Moisture Variation in Expansive Subgrade Through Field Instrumentation and Geophysical Testing

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Abstract. Seasonal climatic variations in subgrade soil affect pavement responses and can reduce pavement serviceability. In addition to causing shrinkage and swelling in expansive subgrade, variations in moisture suction may alter the material properties of soil, which ultimately affect pavement performance. The current study monitored the seasonal variation of subgrade moisture content, rainfall, and pavement deformation of a section over State Highway 342, in Dallas, Texas. Moisture sensors were installed at different depths up to 4.5 m. The soil was found to be highly plastic clay (CH) in the selected site. In addition to acquiring real-time moisture data from sensors, geophysical testing was also conducted on the slope of the pavement. Electrical Resistivity Imaging (ERI) was carried out at the slope of the instrumented pavement section to observe the moisture flow at the edge of the pavement. Based on the field monitoring data, moisture variation ranged from 5% to 14%, with higher moisture contents correlating with rainfall events. While moisture sensors provided point information, resistivity imaging yielded a continuous portrayal of subsurface moisture flow. Furthermore, rainfall-associated deformation of the pavement was monitored. Based on the monitored data, it was observed that pavement deformation varied with rainfall. A total deformation of 38 mm was recorded over the monitoring period.

1 Introduction

The engineering properties of expansive soils are highly dependent on moisture content changes in the active zone. Such soils undergo volumetric deformation that gradually damages essential infrastructure such as foundation slabs, bridges, roadways, and residential homes. Present in both humid and arid/semi-arid environments, expansive soils cover nearly a quarter of the area of the United States (Nelson and Miller 1992). Annually, expansive soils alone incur more financial losses to US property owners than

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earthquakes, flood, hurricanes, and tornadoes combined (Jones and Jefferson 2012). In a typical year, the associated financial losses can be as high as 15 billion dollars (Jones and Jefferson 2012). Their low stiffness, light loading, and extended presence over the country render pavements especially susceptible to deterioration caused by expansive subgrades. Continuous volumetric deformation of the problematic soils increases the pavement's roughness, resulting in reduced serviceability. Consequently, a better understanding of the causes of pavement distress and the behavior of expansive soils is necessary for acceptable pavement performance and design (Sebesta 2002).

Climatic factors, especially moisture variations, induce substantial changes in the structural characteristics of pavement systems. Fluctuations in moisture content can have major impacts on the long-term performance of pavements. Principal sources of moisture variation are rainfall, intrusion from cracks, freeze-thaw cycles, leakage, and evapotranspiration. Moisture variation affects the hydraulic conductivity, shear strength, chemical diffusivity, specific heat, and thermal conductivity of a soil Lu 2015). Furthermore, the success or failure of a pavement system is dependent on the support provided by subgrade layers. An increase in moisture content has been shown to decrease the resilient modulus, which quantifies the support that the subgrade can offer (Mehrota 2011). Moreover, variation in moisture content may cause swelling and shrinkage in highly plastic subgrade soils. Surficial cracks are generated due to this behavior and require departments of transportation to increase expenditures related to pavement maintenance (Zapata and Houston 2008). Because expansive subgrade is seldom identified as the source of pavement failure, maintenance routines typically only consist of roadway surface treatment. Consequently, surface roughness can reappear a short period of two years and six months later. For 18 out of 52 Texas Department of Transportation (TxDOT) districts, such problems are commonplace (Wanyan et al. 2010).

To consider the possible effects of moisture in the design procedures, many researchers have conducted field-based analyses to relate subgrade characteristics with environmental factors. Bayomy and Salem (2004) instrumented five different sites in Ohio. After monitoring for a period of five years (1999–2003), the researchers reported the presence of seasonal moisture variation. Manosuthkij (2008) monitored four instrumented sites in Texas and found that when the mean moisture content, or the difference between the maximum and minimum moisture content of each month, was greater than 20%, edge cracking was likely to occur. In Ohio, Heydinger (2003) obtained both seasonal variation and temporal variation due to precipitation at two instrumented sites.

In addition to installing moisture sensors that monitor moisture variation, geophysical investigation can also be significant when observing the moisture flow in subgrade. ERI is widely used in hydrogeological, environmental, and geotechnical research due to its potential to reveal the subsurface image (Aizebeokhali 2010). It is a convenient method for determining spatial variations of moisture in subsoil (Kibria and Hossain 2012). In the geotechnical and geomorphological fields, ERI is gaining popularity for the user-friendly data acquisition system inherent to the method. The technology is used in geotechnical applications to determine unknown foundation depths, investigate slope and foundation failures, detect cracks and the existence of sinkholes, record moisture variation in pavement base materials, and track soil movement with accurate results. ERI can measure both the horizontal and vertical variability of soil arrangement over several meters of a perspective area (Tabbagh et al. 2000).

The resistivity profile provides a comprehensive interpretation of the subsurface condition. The most interesting and important advantage of using ERI is that the resulting resistivity profile offers a clear picture of the moisture distribution within the test area. Accordingly, numerous studies have utilized ERI to study moisture distribution in soil. Benderitter and Schott (1999) observed the water content variation in an unsaturated soil and the effect of rainfall by observing the short-term variation of resistivity. Clarke (2006) measured subgrade resistivity over nine months to determine the active zone, edge moisture variation distance, and long-term equilibrium moisture beneath the covered area. The author also monitored the seasonal fluctuations of moisture at the edge. The study found that the most extreme changes occurred at the surface and diminished with depth. Kean et al. (1987) studied the moisture migration in the vadose zone using resistivity tomography. Finally, Zhou et al. (2001) performed spatial and temporal monitoring of soil water content using electrical resistivity tomography.

During the current study, both dielectric sensors and two-dimensional electrical resistivity imaging techniques were utilized to study the moisture variations in expansive subgrade and pavement slope. The objective of the study was to determine the variation of subgrade moisture due to both seasonal variation and precipitation events. The study was conducted in a state highway designated as SH 342 in Ellis County, Texas, USA. Sensors were installed up to 4.5 m depth beneath the driving lanes. ERI was conducted at the slope of the pavement during different seasons. A rain gauge was also installed to record the precipitation events.

2 Project Background and Site Description

The effects of moisture on soil depend on the soil properties. Based on accessibility, distance from the flooding zone, and TxDOT recommendations, a section on State Highway (SH) 342, a two-lane hot mix asphalt road, was selected for investigation. Two 3.3 m (11 ft.) wide lanes with a 3.3 m (11 ft.) wide shoulder on each side of the road were present at the site. Details of the chosen section can be seen in Fig. 1. The project site was located near Lancaster, Texas, on the border between Ellis and Dallas counties. While the pavement was fairly level, edge cracking and other pavement distresses were observed. Adjacent to the pavement, the ground was covered with grass. Additionally, dense trees could be observed on both sides approximately 6 m (20 ft.) from the pavement. To the west, a rail line ran parallel to the roadway. Further northeast, the road overpassed Bear Creek, while a residential area was located a short distance to the southeast. No water body was directly observed nearby.

Fig. 1. State Highway (SH 342) in Dallas, Texas, USA

3 Field Instrumentation

A comprehensive field instrumentation plan was implemented at SH 342 to monitor the moisture variations in the subgrade soil. Decagon 5TM moisture sensors, an ECRN-100 high resolution tipping-bucket rain gauge, an EM50 data logger, and a horizontal digitilt inclinometer probe were installed at the site. The moisture sensors and the 85 mm horizontal inclinometer casings were installed from the centerline to the edge of the northbound lane, as seen in Fig. 2.

Continuous monitoring of moisture content, rainfall, and vertical deformation were obtained from field instrumentation. Data loggers were programed to take hourly readings of moisture content, and rainfall data. Furthermore, the pavement site was visited monthly to obtain inclinometer readings. Fifteen moisture sensors and six 3 m (10 ft.)

long horizontal inclinometer castings were installed. The depth of the sensors ranged from 1.2 m (4 ft.) to 4.5 m (15 ft.) below the pavement.

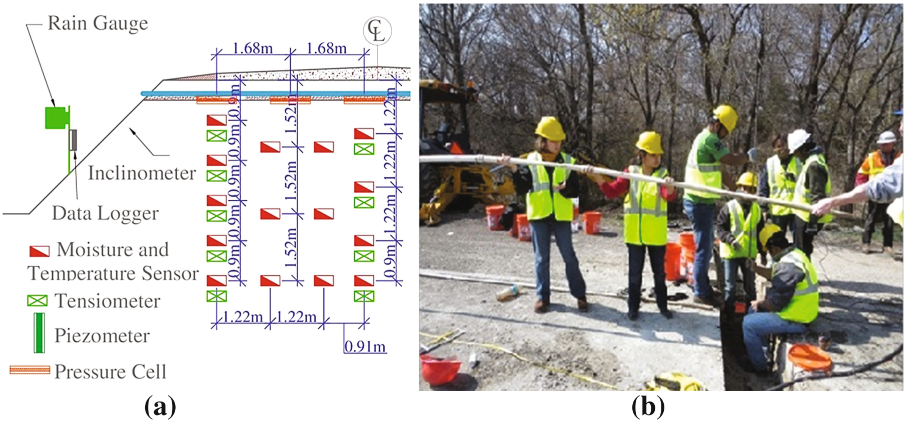


Fig. 2. (a) Instrumentation Plan, (b) Instrumentation at the site SH 342

4 Soil Properties

The geotechnical properties of soil samples collected from SH 342 during field instrumentation were obtained through laboratory testing. Upon investigation of the particle size distribution, the samples contained very fine subgrade soil. All samples were composed of over 85% clay. The liquid limits ranged between 50% and 64%, while plasticity ranged between 28% and 42%. As specified by the Unified Soil Classification System (USCS), sieve analysis and Atterberg limits results indicated that the soil samples were high-plastic clay (CH). Specific gravity ranged between 2.68 and 2.72, with an average of 2.70. Optimum moisture content was determined to be 22%, and dry density at the optimum moisture content was found to be 18.9 kN/m^3.

5 Moisture Variation in Subgrade by Sensor

Subgrade moisture sensor data was recorded along the center and edge of pavement at SH 342 from March 2014 to April 2016. Moisture content variation was determined through analysis of the recorded moisture data. The following discussion presents interpretable results obtained from the center borehole, which were representative of data obtained from remaining sensors at the edge.

To obtain moisture data, sensors were installed in the center borehole at depths of 1.2 m (4 ft.), 2.4 m (8 ft.), 3.6 m (12 ft.), and 4.5 m (15 ft.). Moisture variation in the center borehole is shown in Fig. 3. While rainfall was immediately detected by the shallower sensors, the deepest sensor (TM 15, located at 4.5 m [15 ft.] depth) observed no detectable moisture content changes in response to rainfall. TM 15 recorded an

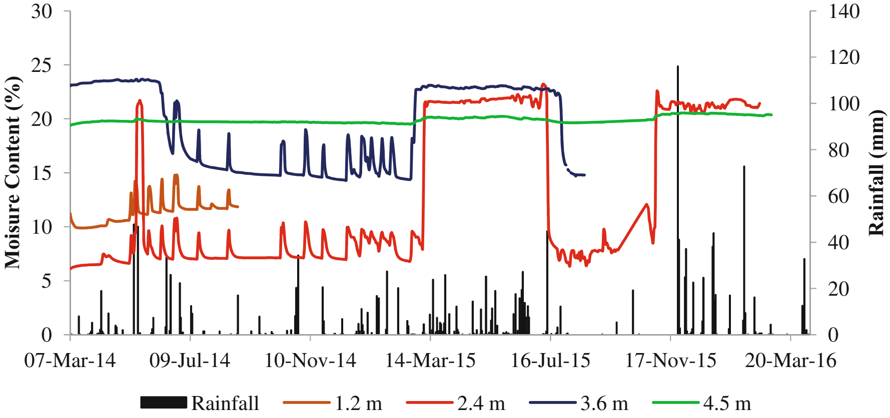


Fig. 3. Moisture variation across center borehole (BH-5)

average soil moisture content of 19%, which corresponded to the point of saturation at the depth of 4.5 m (15 ft.). Moisture contents stabilized to equilibrium moisture contents at all depths. Respectively, equilibrium moisture contents for TM 4, TM 8, and TM 12 were 11%, 6%, and 15%. Moisture readings immediately following rainfall events rose 4% to 15% in amplitude, with increases limited to the temporary saturation point at the respective depths. Shallow sensors experienced greater increases in moisture content. After draining, moisture contents returned to equilibrium. Temporary changes in moisture content are important to study in the case of expansive clay soils. Brief fluctuations in moisture can significantly affect the volumetric deformation of the soil.

The monthly variation in total rainfall and maximum moisture content recorded by the sensors is shown in Fig. 4. At shallow depths, the rises and falls in maximum moisture content mirrored the behavior of rainfall. That is, when precipitation

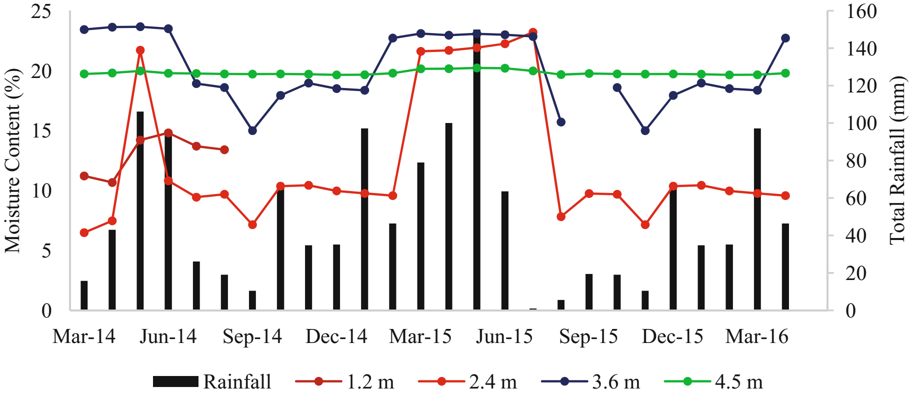


Fig. 4. Maximum moisture variation across center borehole (BH-5)

experienced a decline during the dry season, maximum moisture content also dropped. For example, the dry periods from May to September 2014 and May to August 2015 saw sensors at 2.4 m (8 ft.) experience a net decrease of up to 15% in recorded moisture content. Conversely, rising levels of rainfall during the wet season produced increasing magnitudes of moisture content. For instance, the accumulation of nearly 91 mm (3.6 in.) of rainfall between March and May 2014 returned a net increase of 15% in moisture content. Due to the expansive nature of clayey subgrade, the pavement at SH 342 could be expected to deform seasonally in response to the rises and falls in moisture content.

While subgrade moisture content varies in response to rainfall events, moisture content may also vary due to seasonal effects. Seasonal contributions to moisture variation can depend on the soil compaction, soil type, ground water table, and initial moisture content. Consequently, some locations observe seasonal variations while others do not. After five years of monitoring in Ohio, Heydinger (2003) reported that a seasonal effect on moisture variation existed at the study site. In Texas, Manosuthikij (2008) found a seasonal contribution to moisture variation at sites in Fort Worth and Houston, whereas the study site in San Antonio did not experience a seasonal trend. To ascertain if a seasonal pattern existed at SH 342, electronic resistivity imaging (ERI) was performed across the grass slope adjacent to the pavement. This method of geophysical testing provides a continuous picture of moisture content distribution. Comparison of ERI results obtained from a monthly basis could help conclude whether moisture variation at the site underwent seasonal changes.

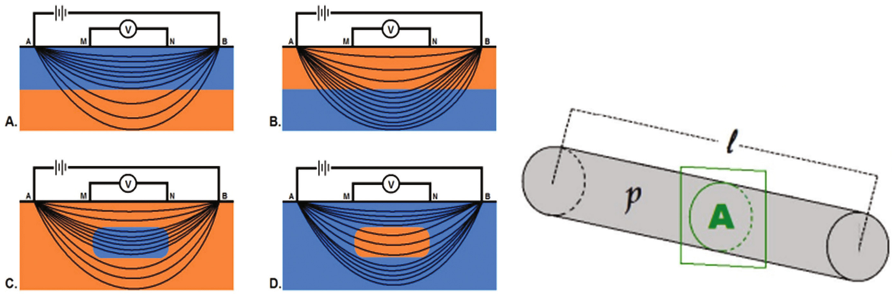
6 Theory of ERI

ERI is an active geophysical method which measures the electric potential differences at specific locations after injecting a controlled electric current at other locations. By controlling the current injected in an entirely homogeneous half-space, a resistivity value can be calculated for the subsurface by measuring the resulting electric potential difference. Figure 5 illustrates the concept of subsurface electric current flow and the influence of subsurface heterogeneities.

The ERI method follows Ohm's law in that resulting potential differences are measured by transferring artificially generated currents to the soil. The electrical resistivity depends on several factors of the subsurface condition. Main factors influencing resistivity include the size, shape, arrangement, mineralogy, voids distribution, porosity, connectivity between the particles, degree of saturation, concentration of soluble minerals, and temperature of the subsurface soil.

For a simple soil body, the resistivity ρ (ohm-m) is defined as:

$$\rho = \mathrm{R}(\mathrm{A}/\mathrm{L}) \tag{1}$$



(a) (b)

Fig. 5. (a) Variations in subsurface electric current density (Aizebeokhai 2010) (b) Relation between resistance and resistivity (Tabbagh et al. 2000)

Where, R is the electrical resistance, L is the length of the cylinder (m) and A is the cross-sectional area (m^2). The electrical resistance of a cylindrical body is defined by Ohm's law:

$$R = V/I \tag{2}$$

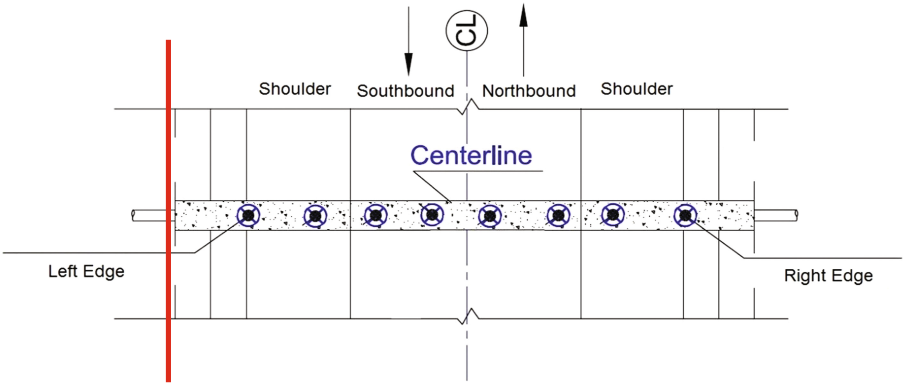
Where, V is the potential difference measure in Volt, and I is the current in Ampere.

7 Geophysical Testing by Resistivity

While moisture sensors returned distinct moisture content recordings, further information regarding moisture variation was desired. Thus, geophysical testing in the form of resistivity imaging was utilized. Geophysical testing provides a continuous picture of the moisture variation beneath the pavement. Since sensors were not installed beneath the grass slope adjacent to the pavement, geophysical testing allowed for determination of the moisture variation beneath the slope beside the pavement.

Instrumentation required for ERI included a super-sting R8/IP resistivity meter manufactured by Advanced Geosciences Institute (AGI) and a switch box with a 12-volt battery for power supply. RI testing was conducted with 28 electrodes placed at 0.9 m (3 ft.) intervals, resulting in a test line of 24.7 m (81 ft.). Improved resolution in the horizontal and vertical directions was obtained by employing a dipole-dipole array (Manzur et al. 2016). The schematic of the layout of testing and site photos are presented in Fig. 6. The collected data were analyzed in the Earth Imager 2D software (AGI 2004), which uses a forward modeling technique to calculate apparent resistivity values from the field data. The software uses non-linear least-squares optimization technique to yield the final output as 2D resistivity image of the subsurface.

(a)

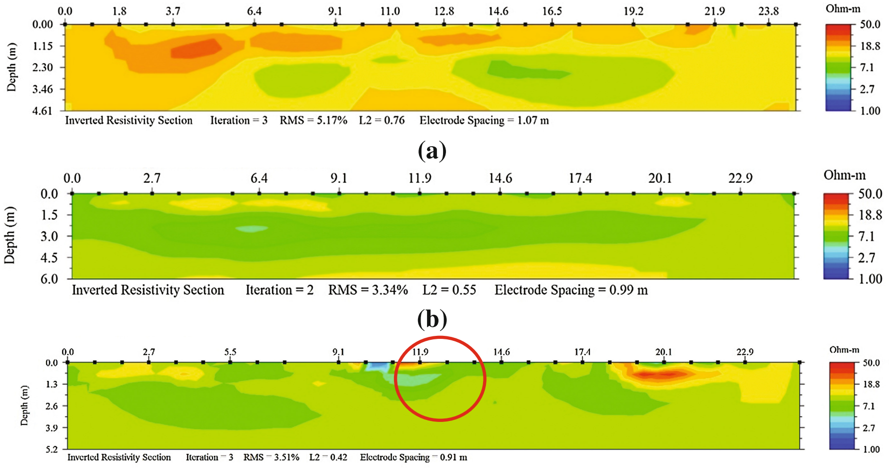


(b)

Fig. 6. (a) Field setup for resistivity (b) schematic at slope of pavement

8 Moisture Variation in Subgrade by Resistivity

ERI provided a continuous picture of the moisture content distribution at different levels and locations of the subgrade soil. An inverse relationship between resistivity and saturation was used to interpret the qualitative data presented in Fig. 7. High readings of resistivity corresponded to lower moisture contents, while low readings of resistivity translated to higher moisture contents. The scale from red to blue in Fig. 7 indicated levels of high and low resistivity values, respectively. ERI performed during the dry season (from May to October) returned high resistivity readings and produced the image depicting moisture content distribution shown in Fig. 7(a). Conversely, ERI testing during the wet season (from November to April) produced Fig. 7(b) with low resistivity values. ERI conducted immediately following a rainfall event revealed the



(a)

(b)

(c)

Fig. 7. Resistivity variation in (a) dry period, (b) wet period, and (c) moisture intrusion through edge after rainfall

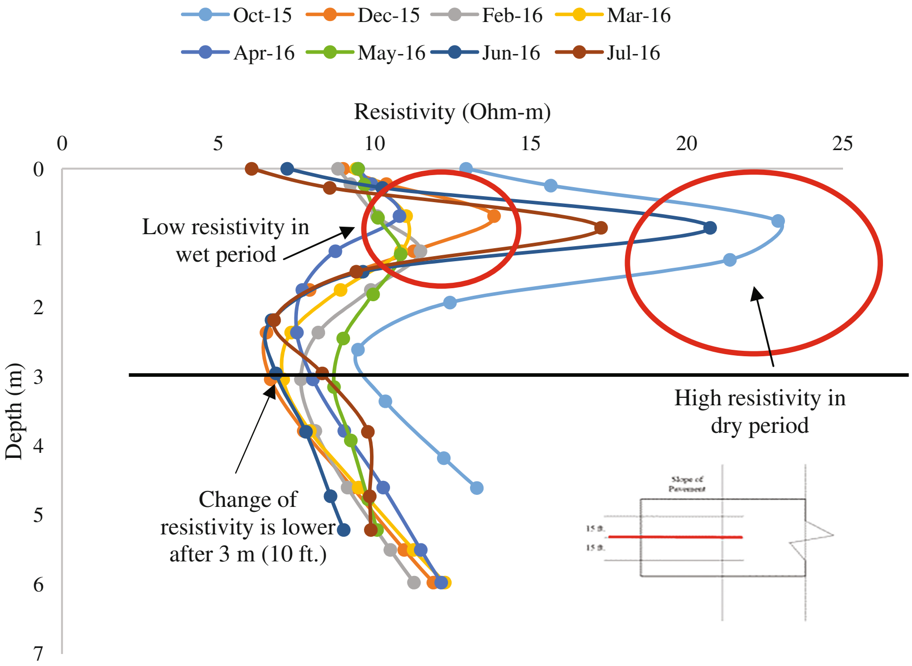


Fig. 8. Variation of resistivity across depth in central section

presence of cracks or holes in the pavement. An apparent edge crack appeared in May 2016, as seen from the region of low resistivity developing in Fig. 7(c). Low resistivity values where higher values were previously recorded can indicate the presence of cracks, potentially serving to determine which areas of pavement need the most maintenance.

Results of resistivity variation across depth produced the plot shown in Fig. 8. Resistivity values ranged between 7 to 13 ohm-m between the months of November and April, translating to high readings of moisture content. Thus, the period was identified as the wet season. In contrast, the period between May and October returned resistivity values as high as 23 ohm-m, corresponding to the dry season. Geophysical testing revealed the presence of a seasonal trend. Given the relationship between resistivity and moisture content, a seasonal effect on resistivity suggested that a seasonal effect on moisture content variation also existed. Below a depth of 3 m (10 ft.), resistivity did not undergo significant fluctuations. This finding corroborated findings obtained from other studies conducted in the same area, which identified 3–3.66 m (10–12 ft.) as the depth of the active zone (Khan et al. 2015).

9 Deformation Analysis

Both temporal and seasonal changes in subgrade moisture content induce volumetric deformation in expansive clay soils. Pavement performance can be negatively affected as a response to subgrade deformation. To monitor the pavement deformation at SH 342, monthly inclinometer results were obtained over a period of two years and are presented in Fig. 9.

The inclinometer profile showed that swelling and shrinking of the expansive subgrade caused up to 38 mm (1.5 in.) of vertical movement across the pavement. A cyclical trend in deformation was readily observed by plotting pavement deformation

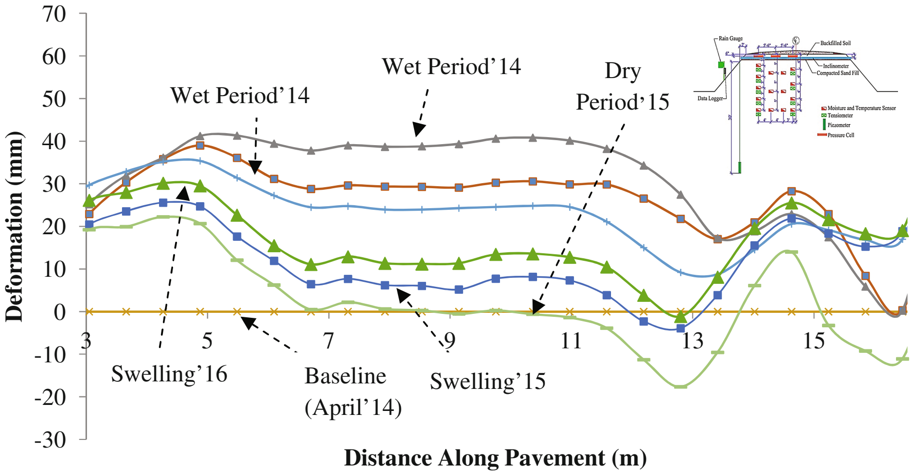


Fig. 9. Variation of deformation along distance in central section

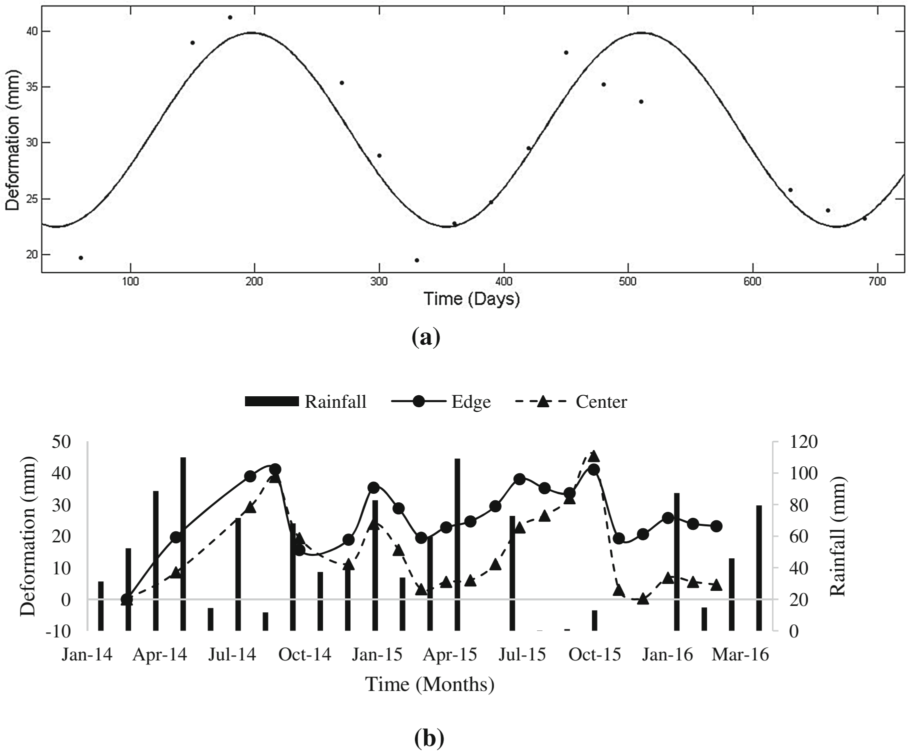


Fig. 10. (a) Seasonal trend in deformation, (b) movement in response of rainfall events

of edge over time (Fig. 10a). Seasonal effects were further examined by including precipitation in a plot of deformation over time (Fig. 10b). Changes in pavement elevation were seen to correlate with rainfall events. For example, the center of the pavement experienced 38 mm (1.5 in.) of swelling as the result of 114 mm (4.5 in.) of rainfall during the wet season from March to May 2014. After the summer of 2014, during which precipitation levels declined, the pavement dropped by almost 25 mm (1 in.). Another pattern of swelling and shrinkage was observed in October 2015, when the pavement dropped 38 mm (1.5 in.) in response to a decrease in rainfall. However, pavement elevation rose again as precipitation levels increased upon the arrival of the wet season. Pavement deformation mirrored rainfall patterns which followed a seasonal trend. Thus, pavement deformation was also concluded to adhere to a seasonal trend.

10 Conclusions

The current study was conducted to determine the variation in subgrade moisture content resulting from seasonal effects and rainfall events. A two-lane road identified as SH 342 in Dallas, Texas, USA was instrumented with moisture sensors to record moisture content and a rain gauge to record precipitation. Geophysical testing using electrical resistivity imaging was conducted to determine the presence of a seasonal effect on subgrade moisture variation. Pavement deformation was recorded using a horizontal inclinometer installed at the site. The observed results are summarized below.

- Laboratory testing indicated that subgrade soil at SH 342 was made of highly plastic clay.
- Moisture sensors installed in the pavement captured temporary net increases of 4% to 15% moisture content following rainfall events.
- Electrical resistivity imaging performed across the grass slope adjacent to the pavement captured the presence of a seasonal effect on moisture variation. The detection of water intrusion also revealed the development of cracks in the pavement.
- Subgrade shrinkage and swelling was observed to follow a seasonal trend. Wet periods (from November to April) caused a rise in pavement elevation, while dry periods (from May to October) resulted in a drop. Up to 38 mm (1.5 in.) of deformation was recorded.

The observation of moisture variation beneath pavement can be linked to deformation behavior of the pavement built on expansive subgrade. A complete deformation model in response to the moisture variation can be effective to predict the pavement performance. It will ultimately lead to better pavement preservation technique.

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