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# Effect of Climate Change on Migration of Wetting Front in Expansive Soils

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ABSTRACT: Expansive soils can exhibit significant volume change due to moisture fluctuations, posing risks to infrastructure such as pavements and foundations. Climate change affects the water content profile in the subsoils, which in turn will affect the volume change profile. This study examines how future climate scenarios can influence the water content profile in expansive soils. Numerical simulations were conducted using the computer software SEEP/W. The models were calibrated and validated with field and laboratory data from the TRACON site at Denver International Airport, Colorado, USA. Historical climate data and projections under two CMIP6 scenarios, including SSP126 (low-carbon emissions) and SSP585 (high-carbon emissions), were used to evaluate water migration in generalized soil profiles in eastern Colorado. A conventional modeling approach using cyclic historical data was also analyzed for comparison. The results show continuous advancement of the wetting front across all scenarios, with future climate conditions producing slightly shallower wetting depths compared to the conventional case. While wetting depths were similar under both climate scenarios, SSP585 produced drier subsurface conditions due to progressive drying from the surface. These findings suggest that climate change may alter both the depth and degree of saturation in expansive soils, which has implications for long-term foundation performance.

KEYWORDS: Climate change, expansive soil, depth of wetting, wetting front.

## 1 INTRODUCTION

Expansive soils generally have a high content of montmorillonite clay particles, which increase in volume when wetted and decrease in volume when dried. This volume change property of the soil can cause significant distress in structures built on it. Therefore, the prediction of water movement within expansive soils is important over the design life of the structure. Numerical modeling of water migration in unsaturated expansive soils is complex due to a number of factors that influence water movement (Rutqvist and Stephansson, 2003; Singhal and Gupta, 2010; Fredlund et al., 2012; Chao et al., 2014; Nelson et al., 2015; and Chao et al., 2018). Some of the key factors that influence water movement in unsaturated expansive soils include climate factors, such as precipitation, air temperature, solar radiation, humidity, and wind speed (Amarathunga et al., 2022). Therefore, climate change must be taken into account when predicting wetting front migration within foundation soils and pavement subsoils.

This study examines the impact of climate change on the migration of the wetting front into expansive soils. Numerical modeling was conducted using data collected at the Terminal Radar Approach Control (TRACON) facility at Denver International Airport in Denver, Colorado. The models were used to predict water movement over a 100-year period. To calibrate and validate the model of water flow, the volumetric water content profiles observed from 2001 to 2006 at the TRACON site have been used. Climate data, including historical climate data and future projected data for the TRACON site collected from the NASA Center for Climate Simulation (NCCS), have been used in the model for calibration, validation, and future prediction of water migration. The soil profile from the TRACON site has been used primarily for calibration and validation purposes. After the model was validated, several generic soil profiles encountered in Colorado were modelled to predict the long-term water migration for a period of 100 years under different climate change scenarios. The results for different climate scenarios were then compared to the water migration predicted using the conventional approach, where historical climate data is repeated over selected time intervals to account for future climate conditions.

## 2 SOIL PROFILES AND PROPERTIES USED IN ANALYSES

### 2.1 *TRACON Site Profile*

The field investigation conducted at the TRACON site included drilling of thirty-seven (37) exploratory borings, installation of nine (9) pneumatic piezometers, five (5) standpipe piezometers, twelve (12) subsurface nuclear gauge tubes, three (3) deep benchmarks, and elevation surveying of fifty (50) monitoring points on slabs and foundation piers within the TRACON building (Chao, 2007). The subsoils at the site generally consist of 0.3 to 3.4 meters of fill and native soils, underlain by weathered claystone, and interbedded or alternating layers of claystone and sandstone bedrock. At a depth of approximately 10.5 m, a coal seam was encountered, which was considered to potentially act as a seasonal groundwater source.

A borehole location labelled as MA2A was selected for analysis in this study due to its accessibility and the available laboratory test data. Figure 1 shows the soil stratigraphy at the MA2A location. The soil profile shown in Figure 1 was used along with the associated soil properties to calibrate and validate the model, incorporating the climate data from the Denver site as a surface boundary condition.

### 2.2 *Generic Soil Profiles*

Once the model was calibrated and validated, the hydraulic properties of materials such as silty clay and claystone were integrated into representative soil profiles commonly found in the high plains in the Front Range of the Rocky Mountains in Colorado. Two representative soil profiles were used, as shown in Figure 2. Each profile consisted of a clay layer, either 3 or 5 meters in depth, overlying claystone formations. These profiles were selected based on results of soil investigations conducted at multiple sites throughout the Front Range region of Colorado (Overton et al., 2006; Chao et al., 2006; Nelson et al., 2017).

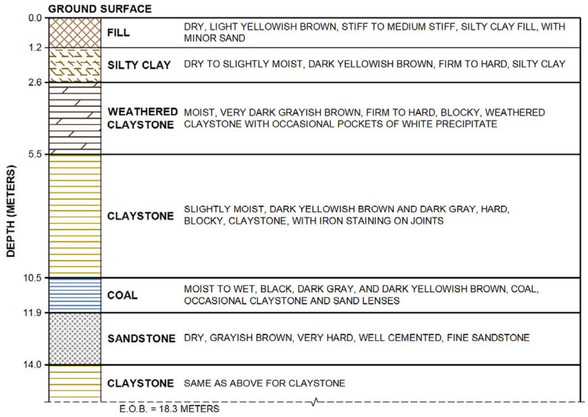


Figure 1. Stratified soil profile at the TRACON site, Denver, Colorado, USA (Chao, 2007).

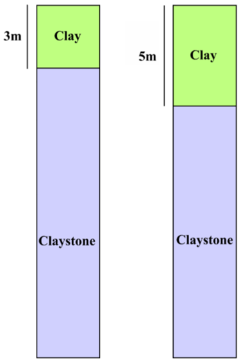


Figure 2. Generalized soil profiles used in this study.

### 2.3 *Soil Properties*

Properties of the soil profile at the TRACON site were measured by Chao (2007). Laboratory tests were conducted to determine values of parameters such as the dry density, natural water content, specific gravity, swell percentage, consolidation swell pressure, and Atterberg limits. The results indicated that the underlying claystone exhibited a high expansion potential, having swelling pressures as high as 1400 kPa at some locations. In contrast, the overlying silty clay layer had much lower swelling pressures, ranging from 50 to 60 kPa. Table 1 summarizes the swelling properties of the soil profile at the TRACON site.

To accurately simulate water migration within the soil profile, several key hydraulic properties were incorporated into the model. These included saturated hydraulic conductivity, the ratio of horizontal to vertical permeability, and residual hydraulic conductivity, among others. The values of the hydraulic properties used in the preliminary model, which are shown in Table 2, were obtained from Chao (2007), Chao et al. (2008), and Nelson and Chao (2014). The values were adjusted during the calibration and validation process, as discussed in Sections 4 and 5 of this paper. The calibrated and validated parameters are shown in Table 2.

Table 1. Swelling properties of the soil and rock layers at the TRACON site.

| Soil Type | Consolidation-Swell Test (1) | |
|---|---|---|
| | Percent Swell (%) | Swell Pressure (kPa) |
| Silty Clay Fill | 0.4 – 0.8 | 50 – 60 |
| Silty Clay | - | - |
| Weathered Claystone | 4.3 – 8.4 | 290 – 530 |
| Sandstone | - | - |
| Claystone | 3.0 – 10.2 | 290 – 1400 |
| Coal | - | - |

Note: (1) Inundation Pressure, $\sigma_i' = 24$ kPa

Table 2. Hydraulic properties used in the preliminary model of water migration in SEEP/W (Chao, 2007).

| Soil Type | Saturated Hydraulic Conductivity (cm/sec) | $K_h/K_v$ | Saturated Volumetric Water Content (vol./vol.) | Residual Volumetric Water Content (vol./vol.) |
|---|---|---|---|---|
| Silty Clay Fill | $6.35 \times 10^{-6}$ (3) | 1 (4) | 0.40 (1) | 0.22 (1) |
| Silty Clay | $5.64 \times 10^{-6}$ (3) | 1 (4) | 0.40 (1) | 0.22 (1) |
| Weathered Claystone | $3.60 \times 10^{-7}$ (3) | 10 (4) | 0.46 (2) | 0.07 (2) |
| Claystone | $3.53 \times 10^{-7}$ (3) | 10 (4) | 0.46 (2) | 0.07 (2) |
| Coal | $5.00 \times 10^{-3}$ (3) | 10 (4) | 0.48 (1) | 0.04 (1) |
| Sandstone | $1.50 \times 10^{-4}$ (3) | 10 (4) | 0.44 (1) | 0.13 (1) |

Notes: (1) SoilVision Database
(2) Laboratory data
(3) Calibrated and validated values
(4) Assumed values

## 3 CLIMATE DATA COLLECTION

For the analyses at the TRACON site, both historical data and projected future climate data were used. The historical dataset, spanning the period from 2001 to 2004, was used for model calibration, while data from 2004 to 2006 were used to validate the performance of the model. After successful validation, the calibrated soil and rock parameters were integrated into the generic soil profiles and were applied in predictive simulations to estimate water migration over 100 years, using the bias-corrected future climate projections.

The open-access climate data portal of the NASA Center for Climate Simulation (NCCS) was selected for the acquisition and processing of both historical and future climate data under the Coupled Model Intercomparison Project Phase 6 (CMIP6). As reported by Thrasher et al. (2021) and Thrasher et al. (2022), the NCCS portal not only provides downscaled climate datasets but also offers future climate projections that have been pre-processed through bias correction. This feature eliminates the need for users to conduct manual bias correction, which was previously necessary.

Among the various climate scenarios available under the Shared Socioeconomic Pathways (SSPs), including SSP126, SSP245, SSP370, and SSP585, two scenarios were selected for this study: These included the SSP126 scenario, representing a low-carbon emission pathway, and the SSP585 scenario, representing a high-carbon emission pathway. For both scenarios, historical and projected future climate data were obtained and processed. These datasets included daily maximum and minimum near-surface air temperature, precipitation, relative humidity, wind speed, and solar radiation. The General Circulation Model (GCM) ACCESS-CM2 was chosen for this study, as it has been identified as one of the most suitable models for predicting future climate conditions in the state of Colorado (Ashfaq et al., 2022).

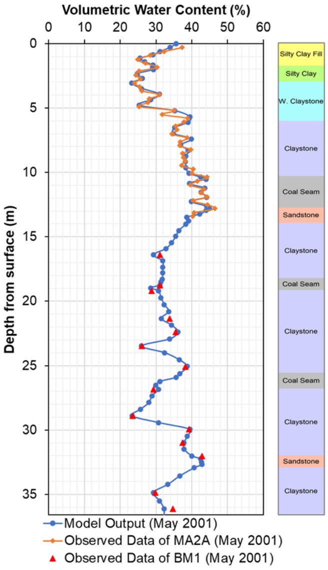
## 4 MODEL CALIBRATION

The finite element modeling software SEEP/W was used to simulate water migration within the soil profile at the TRACON site. To establish the initial water content profile, the model was first analyzed under steady-state conditions using Darcy's Law. For simulating long-term, time-dependent water movement, the Richards equation was applied, where water moved node to node over time. A one-dimensional (1D) simulation was conducted, as vertical water migration is of primary concern in the Denver area and the relatively flat terrain of eastern Colorado. The mass-balance equation was utilized in the modeling to quantify the water influx at the surface resulting from climate-driven land-climate interactions. Observed volumetric water content profiles from 2001 to 2006, obtained from Chao (2007), were used for model calibration and validation.

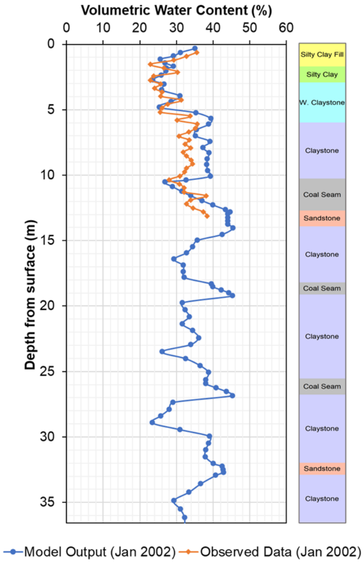
The soil profile of the TRACON site, shown in Figure 1, was modeled using SEEP/W with the geotechnical and hydraulic properties summarized in Table 2. Initial volumetric water content values were assigned at various depths within the profile (refer to Figure 3(a)). The surface boundary condition was defined using historical climate data from 2001 to 2004. The model was then iteratively adjusted by fine-tuning the hydraulic parameters within reasonable and justifiable limits to achieve a close match between the simulated and observed volumetric water content profiles. Figures 3(b) to 3(d) illustrate the results of the model calibration from 2001 to 2004. Based on the close agreement between the predicted and observed values of water content, the models were considered calibrated.

## 5 MODEL VALIDATION

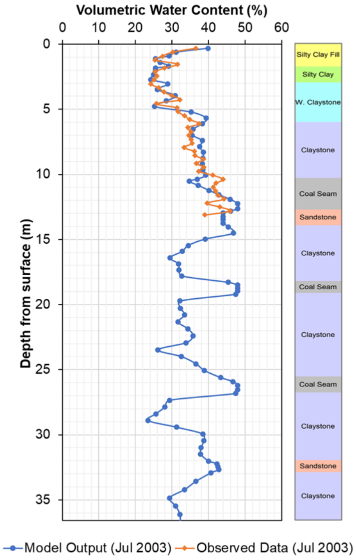
After completing the model calibration, additional simulations were conducted for the period from 2004 to 2006 using historical climate data corresponding to that timeframe. The simulated volumetric water content profile for the year 2006 was then compared with the observed field data to evaluate the predictive accuracy of the model. Figure 4 presents the comparison between the predicted and measured volumetric water content profiles at the location of MA2A. Figure 4 indicates that there is good agreement between the predicted water content distribution and the measured data. This demonstrated the consistency and validation of the model. The soil properties obtained from the calibrated and validated model were used in the long-term water migration modeling.



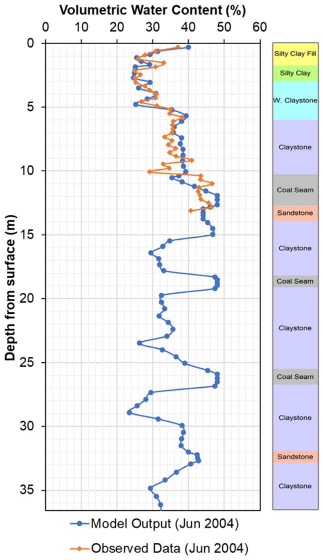
(a) Year 2001 Water Content Profiles



(b) Year 2002 Water Content Profiles



(c) Year 2003 Water Content Profiles



(d) Year 2004 Water Content Profiles

Figure 3. Model calibration from 2001 to 2004

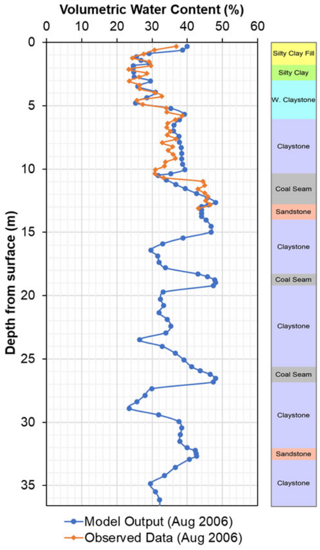


Figure 4. Model validation with the observed data from 2006.

## 6 LONG-TERM WATER MIGRATION

The calibrated soil properties were incorporated into the generic soil profiles shown in Figure 2 to simulate long-term water migration under two distinct climate scenarios: SSP126 and SSP585. In addition, a conventional approach was also used as a baseline for comparison with the results obtained from the SSP126 and SSP585 scenarios. The model analyzed a period of 100 years, which is a common design life of foundations (Schmalz and Stiemer, 1995; Chao and Nelson, 2019).

### 6.1 *Conventional Long-Term Water Migration*

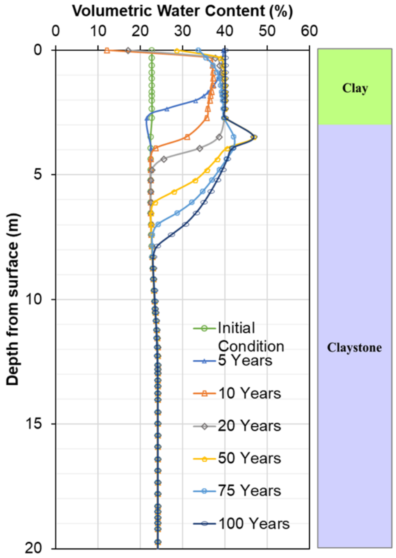
In the conventional approach, future climate conditions are represented by repeating observed historical climate data over selected time intervals. In this study, a 24-year interval of historical climate data was cyclically repeated to simulate future conditions over 100 years. In practice, a 5-year interval is also commonly used; however, a larger interval better captures long-term variations with reduced error. Since this study was conducted in 2024 and aims to project conditions up to the year 2100, a 24-year interval was selected to provide the most representative results.

Both soil profiles shown in Figure 2 were simulated using repeated historical climate data over 100 years. The initial volumetric water content used in the model was 22%, which is consistent with natural volumetric water contents of the clay and claystone materials in Colorado (Chao et al., 2006a and Chao et al., 2006b).

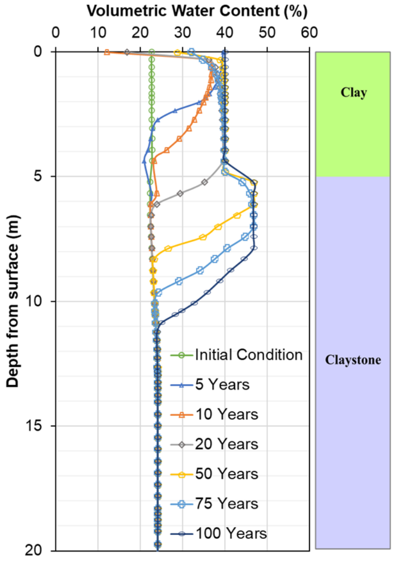
Figures 5a and 5b present the long-term water migration profiles obtained under the conventional modeling approach for the 3 m and 5 m clay layer profiles, respectively. It is observed in Figures 5a and 5b that after approximately 20 years, complete saturation of the clay soil layer occurred in both profiles. When the wetting front reached the underlying claystone, perched water conditions developed, inducing an upward migration of moisture within the clay soil and resulting in full saturation. Over time, the wetting front continued its downward progression, as depicted in Figures 5a and 5b. After 100 years, the wetting depth extended to 8.23 m from the surface in the 3 m clay soil profile and 11.28 m in the 5 m clay soil profile. The depths of the wetting front align closely with the findings presented in Walsh et al. (2009) and Nelson et al. (2011).

### 6.2 *Long-Term Water Migration under SSP126 Scenario*

In the SSP126 (low-carbon emission) scenario, the primary distinction from the conventional approach is the use of future climate data. Rather than repeating historical climate records, projected climate data for the next 100 years under this scenario was applied as the surface boundary condition. The model was then simulated over 100 years.



(a) 3 m Clay Layer Profile

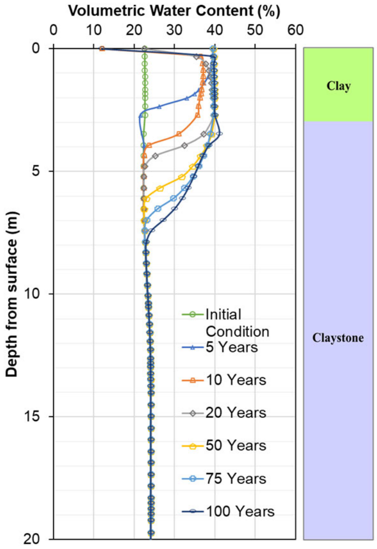


(b) 5 m Clay Layer Profile

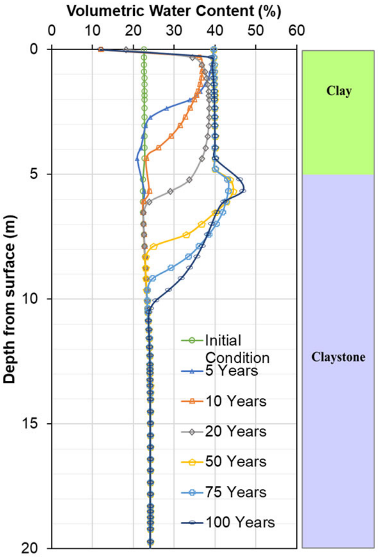
Figure 5. Long-term water migration under conventional approach.

Figures 6a and 6b present the long-term water migration profiles for the 3 m and 5 m clay layer profiles, respectively, for the SSP126 Scenario. In Figure 6a, the water content profile after 20 years exhibited the development of a perched water condition within the 3 m clay soil profile. This is similar to the profile shown in Figure 5a. It is interesting to note that a mild drying trend is observed near the surface, suggesting potential fluctuations in moisture availability over time. This could be attributed to variations in precipitation or evapotranspiration. This drying trend near the surface may also indicate the temporary depletion of moisture as the upper soil layers reach a balance between infiltration and evaporation. For the 5 m clay soil profile shown in Figure 6b a perched water table began to form at the bottom of the clay layer between 20 and 50 years of infiltration.

As shown in Figures 6a and 6b, after a period of 100 years, the wetting front depth extended to 7.93 m in the 3 m clay soil profile, whereas in the 5 m clay soil profile, it reached 10.37 m.



(a) 3 m Clay Layer Profile



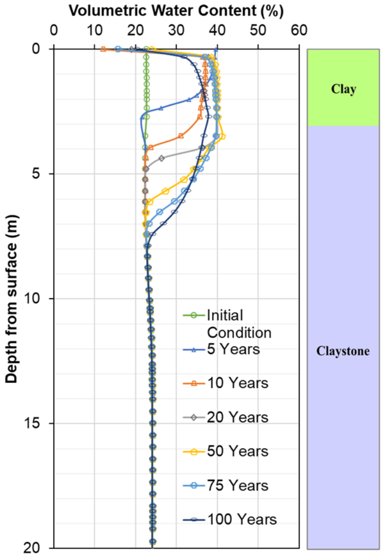
(b) 5 m Clay Layer Profile

Figure 6. Long-term water migration under SSP126 scenario.

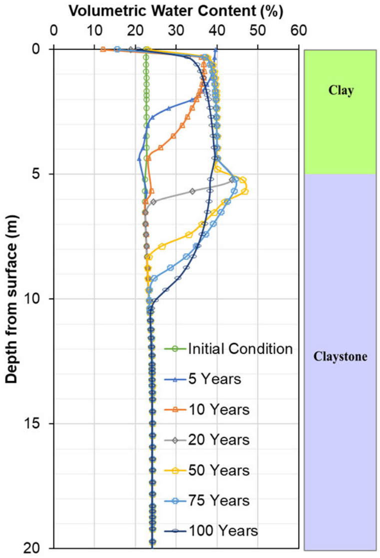
### 6.3 *Long-Term Water Migration under SSP585 Scenario*

SSP585 represents the high-carbon emission scenario. In this case, the projected climate data from the scenario was applied as the surface boundary condition, and the model was simulated over 100 years. The results of the long-term water migration profiles for the 3 m and 5 m clay layer profiles under the SSP585 Scenario are presented in Figures 7a and 7b, respectively.

Similar to the results of the wetting front profiles for the SSP126 Scenario, the wetting front depths in 100 years remain at 7.93 m and 10.37 m for the 3 m and 5 m clay soil profiles, respectively. However, a significant difference in the degree of saturation of the clay and claystone was observed in Figures 7a and 7b, compared to the results for the SSP126 Scenario. In both the 3 m and 5 m clay soil profiles for the SSP585 Scenario, saturation levels increase steadily up to approximately 75 years. However, beyond this period, a drying process initiates from the surface, progressively depleting moisture not only from the clay layer but also from the underlying claystone.



(a) 3 m Clay Layer Profile



(b) 5 m Clay Layer Profile

Figure 7. Long-term water migration under SSP585 scenario.

### 6.4 *Comparative Analysis of Wetting Front Profiles under Different Scenarios*

Using the conventional approach as a baseline, the results indicate that projected climate scenarios lead to slightly shallower wetting depths. After 100 years, the wetting depths for the 3 m and 5 m clay profiles under the conventional approach were 8.23 m and 11.28 m, respectively (refer to Figures 5a and 5b). In contrast, under future climate scenarios, the depths reduced to 7.93 m and 10.37 m (refer to Figures 6a and 6b and Figures 7a and 7b). Figure 8 illustrates the comparative changes, showing percentage reductions of 3.65% (SSP126) and 8.07% (SSP585) relative to the conventional case. The 5 m clay profile exhibits a greater reduction (8.07%), suggesting that deeper clay layers may be more sensitive to projected climate changes.

Figures 6a and 6b and Figures 7a and 7b show that the 100-year predicted wetting front depths for the 3 m and 5 m clay layer profiles are 7.93 m and 10.37 m, respectively, and are identical under both the SSP126 and SSP585 scenarios. However, the degree of saturation of the clay and claystone differs between the two scenarios. The 100-year wetting front profiles shown in Figures 7a and 7b for the SSP585 Scenario are drier compared to those shown in Figures 6a and 6b for the SSP126 Scenario. This condition suggests that under the high-carbon emission scenario (SSP585), the soil becomes drier over time, reflecting increased aridity due to climate change.

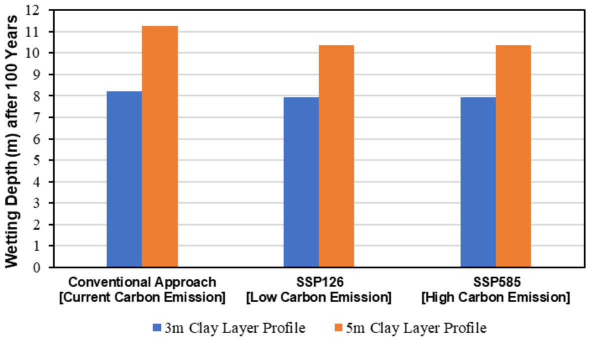


Figure 8. Wetting depths comparison under different climate scenarios.

## 7 CONCLUSIONS AND RECOMMENDATIONS

This study offers an in-depth examination of the potential effects of future climate change on the movement of the wetting front in expansive soils in Colorado, USA. The key findings and recommendations are summarized below.

- The wetting front was continuously advanced throughout the entire 100-year simulation period across all climate scenarios analyzed. This progressive migration indicates that moisture can penetrate deeper into expansive soil layers over time, potentially activating swelling behavior at greater depths. For foundation design, this underscores the need to consider long-term changes in subsurface moisture conditions when evaluating heave potential and determining design depths for foundations.
- The study indicated that the climate scenarios (SSP126 and SSP585) led to slightly shallower wetting depths compared to the conventional approach, with greater reductions in the 5 m clay profile (8.07%) than in the 3 m profile (3.65%). This suggests deeper clay layers are more sensitive to future climate change.
- The comparison of wetting depths shows similar values for both SSP126 and SSP585 scenarios. However, the degree of saturation differs notably. Under SSP585, saturation levels gradually decline from 75 to 100 years, resulting in the lowest saturation after 100 years. In contrast, the conventional approach exhibits the highest saturation, followed by the SSP126 Scenario. This pattern is consistent across both the 3 m and 5 m clay profiles. These findings suggest that the high-carbon emission scenario leads to progressively drier soil conditions over time.
- It is recommended to utilize climate data from multiple sites, in conjunction with representative soil profiles, to evaluate spatial variability in model outcomes and to assess the reliability of using single-location climate data for regional analyses.
- It is recommended that foundation designs in expansive soil regions incorporate the wetting front profiles developed in this study to more accurately assess long-term moisture-related soil behavior and potential heave risks.

## 8 REFERENCES

Amarathunga, T., Chao, K.C., and Nelson, J.D. 2022. Effect of climate change on rainfall induced failures for embankment slopes in Timor-Leste. *Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering*, Sydney, Australia. May.

Ashfaq, M., Rastogi, D., Kitson, J., Abid, M. A., & Kao, S. 2022. Evaluation of CMIP6 GCMs over the CONUS for downscaling studies. *Journal of Geophysical Research Atmospheres*, *127*(21).

Chao, K. C., Overton, D. D., & Nelson, J. D. 2006a. The effects of site conditions on the predicted time rate of heave. *Unsaturated Soils 2006.* 2086-2097.

Chao, K.C. 2007. Design principles for foundations on expansive soils. Ph.D. Dissertation, Colorado State University, Fort Collins, CO, USA.

Chao, K.C. and Nelson, J.D. 2019. Validation of foundation design method on expansive soils. *Geotechnical Engineering Journal of the SEAGS & AGSSEA*. 50(1). March.

Chao, K.C., Kang, J.B., and Nelson, J.D. 2014. Challenges in water migration modeling for expansive soils. *Proceedings of the GeoShanghai Conference*, Shanghai, China.

Chao, K.C., Kang, J.B., and Nelson, J.D. 2018. Evaluation of failure of embankment slope constructed with expansive soils. *Geotechnical Engineering Journal of the SEAGS & AGSSEA*. 49(2).

Chao, K.C., Nelson, J.D., Overton, D.D., and Cumbers, J.M. 2008. Soil water retention curves for remolded expansive soils. *Proceedings of the 1st European Conference on Unsaturated Soils*, Durham, UK.

Chao, K.C., Overton, D.D., and Nelson, J.D. 2006b. Design and installation of deep benchmarks in expansive soil. *J. Surv. Eng.*, 132, 124-131.

Fredlund, D.G., Rahardjo, H., and Fredlund, M.D. 2012. Unsaturated soil mechanics in engineering practice. *John Willey and Sons, Inc.*, New York., USA.

Nelson, E.J., Chao, K.C., Nelson, J.D., and Overton, D.D. 2017. Lessons learned from foundation and slab failures on expansive soils. *J. Perform. Constr. Facil.* 31(3).

Nelson, J.D. and Chao, K.C. 2014. Relationship between swelling pressures determined by constant volume and consolidation-swell oedometer tests. *Proceedings of the Sixth International Conference on Unsaturated Soils, Unsat.* Sydney, Australia. July.

Nelson, J.D., Chao, K.C., and Overton, D.D. 2011. Discussion of “method for evaluation of depth of wetting in residential areas” by Kenneth D. Walsh, Craig A. Colby, William N. Houston, and Sandra L. Houston. *Journal of Geotechnical and Geoenvironmental Engineering*, 137(3), 293–296.

Nelson, J.D., Chao, K.C., Overton, D.D., and Nelson, E.J. 2015. Foundation engineering for expansive soils. *John Wiley & Sons, Inc.,* Hoboken, NJ, USA.

Overton, D. D., Chao, K. C., and Nelson, J. D. 2006. Time rate of heave prediction for expansive soils. *GeoCongress 2006: Geotechnical Engineering in the Information Technology Age*. 1-6.

Rutqvist, J. and Stephansson, O. 2003. The role of hydromechanical coupling in fractured rock engineering. *Hydrogeology Journal*, 11, 7–40.

Schmalz, T.C, and Stiemer, S.F. (1995). Consideration of design life of structures. *Journal of Performance of Constructed Facilities*, ASCE, 9(3), 206-219.

Singhal, B. B. S. and Gupta, R. P. 2010. Applied hydrogeology of fractured rocks, 2nd edition, *Springer Science+Business Media*, New York.

Thrasher, B., Wang, W., Michaelis, A., & Nemani, R. 2021. *NEX-GDDP-CMIP6*. NASA Center for Climate Simulation.

Thrasher, B., Wang, W., Michaelis, A., et al. 2022. NASA global daily downscaled projections, CMIP6. *Scientific Data, 9*(262).

Walsh, K. D., Colby, C. A., Houston, W. N., and Houston, S.L. 2009. Method for evaluation of depth of wetting in residential areas. *Journal of geotechnical and geoenvironmental engineering*, 135(2), 169-176.