Data-Based Real-Time Moisture Modeling in Unsaturated Expansive Subgrade in Texas

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Abstract
Moisture variations significantly influence the strength and stiffness of expansive subgrade soils, shortening the service lives of pavements and increasing the associated maintenance costs. Accurate measurements of soil moisture can be obtained through soil sampling and testing, but the process can be extensive and costly. Empirical models can accurately predict the moisture variations in an expansive subgrade in a shorter period of time, with lower accompanying costs. The objective of the current study was to develop moisture models, using real-time field monitoring data from two hot mix asphalt roads in North Texas. The collected data were analyzed in a statistical environment to solve two first degree Fourier series. The solution produced a moisture variation model that captured variations associated with seasonal effects and temporary variations associated with rainfall. The outputs of this model were within 90% of the values measured on site. Application of the developed models will facilitate noninvasive estimations of the response of soil strength and stiffness properties to variations in moisture.

Expansive soil is a worldwide problem and constitutes approximately 25% of the soil in the United States (1, 2). Volume changes of these soils occur through adsorption or desorption of moisture, leading to cyclic swelling and shrinkage. On average, the nation’s infrastructure incurs more financial losses from expansive soils than from earthquakes, floods, hurricanes, and tornadoes combined (3). Nelson and Miller (1) estimated 9 billion USD of damages annually, and Jones and Jefferson (4) calculated a total financial loss of 15 billion USD. The Texas Department of Transportation (TxDOT) spends 25% of its annual outlay on maintenance and repair of damaged pavements (5). Addressing the effects of expansive subgrade soils in both the design and construction stages could reduce future maintenance costs and extend the service lives of pavement systems.

The strength and performance of a pavement built on expansive subgrade is most influenced by moisture (6). Hedayati reported moisture content variation, which typically induces pavement cracking, as the prime cause of subgrade deformation in expansive soil (7). Fluctuations in moisture content are influenced by the pavement subgrade compaction site, environmental site conditions, location of roadside trees, and the presence of nearby drainage ditches (3). Moisture variations cause significant changes in the shear strength, resilient modulus, and permeability of subgrade soils (8, 9). They also affect hydraulic conductivity, chemical diffusivity, specific heat, and thermal conductivity (10). The success or failure of a pavement system is dependent on the support provided by the subgrade layers. An increase in moisture content has been shown to decrease the resilient modulus, which quantifies the support that the subgrade can offer (11).

Researchers have developed different subgrade moisture prediction models over the years. Their methods ranged from simple to complex in nature, that is, a single input of soil property to statistical and numerical modeling. Swanberg et al. estimated moisture variation by employing only the plastic limit value (12), and some studies categorized subgrade and climatic conditions by subdividing geographic areas into regions per the Thornthwaite’s Moisture Index (TMI) (13, 14). With the

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advancement of technology, researchers have utilized complex mathematical relationships between soil properties and environmental conditions to predict moisture variation. Currently, the Mechanistic-Empirical Pavement Design Guide (MEPDG) recommends using the Enhanced Integrated Climatic Model (EICM) to predict moisture changes (15).

Other moisture variation estimation methods include soil sampling at regular time intervals (16), assuming seasonal variations or constant equilibrium moisture content for several years after construction (15). Hall et al. estimated the upper and lower equilibrium moisture content of specific sites rather than predicting the real-time variations (17). Recent research has incorporated numerical modeling in estimating moisture variations. For example, Abed (18) used 2D PLAXFLOW analysis to examine the swelling and shrinkage behavior of expansive soil caused by moisture variations, and Puppala et al. (19) performed 3D static analysis in Abaqus to study swelling behavior.

Neither sort of developed method, from soil properties or from computational techniques, can accommodate the temporary moisture variations that are caused by rainfall. Various field studies have reported that following rainfall, increases in moisture content can be up to 20% in amplitude from the baseline moisture content (20, 21, and 22). Hedayati et al. reported that this additional increase in moisture can severely deteriorate the pavement structure, a factor which is overlooked in the current models (21).

Therefore, it is highly recommended that moisture prediction models incorporate both seasonal and temporal variations to reflect the real-time scenario. Although moisture content can accurately be measured, soil sampling and the consequent testing required can be lengthy, destructive, and expensive (23). The objective of the current study was to develop moisture and temperature models, using real-time field monitoring data from two hot mix asphalt roads in North Texas. After 2 years of monitoring, the collected data were analyzed in a statistical environment to develop moisture prediction models that incorporated both seasonal and sudden increases in moisture associated with climatic factors. The predicted models were compared against the measured values of current study sites, and the models were checked against previous study to validate their accuracy.

Site Selection

Based on the recommendations of TxDOT engineers, two sites were selected to determine the causes of roadway cracking and to provide possible remedial measures. The first site is situated in Kaufman County, 1.80 miles from the intersection of FM 2757 and I-20. The second site is located on SH 342 in Lancaster, Texas.

Several structural distresses were observed on the roadway during the initial field investigations. The sites had experienced continuous edge and surface cracks, as well as bumps, punch outs, and surface unevenness. Edge cracks up to 3 in. wide and several feet long were observed. In some cases, the depth of the crack was more than 1 ft, which resulted in complete separation of the edge from the pavement structure.

Site Description

The test site in Kaufman County is located on a farm-to-market road identified as FM 2757 in Forney, Texas. The low-volume road consists of two lanes, each measuring 11 ft wide, with no shoulder. The side slopes on both sides are covered with grass and dense trees. Small bodies of water are present to the east and west of the road. Edge cracks of 3 in. in thickness and extending up to 12 in. in depth, as well as other surface pavement distresses, indicate the presence of expansive subgrade soil and rainwater intrusion.

The SH 342 test site is situated in Lancaster, Texas, at the border between Dallas and Ellis counties. The two lanes are each 11 ft wide, and an 11 ft shoulder is present on both sides of the road. The pavement is fairly level with the ground and is flanked by grass and dense trees on both sides. To the west, a rail line runs parallel to the roadway. An edge drop up to several inches in depth was observed in the pavement shoulder. No water bodies were observed nearby.

Instrumentation Plan

Both sites were instrumented with 5TM soil moisture sensors manufactured by Decagon Devices (currently METER), a 100ECRN high-resolution tipping bucket rain gauge, and 85 mm horizontal inclinometer casings to continuously monitor moisture variations, rainfall recordings, and vertical deformations of pavement. In each 5TM sensor, dielectric permittivity is used to measure the moisture content of soil. An electromagnetic field is created to determine the dielectric permittivity of the surrounding material. Based on the manufacturer’s calibration, dielectric permittivity is converted to volumetric moisture content which is further converted to gravimetric moisture content relating with soil properties. Data loggers were programmed to take hourly readings of moisture content and rainfall data. The typical sensor locations for both sites are illustrated in Figure 1a, and Table 1 gives the notation of sensors for both FM 2757 and SH 342 sites. For example, K 1/2 corresponds to the sensor of Kaufman (FM 2757) site located in borehole 1 and is sensor number 2 in that borehole. The table shows K 1/2 sensor was installed at a depth of 8 ft. Figure 1b shows some photos of field installations.
During installation, soil samples were collected from several boreholes to determine the basic soil properties. Atterberg limits, grain size distribution, specific gravity, and unit weight tests were conducted to aid in understanding the soil behavior.

Soil Properties

According to particle size distribution, samples from both sites were composed of over 85% clay, indicating the presence of very fine subgrade soil. The liquid limit of the samples varied between 50% and 64%, and the plasticity index ranged between 28% and 42%. The soil was classified as high plastic clay (CH) according to the Unified Soil Classification System (USCS) and based on the results of sieve analysis and the Atterberg limits. Specific gravity ranged between 2.68 and 2.72, with an average of 2.70. Optimum moisture content was 22%, and dry density at the optimum moisture content was 121.4 lb/ft³ obtained from standard proctor test.

Moisture Variations in Subgrade

Because expansive clay renders pavement susceptible to edge cracking caused by moisture variations (6), moisture sensors were installed in four boreholes at both sites to investigate the effects of moisture variations on expansive subgrade. Only the results from the edge borehole of the Kaufman County site and center borehole of SH 342 are presented below, as the data mirror what was recorded by the remaining sensors.
Figure 2a represents data collected from April 2012 to December 2014 at the Kaufman site. Sensors K 4/1 and K 4/2, at respective depths of 3 ft and 6 ft, exhibited both seasonal effects and temporary saturation caused by rainfall. Wetter seasons yielded a rise in the moisture variation curve, which then dipped during drier periods. Additionally, rainfall events registered instantaneous spikes in moisture content ranging from 1% to 8% in amplitude. The peaks suggested that the soil became temporarily saturated before returning to equilibrium. At greater depths, moisture content remained stable. K 4/4 and K 4/5, located at 12 ft and 15 ft depths, maintained respective moisture contents of 16% and 20%.

Data collected at SH 342 from March 2014 to June 2015 produced the curve shown in Figure 2b. All sensors maintained stable moisture content that responded only to individual rainfall events. Previous studies confirmed that soil properties determine whether or not a seasonal effect on moisture variation exists at a given location (24, 25). Furthermore, the shoulder at SH 342 might have delayed the movement of moisture, deferring the seasonal contribution. Nevertheless, SH 342 experienced temporal variations associated with rainfall. S 1/1, S 1/2, and S 1/3 (located at respective depths of 4 ft, 8 ft, and 12 ft) yielded average moisture contents of 12%, 6%, and 16%, respectively. Moisture content rose to 14% at 8 ft and 8% in amplitude at 12 ft because of temporary saturation induced by continuous rainfall. At 15 ft, S 1/4 registered no appreciable changes in moisture content and remained just below 20%.

Theory of Moisture Modeling

Annual variation of subgrade moisture can be described by the following one-dimensional nonlinear diffusion function (21, 23):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left( D(\theta) \frac{\partial \theta}{\partial z} \right)$$

where $\theta$ = volumetric moisture content at any time $t$ at depth $z$, and $D(\theta)$ = Soil moisture diffusivity.

Assuming a constant $D$, the previous equation can be solved as a first degree Fourier series:

$$\theta(z,t) = \theta_0 + \theta_a \sin \left( \omega t - \frac{\pi}{d} + C_0 \right)$$

where

- $\theta(z,t) =$ volumetric moisture content at depth $z$ at time $t$,
- $\theta_0 =$ average moisture content over time at depth $z$,
- $\theta_a =$ domain of moisture variation,
- $\omega =$ angular frequency (equal to $2\pi/365$),
- $d =$ damping depth, and
- $C_0 =$ phase correction factor.

The first term of the solution captures the yearly average moisture content at any depth, whereas the second term accounts for the seasonal variations of moisture. Temporal variations associated with rainfall must also be addressed to capture all of the moisture variations in subgrade soil (21). Previous studies showed that soil and site conditions affect the seasonal and temporal variations of subgrade moisture (24, 25). Some soil (e.g., low plasticity clay in Ohio) experiences a sinusoidal seasonal variation (24), whereas other soils (expansive subgrades on high plasticity clay in Texas) tend to maintain equilibrium moisture content, not changing with the season (22). Therefore, soil characteristics and specific site conditions are the most important elements in determining the moisture variations. Seasonal and temporal variations of moisture content of the subgrade were statistically analyzed and incorporated in the presented model.
Moisture Data Analysis

The moisture prediction model was developed using the data from sensors with the most interpretable readings over the course of 2 consecutive years (i.e., K 1/2, K 4/2). Four sets of data were used for model development, and one sensor was randomly chosen from both the Kaufman (K 3/2) and SH 342 sites (S 1/3) for model validation.

Seasonal Trend Analysis

As discussed earlier, moisture sensors at the Kaufman County site exhibited seasonal variations, while sensors at the SH 342 site maintained an equilibrium moisture content that displayed instantaneous responses to rainfall. To determine the seasonal trends, moisture peaks associated with rainfall were removed from the Kaufman site. The seasonal output is shown in Figure 3a. After several trials, the seasonal trend was found to follow the first degree Fourier series. The variables were found by solving the following equation (26):

$$f(t) = a_0 + \sum_{n=1}^{\infty} \left( a_n \cos \frac{2n\pi x}{T} + b_n \sin \frac{2n\pi x}{T} \right)$$

The result of the series followed the form:

$$f(x) = a_0 + a_1 \cos(x \cdot w) + b_1 \sin(x \cdot w)$$

where, $a_0$ is the average value of the dataset, $a_1$ and $b_1$ are real numbers independent of the variable $x$, which accounts for the amplitude of the dataset, and $w$ is the frequency (day$^{-1}$). As 1 year of data was used to develop the model, and seasonal trends follow annual variations, the frequency was set equal to $2\pi/365$ (0.0172 day$^{-1}$).

Variations of the values of $a_0$, $a_1$, $b_1$, and $w$ are shown in Figure 3a. The moisture content of the sensors remained around 16–17%, which can be attributed to the soil’s field capacity (18). Modeling the seasonal variation was simplified by incorporating average values of the different parameters comprising the Fourier series. For example, values of $a_0$ were found to be 18.85, 17.64, 16.22, and 16.42 in the four graphs in Figure 3. The

![Figure 3](image-url)

Figure 3. (a) Seasonal trend of moisture variation and (b) comparison of seasonal model with Heydinger (24).
average of these four values, 17.2825, was selected for
the seasonal variation model. Values for \(a_1\), \(b_1\), and \(\omega\)
were similarly obtained by calculating the average. The
completed model followed the form:

\[
\text{Seasonal M.C.} = 17.2825 \frac{1}{C^0} - 0.46828 \cos(x*0.01864) + 0.5417 \sin(x*0.01864)
\]

where M.C. = moisture content.

As the sensor began recording data in April 2012, the
first day of April was set as day one (i.e., \(x = 1\)). It fol-
lowed that March 31 was set as \(x = 365\).

After developing the seasonal model, it was compared
with a prominent previous study by Heydinger (24). It
can be observed that the developed and the previous
result by Heydinger overlap considerably (Figure 3).
The next phase of the study was to find out the effect
created by rainfall.

**Moisture Fluctuations Associated with Rainfall**

Peaks in the moisture data (Figure 2, a and b) depicted
temporary rises caused by precipitation. The increase of
moisture content was analyzed separately to determine the
relationship between rainfall and an increase in moisture
content. Peaks were separated if the change in moisture
content displayed a difference of 1% or more from the pre-
viously recorded rainfall event. A preliminary inspection of
the plot showed that, in spite of an increasing magnitude in
precipitation, the resulting moisture content of the soil typi-
ically only rose to a specific value that corresponded to the
saturation point of the soil (Figure 4a). It can be observed
from Figure 4a that in spite of different rainfall events, the
moisture increase remains the same at some points. At this
point, all of the medium’s voids were filled with water.
However, the current status of moisture content in the soil
is the most determining factor for the increase of moisture
the soil can experience. Thus, the more reliable plot was
obtained by including only those points that exhibited an
increase in moisture content caused by rainfall from the
equilibrium moisture content. It was concluded that the lin-
ear plot best described the trend of moisture increase
caued by rainfall, as shown in Figure 4, b and c, for a
selected sensor for consecutive 2 years. Similar results were
reported by previous researchers (21, 27). Parameters (i.e.,
slope and intersection) of the four sensors were averaged to
find the increase in moisture content caused by rainfall.
Average values of 1.39 for the intersection and 2.2085 for
the slope were used in the final moisture model.

**Final Moisture Model**

Based on the overall analysis (i.e., seasonal trends and
temporary increases associated with rainfall), moisture
content at different depths could be explained as

\[
\text{M.C.} = \text{[Seasonal Variation]} + \text{[Variation due to rainfall]}
= a_0 + a_1 \cos(x*0.01864) + b_1 \sin(x*0.01864) + f\text{(Rainfall)}
= [17.2825 - 0.46828 \cos(x*0.01864) + 0.5417 \sin(x*0.01864)]
+ \{(1.39 + 2.2085*Rainfall)\}
\]

where \(x = \text{days}\) (April 01 as day 1), and rainfall is in
units of inches.

The average moisture content was generally observed
to remain at the soil’s field capacity of 17.5% (21).
Monitoring of moisture variations in plastic clay in
Delaware County, Ohio for a period of 5 years (1996–
2001) exhibited an average moisture content of around
15–17% (24). Similar field monitoring conducted in high plastic clay in Houston and Fort Worth, Texas for 2 years (2007–2008) showed average moisture content of 15–18% (25). Therefore, the applicability of the model is limited to specific soil conditions. In addition, it also considers the specific region in which the study sites are located.

Validation of the Developed Moisture Model

Sensor K 3/2 was randomly selected and tested for a period of 6 months (from April 2013 to October 2013) to determine the accuracy of the developed model. A sensor from the SH 342 site (S 1/3) was selected for model validation.

Figure 5a illustrates that the developed model captured both the seasonal and temporal variations associated with rainfall. A comparison of the predicted and measured values in Figure 6a showed that more than 90% of the data fell in the 90% confidence bands. In case of SH 342, only the increase in moisture associated with rainfall was compared against the actual increase in moisture content. A comparison of the modeled and actual increases in moisture content after randomly selected rainfall events is presented in Figure 5b. The model’s results were compared with results obtained from previous studies (Figure 6b) after converting gravimetric values to volumetric moisture contents (23). Including the temporal variation significantly improved the model’s predictions, as is depicted in Figure 6b.

Limitations of the Models and Further Development

The models have limitations that need to be addressed, which are that the study was based on the assumption of a homogeneous soil layer, and evaporation was not considered. To further increase the acceptance of the model, it was checked against some sensor results installed in the grassy side slope, as shown in Figure 8a. The rationale of selecting the grassy side was to include the effect of evaporation, as the sensors installed beneath the pavement did not include evaporation. It was observed that the sensors exhibited both seasonal and temporal variations similar to the sensors installed beneath pavement, but the average moisture content data was different. Therefore, the first version of the developed moisture model was replaced by the average moisture content of the selected sensor, and the rest of it remained the same. As such, the modified moisture model is

\[
MC = \frac{X}{C_0} + 0.5417 \cdot \cos(x^{0.01864}) + 1.39 + 2.2085 \cdot \text{Rainfall}
\]

where \(X\) = average moisture content of the location.

Using the developed moisture model requires manually measuring the average moisture content of the selected site.

The modified moisture model was tested against the sensors installed in the grassy side of the slope. Figure 7 depicts the measured and modeled moisture content, and it is clear that the model was the most accurate at recording the changes in moisture associated with rainfall. The measured and modeled data were further plotted against a 45 degree line because that is where most of the data were clustered (Figure 8b), and hypothesis testing was conducted to verify the modified model.

An independent two-sample \(t\)-test with unequal variance was performed to determine whether there were significant differences between the actual and predicted moisture increase values. The rationale behind the independent test was the non-dependency of the two set values. In the \(t\)-test, the mean of the predicted values was compared with the mean of the observed values. The risk level was taken as 0.1, meaning that the test was conducted at 90% confidence level. The two-tailed test directed the significance level to 0.05 from 0.1. The basic hypothesis of the two-sample \(t\)-test, containing
null ($H_0$) and alternative hypothesis ($H_a$), can be described as

$$H_0 : m_1 - m_2 = 0$$

$$H_a : m_1 - m_2 \neq 0$$

where $m_1$ = mean of the actual moisture, and $m_2$ = mean of the predicted moisture.

The test summary is provided in Table 2. The $t$-value found from the analysis was lower than the critical value of the two-tailed $t$-test. The $p$-value was higher than the significance level ($\alpha/2$). Based on the analysis, it was concluded that the null hypothesis could not be rejected, indicating there was no significant difference between the means of the actual and predicted values. Thus, the developed prediction model is justified.

### Conclusion

Results obtained from the two instrumented pavement sites were used to develop real-time moisture models. The summary of the findings is presented below:

- Moisture data showed that equilibrium moisture content varied from 6% to 20% at different depths of subgrade.
- Temporal increases of moisture caused by rainfall ranged between 1% and 15% in amplitude. Shallower sensors recorded higher variation while deeper sensors experienced less.
- Instantaneous spikes in moisture content were indicative of temporary saturation induced by rainfall. As the free water moved downwards, moisture content readings returned to equilibrium.
Real-time moisture model was developed incorporating both seasonal and temporal variation of moisture by solving a first degree Fourier series. Validation of the model indicated that the outputs of the model were within 90% of the in situ measured values. In addition, comparison with previous studies indicated that the model can capture both seasonal and temporal variation.

The moisture variation model was studied in a homogenous single layer subgrade and specific type of soil, that is, high plastic clay. Moisture variations in different types of soils with different stratigraphy are considered outside the scope of the current case study, limiting the applicability of the model.

It is strongly recommended that the developed models be further modified through additional analysis of different types of soil and various geometric configurations of roads.

References


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