Project No. 01-59

PROPOSED ENHANCEMENTS TO PAVEMENT ME DESIGN: IMPROVED CONSIDERATION OF THE INFLUENCE OF SUBGRADE SOILS SUSCEPTIBLE TO SHRINK/SWELL AND/OR FROST HEAVE ON PAVEMENT PERFORMANCE

APPENDIX 10

STOCHASTIC FORECASTING OF SHRINK-SWELL VOLUME CHANGE

JUNE 2022

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10. INTRODUCTION

This chapter brings together the deterministic shrink-swell soil volume change model and the stochastic TMI model to produce a new method for forecasting the monthly shrink-swell soil volume. A discussion of potential implementation of the proposed stochastic shrink-swell soil volume change model to foundation and pavement performance analysis/design will also be included. The uncertainty and sensitivity of the estimations using the proposed method will be compared to those generated from current practice.

1.1 Objectives

The following objectives were accomplished as part of this study:

- Review and choose the deterministic SSVC framework which is to be incorporated into the stochastic analysis.
- Development of a framework for stochastically estimating the volume change on shrink-swell soils using the previously developed models for random soil property generation and monthly TMI forecasting.
- Exploration of the stability and sensitivity of the proposed shrink-swell forecast model.
- A comparison of the proposed models to the existing engineering practice including the differences in the uncertainty and sensitivity of the estimates.
- Exploration of the potential implementation of the proposed stochastic shrink-swell soil volume change model to foundation and pavement performance analysis/design.

1 Deterministic Shrink-Swell Volume Change (SSVC)

The ability to estimate soil volume change as a function of time is a valuable tool in the design of shallow foundations of pavement structures. Specifically pertaining to pavement design, estimating soil volume change as a function of time allows for the prediction of the potential cumulative International Roughness Index (IRI). The time-varying volume change can also be a valuable tool in the forensic analysis of existing foundation movement of a lightly loaded structure on shallow footings.

The author and members of the ASU research team (Zapata and Mosawi) published a paper in 2021 in the Soil and Rocks International Journal of Geotechnical and Geoenviromental Engineering titled “An Improved Framework for Volume Change of Shrink/Swell Soils Subjected to Time-Varying Climatic Effects”. The paper presents an improved framework for estimating the volume change of shrink-swell soils due to time-varying climatic effects using the Lytton et al. (2005) approach with the suction envelope models created by Vann and Houston (2021). The proposed framework for estimating soil volume change of shrink-swell soils as a function of time is presented with an example calculation with data from an AASHTO Long-Term Pavement Performance (LTPP) Seasonal Monitoring Program (SMP) section TX 48-1068 (FHWA, 1995), which is located approximately 80 miles northeast of Dallas, Texas. The framework presented is applicable to uncovered sites where the groundwater table effects are negligible, but it has been calibrated to account for covered areas and for the spatial variation between the pavement center and edges.

Refer to Appendix B for the full paper which includes a detailed background, evaluation, and recommendations regarding suction-volume change analysis of Shrink-Swell soils. The following outline summarizes the steps of the improved framework for estimating the volume change of shrink-swell soils due to time-varying (monthly) climatic effects:

- Weather station identification and data extraction
- 30-year and monthly Thornthwaite Moisture Index per Witczak et al. (2006)
- Determination of equilibrium suction envelope parameters per Vann and Houston (2021): depth to equilibrium suction and magnitude of equilibrium suction
- Back-calculation of variables for Mitchell's (1979) equation
- Development of long-term wet and dry suction profiles
- Initial estimation of monthly changes in suction at the surface per Perera (2003)
- Fourier equation fit to the monthly suction change at the surface.
- Generation of monthly suction profile
- Suction profile adjustments for varying surface boundary conditions
- Calculation of net normal stress profile
- Estimation of suction compression index (assuming value is not directly measured)
- Calculation of strain monthly
- Calculation of volume change monthly

The above deterministic framework is used in the stochastic analysis presented herein. Figure 5-1 presents a flow chart for the deterministic SSVC procedure.

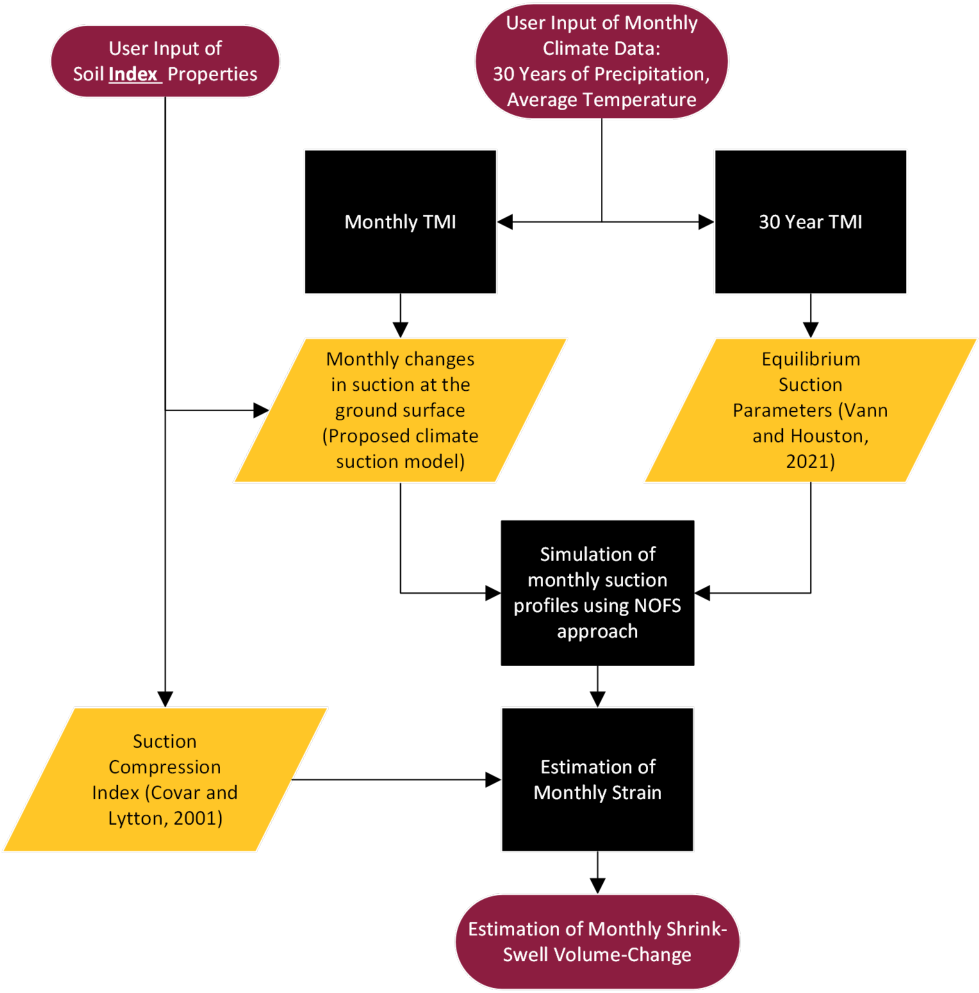

Figure 5-1 Flow of the Deterministic SSVC Analysis Procedure

Refer to Appendix 4 for additional details regarding the deterministic framework of the shrink-swell volume change analysis.

2 Stochastic Framework for SSVC Forecasting

This study presents an example calculation for a Level III analysis for the determination of volume change (shrink/swell) as a function of time. A computer program was developed in order to explain the calculation due to the multiple algorithmic processes contained within. Refer to Table 5-4, which summarizes the models used in the Level III analysis, along with the Level 1 and Level 2 analysis (not presented in this document). Table 5-5 indicates the necessary variables associated with the hierarchical level of analysis.

Table 5-1: Preliminary Plan to Estimate Volume Change Due to Swell/Shrink at Three Hierarchical Levels of Design

<table>
<tr><th>Hierarchical Level</th><th>Climatic Parameters</th><th>Depth to Equilibrium Suction</th><th>Equilibrium Suction</th><th>Time-Based Change in Suction on the Surface</th><th>Suction-Strain Model</th></tr>
<tr><td>1</td><td rowspan="3">30-year average and yearly TMI per Witczak et al. (2006)</td><td colspan="3">User input of suction profile *</td><td>Direct Measurement using OPPD (Olaiz 2017)</td></tr>
<tr><td>2</td><td colspan="2">Vann and Houston (2020) with lab measurements of soil index properties</td><td rowspan="2">NOFS Mitchell (1979) Diffusion Equation</td><td>Surrogate Path Method (SPM) (Houston & Houston 2017) or similar oedometer-based methods</td></tr>
<tr><td>3</td><td colspan="2">Vann (2019) using TMI</td><td>Covar and Lytton (2001) or similar empirical relationships with soil index properties</td></tr>
</table>

*User input of depth of equilibrium suction and magnitude of equilibrium suction indicates that the user knows these values (with a high level of confidence) by direct suction measurements or through significant experience of suction profile measurements in the area.

Table 5-2: Listing of Input Variables for Hierarchical Shrink-Swell Analysis

	Parameter	Levels 1	Levels 2	Levels 3
Pavement Structure Parameters	Pavement type and layer thicknesses	Needed	Needed	Needed
Parameters Related to Boundary Conditions (Environmental)	NOAA Weather Station ID (Longitude & Latitude)	Needed	Needed	Needed
	Groundwater Table Depth	Needed	Needed	Needed
Soil Index Properties	Plasticity Index (PI)	-	Needed	Needed
	Liquid Limit (LL)	-	Needed	Needed
	Percent Passing No. 200 Sieve (P200)	-	-	Needed
	Percent Passing 2-Micron (P02)	-	-	Needed
In Situ Soil Properties	Water Content (w)	-	Needed	Needed
	Density (γ)	Needed	Needed	Needed
	Soil Suction (pF)	Needed	-	-
Strain Parameters	Wetted Oedometer strain (ε_{ob})	-	Needed	-
	Swell Pressure (σ_{cv})	-	Needed	-
	Final Suction Profile	Needed	-	-
	Suction Compression Index	Needed	-	-

The stochastic forecast of shrink-swell soil volume change is accomplished by:

1) Obtaining sufficient historical monthly climate data (minimum of 5 years, recommended 30 years)
2) Obtains site-specific soil data and/or use the best representation based on the historical/prior Beta distributions
3) Perform 10,000 Monte Carlo simulations with each including:
   a. Randomization of input soil parameters using the proposed framework
   b. Estimating the monthly TMI over the structure/pavement design life using the proposed MCMC monthly TMI forecast model
   c. Estimating the monthly volume-change for the given simulation using the proposed deterministic framework
   d. Repeating process for each simulation
4) Calculating monthly and overall statistics for all the simulations combined.

3 Example of the Stochastic SSVC Forecast Model

The Denver study site previously presented herein was used to present an example of the performance of the stochastic SSVS Forecast Model. The results of the randomized input soil property variability and additional output from MCMC TMI climate model are presented in Appendix F. The example analysis was performed for 20 years to provide insight into the stability of the analyses for typical pavement design life periods. The Bayesian forecast for TMI and monthly change in TMI are presented in Figure 5-17. The stochastically prodiced estimates and variability of the monthly SSVC and monthly change in SSVC are presented in Figure 5-18 and Figure 5-19, respectfully.

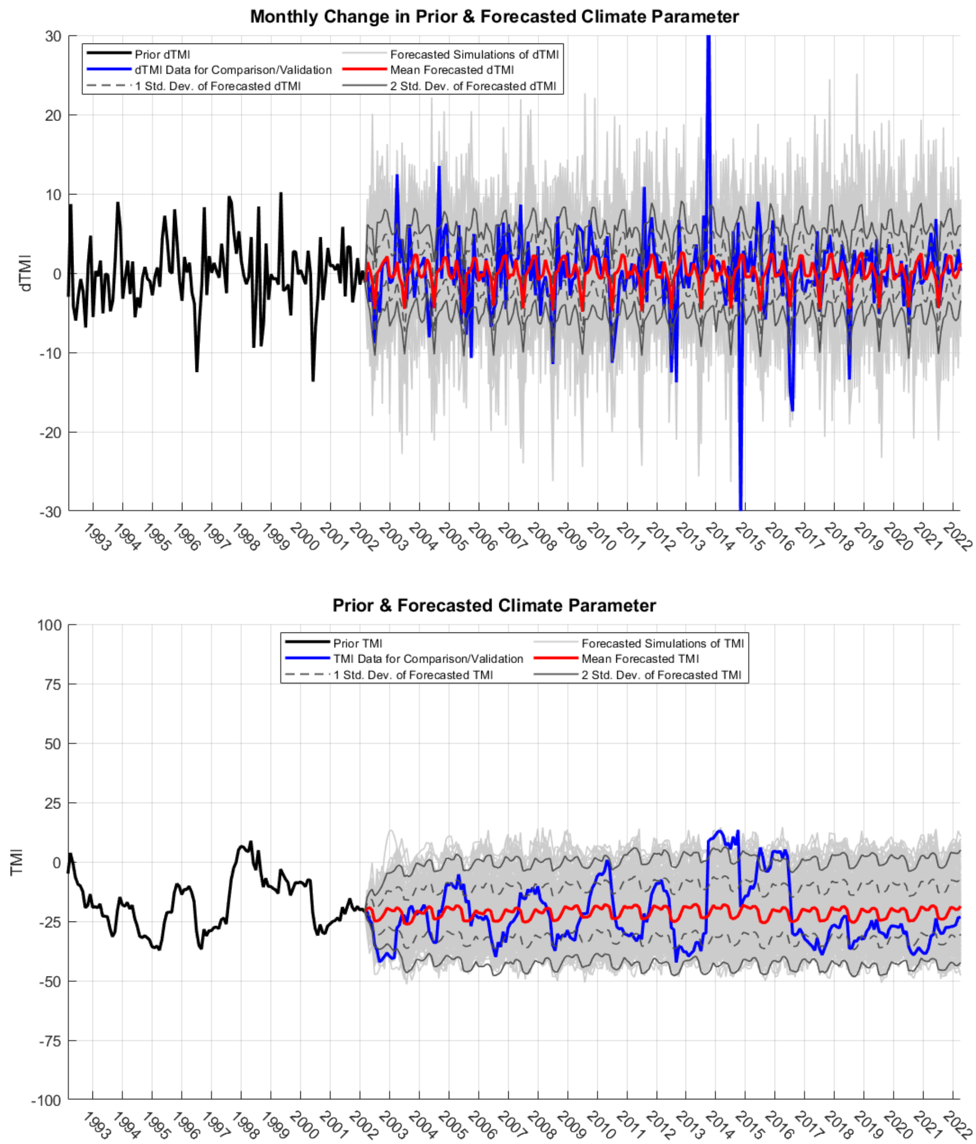

Figure 5-2 Bayesian Forecast of TMI at Denver Study, Including the True Values for Validation, from 03/2002 to 03/2022

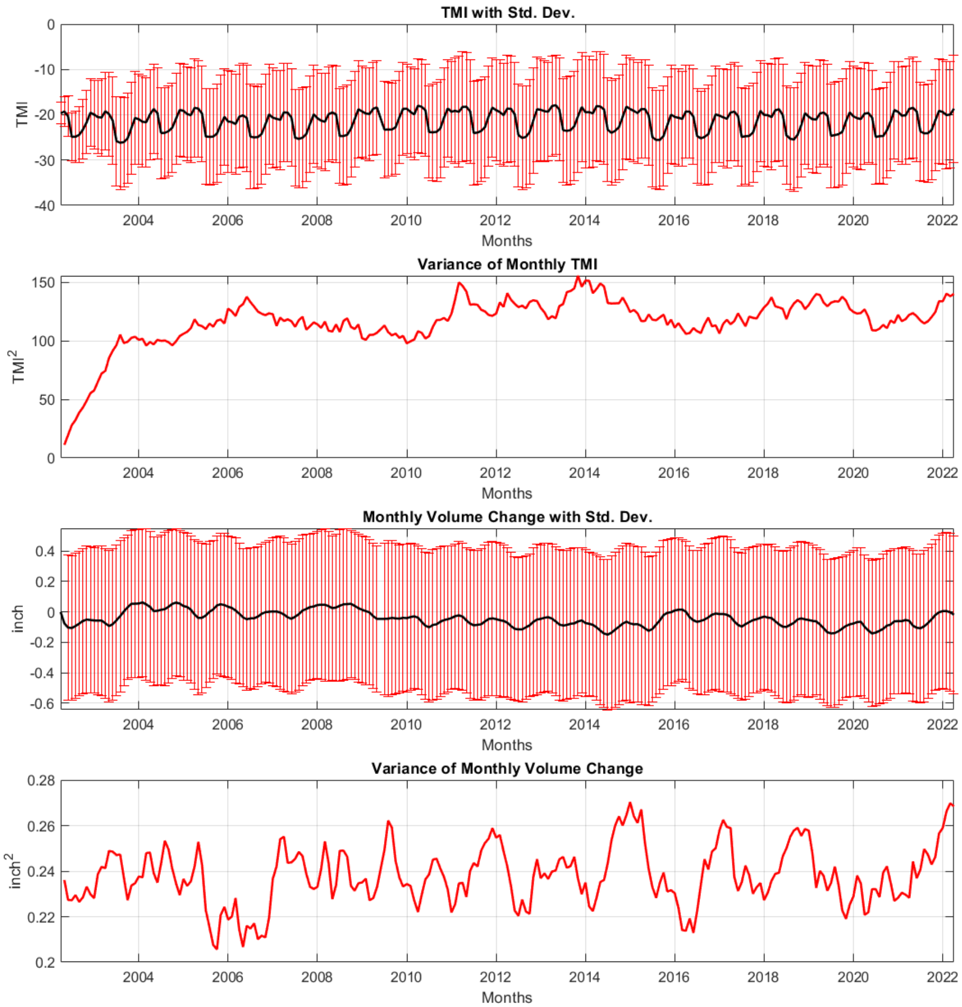

Figure 5-3 Example Results of the Stochastic Shrink-Swell Analysis for the Monthly TMI and Monthly Volume Change for the Denver Study Site from 03/2002 to 03/2022

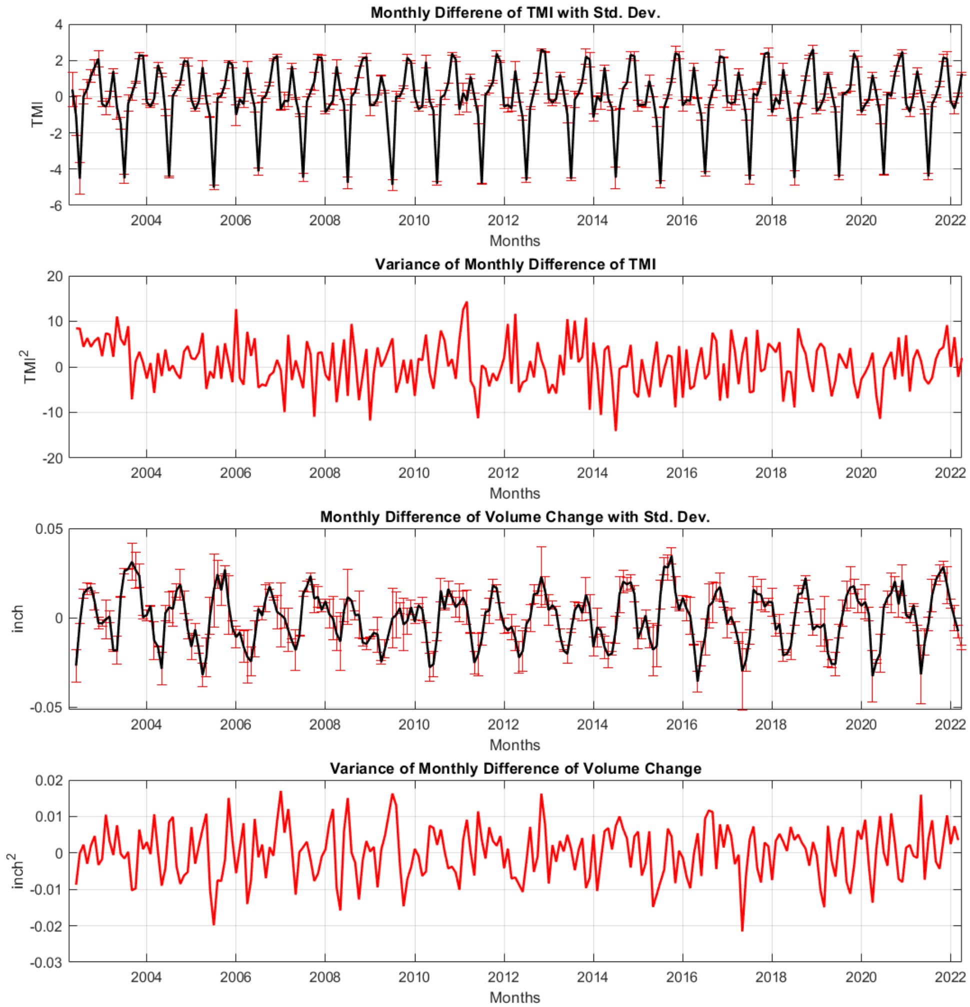

Figure 5-4 Example Results of the Stochastic Shrink-Swell Analysis for the Monthly Difference in TMI (*dTMI*) and Monthly Difference in Volume Change for the Denver Study Site from 03/2002 to 03/2022

4 Performance of the Proposed Stochastic SSVC Model

The stochastic SSVC analyses presented herein provides a method for quantifying the potential volume change and its associated variability monthly based on the variability of the randomized model inputs: soil index properties and forecasted monthly TMI values. As the example output in Figure 5-18 and Figure 5-19 display, the variance of the estimated monthly values continued to oscillate on a seasonal basis as expected, but the overall average of the variance visually appears to stabilize after two to three years. This indicates that the optimal analysis period for scenarios where the model is being used as an indicator for potential shrink-swell issues would be approximately 4 years. However, the results of the example calculation show that the proposed model provides useful insights for analysis periods greater than 4 years, up to 20 years. Generally, the analysis would not cover the full pavement design life as analyses of shorter durations would provide a useful representation of the volume change susceptibility which would typically result in a redesign of the pavement section or possibly a soil improvement effort. Note that this model included 250 Markov chains over the 20-year period (i.e. 60,000 MCMC simulations) with a burn in period of 25% that resulted in an Metropolis-Hastings acceptance rate of approximately 24%.

5 Implementation of the Proposed Stochastic SSVC Model

The proposed framework for stochastically forecasting the SSVC on a monthly basis is being review and considered for implementation into the Pavement Mechanistic-Empirical Design (PMED) design procedures and associated software as part of the NCHRP 01-59 project which this research was funded by. A detailed report was generated by the author and the research team for NCHRP which includes a detailed performance evaluation and implantation examples of the stochastic Shrink-Swell forecast model using the computer program developed by the author. It is anticipated that report will be published by NCHRP in 2023; no drafts or excerpts of the report have been included herein.

Note that the example analysis presented herein included a scenario which forecasted the potential climate-driven volume change. A forecast scenario will typically always result in the largest amount of variability in the resulting estimate. If new site-specific data is obtained (measured soil or climate parameters), they can be used to adjust and improve the forecast performance of the model. Furthermore, the model can be used in a forensic scenario if the variability of past SSVC needs to be understood.

6 Limitations of the Stochastic SSVC Model

Although the proposed Stochastic SSVC model displays preliminary indications that the stability and performance is sufficient for implementation in geotechnical engineering practice, there are several limitations that must be understood, including but not limited to:

- The proposed stochastic SSVC model, and all of its contributing models (Bayesian characterization of general soil properties model and the MCMC TMI forecast model) should be considered preliminary frameworks with have promising initial performance but lack an exhaustive sensitivity and stability evaluation.
- The examples of the model use presented in this document were focused on just 2 sites in the United States which the author and ASU research team had significant measured data at, which provided opportunities for model validation. The two study sites in Denver, CO and San Antonio, TX are in dry temperate to semi-arid climate zones and the site soils exhibit relatively high susceptibility of SSVC, which make the study sites nearly ideal for the application of the proposed models. However, the study sites were also used to produce

several of the empirical unsaturated soil parameter models used in the stochastic analysis. It is recommended that additional site-specific data from sites in differing climate regions be obtained for further validation studies of the full stochastic SSVC model proposed herein.

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