soil-vegetation-atmosphere (SVA) boundary interaction. The reactivity depends on soil minerals such as Kaolinite, Illite, Vermiculite, and Montmorillonite (Devkota et al., 2022, Nelson et al., 2015). Montmorillonite and Kaolinite are the most and least expansive minerals, respectively (Fratta et al., 2007, Mitchell & Soga, 2005). The SVA boundary interaction is driven by the local climate. The behaviour of the same soil is expected to change and can produce different ground movement under a different climate scenario, and can be affected by climate change (Karim et al., 2024, Devkota et al., 2023, Mitchell, 2013).

The Thornthwaite moisture index (TMI) has been used to account for climate change in several past studies (Karim et al., 2024, Devkota et al., 2023, Karim et al., 2021, Mitchell, 2013, Sun et al., 2024) and indicated an increased depth of suction change (H_s) in the future for the majority of Australia. H_s is the depth below which soil suction is assumed to be in equilibrium and is a key input to determine ground movement as per AS2870 (2011). Similar changes can be expected in many other parts of the world. Local soil properties are often not considered in the TMI based methods. Ground movement estimation based on H_s using soil reactivity has been rather simplified (AS2870, 2011). The variation in suction with depth between dry and wet seasons is also simplified in such approaches, e.g., a linear reduction of suction change along the depth from 1.2 pF at the top is recommended by AS2870 (2011). These simplifications can lead to erroneous results (Devkota et al., 2022, Karim et al., 2024).

An alternative method to account for climate change is via analysing SVA boundary interaction using a thermo-hydro-mechanical analysis. Variations in moisture and suction along the depth associated with climate change have been evaluated through numerical simulations in an Australian context (Devkota et al., 2024, Devkota et al., 2025) and showed the shift of such profiles towards the drier side. In other studies by Teodosio et al. (2020) and Shams et al. (2018), ground movement was predicted using a hydro-mechanical model, where the effects of climate change and vegetation were not considered.

Numerical simulations involving multiple physical processes (heat and water transfer, evapotranspiration, and mechanical interaction) at the SVA interface were performed to explore the ground movement under various possible climate scenarios using finite element tools. A series of uncoupled thermo-hydro-mechanical analyses were conducted using a combination of Seep/W (Geo-Slope, 2022) and Abaqus/CAE (2024). Ground movement data from a research site near Adelaide, Australia, was used to validate a model. The ground movements under various future climate extreme scenarios were estimated through the extension of the verified model.

2 RESEARCH SITE

The research site (~4000 m^2) is located ~7.5 km south of Adelaide CBD. The site is surrounded by native trees of varying heights (5-19 m) and has an open area with grasses and weeds. There is no irrigation facility except for the natural rainfall. Cameron et al. (2023) provided a detailed description of the site. The soil samples were obtained from the boreholes to a maximum depth of 6 m. Site geology consisted of a shallow black-earth layer (BE) overlying red-brown (RB), transitional between RB and grey-brown mottled orange clay (GBMOC). The depth of BE varied from 0.25 to 0.7 m. The RB layer extended to nearly 2 m depth. There were some transitional horizons in between. The GBMOC was extended to greater depth with occasional gravel layers and calcareous pockets. The reactivity of soil expressed in shrink-swell index (I_{ss}) indices was 4.7 %/pF, 2.6 %/pF and 2 %/pF for BE, RB and other soils, respectively.

A neutron moisture meter (NMM) was used to monitor moisture movement from 07/10/2022 to 30/06/2025, covering all seasons. In eight access holes from AH-A to AH-H (Figure 1), access tubes were installed to a depth of 6 m. Figure 2 shows an access hole with the NMM in operation. Ground movements were monitored from November 2019 to June 2025 at 64 ground movement measurement pads (Figure 1) installed in a 8 m grid. The details of the pads are shown in Figure 3. The bottom of the concrete pad was 0.4 m deep. A 16 mm diameter bar was installed at the centre of the pad, the top of which was used as the measurement point. The pads were covered by an irrigation valve box. A digital level was used to monitor the movements every two to three months. Based on site investigation, the site was categorised as H2-D (highly reactive–deep-seated movement As per AS2870 (2011).

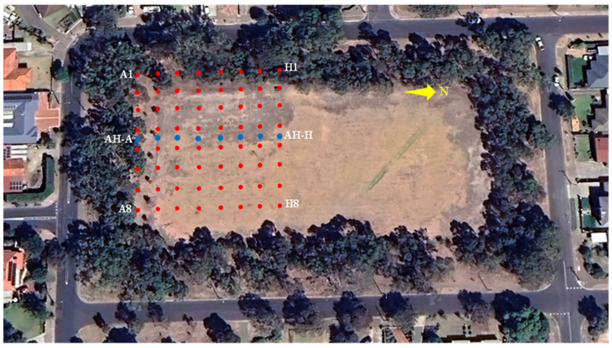

Figure 1. Surrounding of the study area (Google Earth Pro, 2024) showing access holes (AH) and ground movement monitoring points (A1 to A8).

A weather station was installed at ~ 0.9 km south-west of the research site and has been operational since early August 2021. Longer-term (50-years starting from 1973) meteorological data (rainfall, temperature, wind speed, solar radiation, and relative humidity) were collected from a nearby weather station (station number: 23034, Latitude 34.95, Longitude 138.52, located ~ 8 km away from the research site) and were considered as 'current climate' hereafter. To explore the influence of climate change, the representative concentration pathway- RCP8.5 scenario for the years 2050 and 2090 was considered. The RCP8.5 climate data were generated by superimposing projected changes in meteorological parameters (Climate Change in Australia, 2019) on the current climate data.

Devkota et al. (2024) showed that the climate extremes (cycles of droughts or wet years) can be influential in determining design ground movement, and future climate scenarios generated from the superimposition of projected changes may produce misleading results. Climate cycle scenarios generated based on the historical experience of drought and wet years and the statistical analysis of 50 years of data are presented in Table 1, where D and W indicate dry and wet years, respectively. Numbers before the letters represent their respective repetitions. More details of such scenarios can be found in Devkota et al. (2025).

Figure 2. NMM with probe inserted in access hole to take reading.

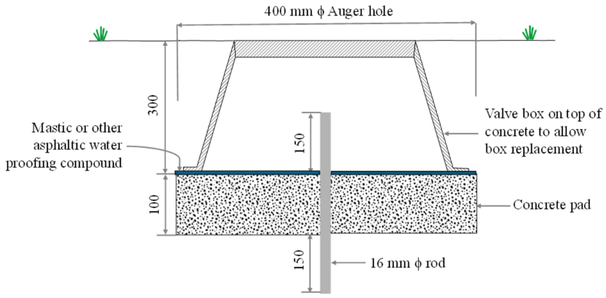

Figure 3. Establishment of ground movement pad.

Table 1. Various climate scenarios from cycles of wet and dry years.

Wet-dry sequence		Dry-wet sequence	
2W10D	3W13D	10D2W	13D3W
3W10D	4W13D	10D3W	13D4W
4W10D		10D4W	

3 NUMERICAL MODEL AND VALIDATION

A series of thermo-hydro-mechanical analyses was performed. Each analysis had two stages. The water diffusion was analysed in the first stage via a coupled thermal-fluid model using Seep/W (Geo-Slope, 2022) where SVA interactions took place at the ground surface. The changes in soil moisture and suction along the depth of soil were determined. Abaqus/CAE (2024) was used to determine soil movement in the second stage through mechanical (stress-strain) analysis with input of the suction profiles.

Figure 4 shows the geometry used in this study. The soil layer represents a location near the access hole AH-B. Please note that the subsoil exploration was limited to 6 m depth. It was assumed that the GBMOC continued the full depth of the model. This was supported by nearby geotechnical investigations (Sheard & Bowman, 1996, Cameron et al., 2023). Horizontal restraints were applied at the sides, and vertical restraints were applied at the bottom of the geometry. Since suction changed rapidly closer to the ground surface, a finer mesh was applied there.

The soil water characteristics curve (SWCC) is one of the important inputs and was developed through the fitting of laboratory test data using Fredlund and Xing (1994) function. Test data included matric suction and volumetric water content (VMC) obtained using pressure plate tests (ASTM D6836-16, 2016). The hydraulic conductivity function (*K*-function) is also needed, which provides changes in the hydraulic conductivity (*K*) with matric suction. Saturated *K* (K_{sat}) acquired from the laboratory tests using a Rowe and Barden cell (GDS, Rowe & Barden, 1966) and SWCC were used as input to define it via Fredlund et al. (1994) function. The moisture swelling curve was taken from Teodosio et al. (2020). Janbu (1963) formulation was used to estimate Young's modulus (E) as a function of confining stress using a user-defined subroutine.

The initial conditions were decided based on the tests on specimens taken on 30 March 2023. The measured suction along the depth was used to determine the initial degree of saturation using SWCC. It was assumed that the constant degree of saturation continued the full depth of the model below 6 m. The initial void ratio was set at 1.5 based on the past studies (Hough, 1957, Terzaghi et al., 1996, Teodosio et al., 2020). The unit weight and height of the soil were used to calculate the initial geostatic stress.

The mechanical analysis in Abaqus/CAE (2024) for validation comprised 13 steps. The first step was a geostatic analysis to ensure the equilibrium before applying loads. The other 12 steps were suction-deformation analysis. The analyses started from 30/03/2023 (initial stage). Other steps were chosen corresponding to the level survey date. Suctions along the depth from seepage analyses were used as inputs.

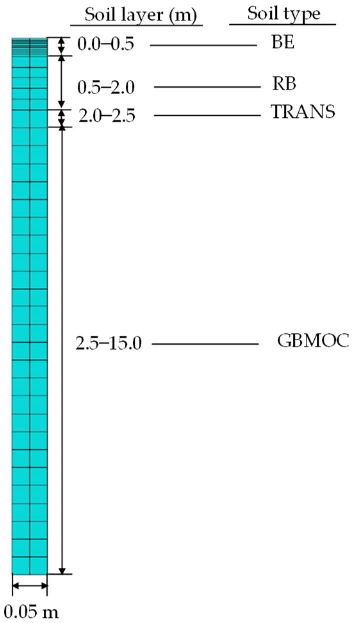

Figure 4. The geometry of the soil model (impermeable boundary conditions were applied at the sides and bottom of the model).

Ground movement and VMC data collected from the research site were used to validate the accuracy of the model. The meteorological data acquired from a weather station established nearby site was used at this stage. Since this research intends to investigate grass-covered open ground, the vegetation parameters were developed for grass, which include leaf area index (LAI), soil cover fraction (SCF), plant moisture limit (PML), root depth (RD), and normalised root density (NRD). The LAI was estimated based on the observed ground cover (fully covered, partially covered or dead dry grass) conditions. The correlation of LAI was used to estimate SCF. PML factor of 1 was taken up to 100 kPa soil suction level (at this level, vegetation has limited uptake) and gradually reduced to zero at 1500 kPa (at this level, uptake stops). The RD and NRD functions were generated based on the observations of roots and their density. The VMC data monitored at access hole, AH-B, from 30/03/2023 to 16/08/2024, were compared to the results from Seep/W (Geo-Slope, 2022) analysis in Figure 5a at 0.5 m depth. The results from the simulation had good agreement with the measured VMCs. The rainfall variation over the validation period is also presented in the same figure. A time lag between the rainfall and the changes in VMC is observed. This lag can be due to the lower hydraulic conductivity of clayey soil, which delays the ingress of moisture after precipitation. The moisture diffusion process was captured with reasonable accuracy. The calculated suction from the diffusion model was used in Abaqus/CAE to calculate the ground deformation and compared against field measurements.

The location of the moisture monitoring did not exactly coincide with the ground movement monitoring point. The average level changes data observed at deformation pads around the access hole AH-B (i.e., A4, A5, B4, B5, C4 and C5) were used. The numerically calculated and measured changes in ground deformation at 0.4 m depth are compared in the Figure 5b. The observed and simulated ground deformation varied between 0 mm to 10.83 mm relative to the measurement on 03/04/2023. Although some deviation in ground movement was observed near the end of January 2024, the temporal variation of simulated and field-measured values was in good agreement (Figure 5b). This indicates the modelling technique can capture ground movement with reasonable accuracy.

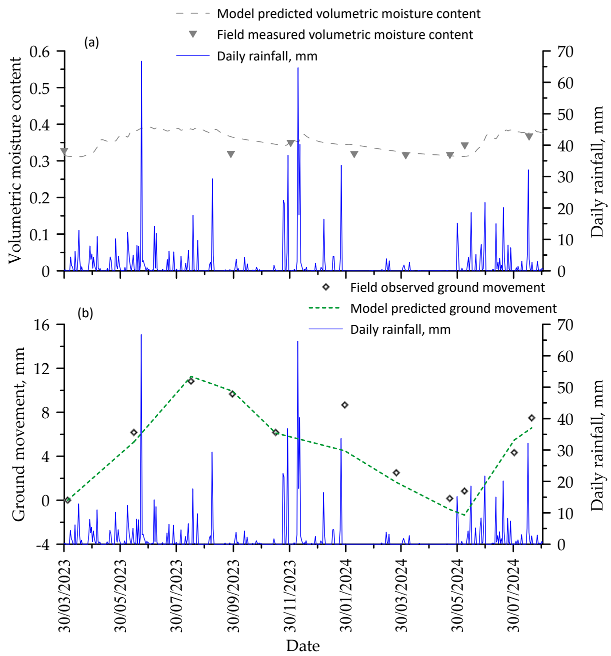

Figure 5. Model validation (a) moisture changes at 0.5 m (b) changes in ground movements at 0.4 m.

4 GROUND MOVEMENT UNDER VARIOUS FUTURE CLIMATE SCENARIOS

Soil deformation under different climate conditions was analysed using the validated model. After the geostatic step, the wettest soil matric suction profile obtained from each climate scenario through SEEP/W analysis was applied in Abaqus/CAE. For seepage analysis under different climate scenarios, climate data were changed as discussed in section 2 to observe the effect of climate change, whereas other parameters, such as vegetation and materials, remained unchanged. Deformation was zeroed i.e., deformation was estimated relative to the displacement under the wettest suction profile, and the change in deformation was obtained in the final step by applying the driest suction profile. The change in surface movement resulting from the numerical simulation as per the changes in wet and dry suctions was denoted by y_n.

Figure 6a shows the maximum and minimum suction profiles obtained from the diffusion analysis under different current climate scenarios. The depth of suction change for the current climate, represented as current H_s, was estimated as 3.7 m. Please note, H_s was determined to be the depth below which the difference between the dry and wet profiles was <0.2 pF (Naiser, 1997, Vann & Houston, 2021, Olaiz, 2022). The change in ground deformation profile for the changes in wet and dry suctions under the current climate is shown in Figure 6b.

Figure 6a also shows the suction profiles RCP8.5 scenario for the years 2050 and 2090. The suction profiles shifted towards the drier side, and H_s reduced slightly compared to the current climate. This observation was opposite to the TMI based past studies (Karim et al., 2024, Devkota et al., 2023, Karim et al., 2021, Mitchell, 2013, Sun et al., 2024). Change in ground movement profiles corresponding to change in wet and dry suctions for the current climate and RCP8.5 2050 scenario were very similar, whereas small differences below 3 m were observed for the 2090 scenario. Despite some observed reduction in H_s, y_n were slightly greater for both RCP8.5 scenarios compared to the current climate. It is to be noted that y_n is proportional to the area enclosed by wet and dry suction profiles. The ground movement calculation assumes that the movement contribution from depth below 15 m is insignificant. From field observation, the majority of movement is contributed from the top 4-5m, even in a semi-arid climate, and the assumption, even though not perfect, can be treated as reasonable. Please note, under current practice, any difference in suction profile (between wet and dry profile) less than 0.2 pF is ignored in the ground movement calculation (Naiser, 1997, Vann & Houston, 2021, Olaiz, 2022). Further, for most clays, the swelling pressure is not sufficient to cause significant movement at depths>15 m due to high overburden pressure (Chen, 1975). Devkota et al. (2024) demonstrated that the simple superposition of expected changes in meteorological parameters in defining future climate may not represent the worst-case scenario, and climate extremes could be another important aspect to be investigated to evaluate ground movement.

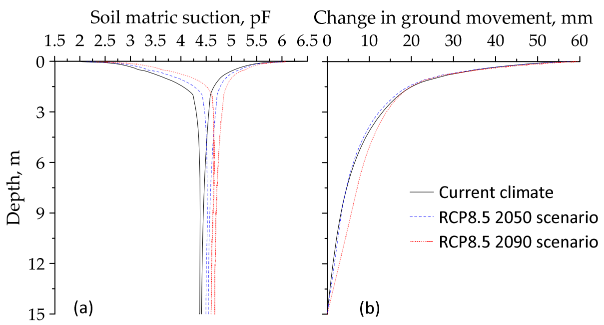

Figure 6. (a) Suction, and (b) changes in ground movement profiles as per the changes in suction profiles under various climate scenarios.

A total of ten additional climate scenarios were simulated using different combinations of wet and dry years, as shown in Table 2. Figure 7a compares suction profiles of climate scenarios of wet years followed by dry years (wet-dry sequences) against the current climate. Changes in ground movement profiles as per the changes in wet and dry suctions for wet-dry sequences were also compared with those of the current climate, as shown in Figure 7b. Suctions and corresponding changes in ground movement profiles for the dry-wet sequence are presented in Figure 8.

Surface movement y_n and H_s for different climate scenarios are shown in Table 2. H_s remained at 3.6 m for 10D2W, 10D3W and 10D4W scenarios. It is interesting to note that, despite the constant H_s, y_n values increased for these scenarios. Similar observations were made for 13D3W and 13D4W scenarios. Under wet-dry sequences, the maximum y_n value was 72.5 mm for the 4W13D scenario. y_n for 2W10D was about 7 mm higher than y_n for the current climate. y_n increased by ~27% for 4W13D scenario as shown in Table 2 under wet-dry sequence as compared to the y_n value under the current climate. Under the dry-wet sequence, y_n were slightly smaller compared to the wet-dry sequence (Table 2). This could be due to the preceding condition of fluid diffusion analysis. Year 2022 was the last year of the current climate and had rainfall greater than the average rainfall, resulting in a comparatively wet initial condition. The ground movement increased significantly in both sequences (wet-dry and dry-wet) for all scenarios compared to the current climate. This can have important consequences for the design of climate-resilient lightweight structures.

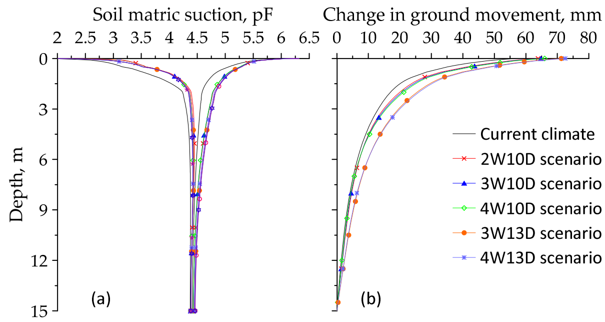

Figure 7. (a) Suction, and (b) changes in ground movement profiles as per the changes in suction profiles under wet-dry sequences.

The effect of an increase in y_n values was demonstrated with a design example of a residential footing in expansive soils. y_n values were taken equivalent to characteristic ground movement. A stiffened raft of 14.5 m × 12 m with 4 long and 5 short beams for a single-storey house was designed using software CORDv8.0 (FMG, 2012).

Initially, the footing was designed under the current climate characterised by H_s and y_n values of 3.7 m and 57 mm, respectively. The raft footing would require a 330 mm deep beam for a brick masonry veneer superstructure. The same footing design was repeated for the 4W13D scenario with its H_s and y_n values (see Table 2). For the increase of 1.5 m H_s and 15.5 mm y_n, the same superstructure would require a 600 mm deep beam. Likewise, the raft footing would require a total 2×12 mm re-bars at the top and bottom of internal and external under the current climate. This reinforcement requirement increased to 4×12 mm re-bars at the top and bottom of external beams under the 4W13D scenario. 3×12 mm and 4×12 mm re-bars were required for the same footing at the top and bottom of internal beams, respectively, under the 4W13D scenario. This indicates the likelihood of increased stiffness demand on the footing under future climate scenarios.

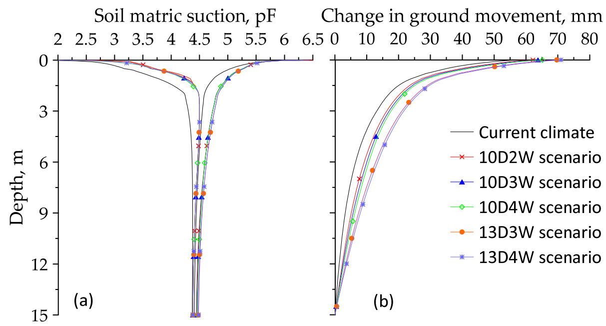

Figure 8. (a) Suction, and (b) changes in ground movement profiles as per the changes in suction profiles under dry-wet sequences.

Table 2. H_s and y_n values under different climate scenarios.

Climate scenario	H_s m	y_n, mm	% change in y_n w.r.t. current climate
current	3.7	57	-

Climate scenario	H_s m	y_n, mm	% change in y_n w.r.t. current climate
RCP8.5 2050	3.3	57.6	1
RCP8.5 2090	2.5	59.6	4
2W10D	4.2	63.9	12
3W10D	4.4	64.8	14
4W10D	4.6	66	16
3W13D	5	71.3	25
4W13D	5.2	72.5	27
10D2W	3.6	62.2	9
10D3W	3.6	63.8	12
10D4W	3.6	65.2	14
13D3W	4.3	69.7	22
13D4W	4.3	71	24

5 LIMITATIONS

Despite reasonable predictions from the methodology adopted, the authors identified a number of limitations in this study. Expansive soils are prone to developing shrinkage cracks that can create a preferential water flow path and can affect ground movement. However, the effect of cracks on ground movement was considered to be limited due to the occurrence of most of the rainfall in winter and the almost disappearance of cracks. An investigation into the effect of shrinkage cracks on ground movement is recommended for future research. The climate scenarios with cycles of dry and wet years were developed based on the statistical analysis of rainfall data to represent the extreme dry and wet years. Based on the past experience of the duration of droughts (dry years) and wet years, the scenarios of 10 to 13 dry and 3 to 4 wet years are likely to represent the worst future climate scenarios. More investigations are recommended to improve the prediction of the frequency of dry and wet years. The geometry of the model was idealised to observe the vertical ground movement while restricting lateral movement. This may lead to overestimation of the vertical movement while considering volumetric changes. This needs to be further investigated in future.

6 CONCLUSIONS

Climate change can significantly influence the built environment. To develop climate-resilient infrastructures, the understanding of SVA boundary interactions is crucial. The conclusions made in this research are below:

- Change in moisture profile and related changes in ground movement could be captured with the defined methodology with reasonable accuracy.
- The H_s under the current climate was estimated to be 3.7 m. It decreased under the RCP8.5 scenarios considered. The suction profiles shifted towards the drier side.
- H_s increased under all wet-dry climate extreme scenarios considered, with a maximum value of 5.2 m under the 4W13D scenario.
- Seasonal changes in weather conditions can cause significant volume changes in expansive soils.
- Model predicted maximum surface movement was observed to be 57 mm under the current climate scenario, and it increased under the RCP 8.5 2090 to 59.6 mm.
- The wet-dry year sequences increased the observed movement up to 72.5 mm under 4W13D scenario.
- The wet-dry sequence showed increased movement as compared to the dry-wet sequence due to the preceding condition of seepage analysis. The last year of simulation, year 2022, had rainfall greater than the average rainfall, resulting in a comparatively wet initial condition in the wet-dry sequence.
- The possible impact of climate change evaluated through a simple footing design on expansive soil. The exercise showed that under future climate scenarios, the same structure may require a significant increase in concrete dimensions and reinforcement.

7 ACKNOWLEDGEMENTS

The first author of this paper was supported by President's Scholarships from the University of South Australia towards his Ph.D. study. The authors would also like to gratefully acknowledge the funding and other support provided by the City of Mitcham, and Green Adelaide South Australia.

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