Using Soil-Moisture Active Passive Satellite Data to Evaluate the Performance of Transportation Infrastructure Foundations - A Feasibility Study

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ABSTRACT

NASA's Soil Moisture Active Passive (SMAP) satellite measures the near-surface soil moisture (0-5 cm depth) everywhere on Earth's surface. It produces global soil moisture maps [in m^3/m^3] at the 9 km spatial and 24-hour temporal resolution. SMAP launched in January 2015 and has been collecting observations for a three-year period (2015-2018), with a 2-3 day temporal resolution. SMAP's global soil moisture maps can be used to improve weather forecasts, increase our understanding of the water and carbon cycle, monitor droughts, and predict timing and location of floods. The radar observations could be superimposed on a map of transportation infrastructures to evaluate their performance under excessive water intrusion. This study included a analysis to evaluate the moisture-induced performance of transportation infrastructure foundations and pavement layers. The SMAP data were extracted within the study area before and during a major weather event. Other remote sensing products that monitor precipitation and groundwater changes were also employed to determine the level of infrastructure inundation. The results of this evaluation process suggest the feasibility of using SMAP data to investigate the performance of transportation infrastructure foundation layers under inundated conditions.

INTRODUCTION

One of the most important components of our transportation infrastructure is the road network. Pavement structures are the main elements of road assets that need to be maintained, rehabilitated and reconstructed. The performance of pavement structure is significantly affected by environmental factors such as extreme hot and cold temperatures, and water intrusion above and below the pavement resulting from heavy precipitation events. Performance assessment of pavements is thus of major interest to highway agencies and stakeholders in coastal regions during extreme weather events.

The road pavement system is in continuous interaction with its environment. Different environmental factors are being considered while designing pavement systems. The Mechanistic Empirical Pavement Design Guide (MEPDG) incorporates the environmental factors as an Enhanced Integrated Climate Model (EICM). The EICM simulates the impact of environmental conditions on pavement characteristics and properties. Initial EICM was developed by Federal Highway Administration (FHWA) and later was implemented in the pavement design guide (Witczak et al, 2004). One of the major components of environmental impacts of pavement structures is the moisture variation in terms of either precipitation or flooding during a storm surge or other extreme weather events. The primary reason to study the moisture variation in pavement systems is the effect of moisture on strength of geomaterial layers in terms of resilient modulus (MR) and stiffness. Increased moisture content in compacted geomaterial layers result in declining strength as the water fill in the voids in materials and decrease the interlocking of soil particles (Sotelo et al. 2014, Mazari et al. 2015, Nazarian et al. 2015). An excessive amount of water in pavement structure may result in a reduction of structural performance and loss of load bearing capacity of the pavement system. This scenario is more likely to happen during or after extreme events such as flash floods, sea level rise and storm surges. Evaluating the short- and long-term structural capacity of pavement structure during and after weather events is of particular interest for decision makers when assessing the resilience of transportation infrastructures.

Water may enter the pavement system from above due to inundation and below due to capillary rise within the subsurface soil layers. Extreme weather events could vastly contribute to the damage proneness of pavement layers, and more specifically foundation soil layers. This was observed by the Louisiana Department of Transportation due to Hurricane Katrina (Zhang et al., 2008). The International Panel of Climate Change (IPCC) projects a sea-level rise of about 60 cm due to melting of the ice caps (IPCC, 2007). This projection indicates that pavement systems in coastal areas can be fully inundated due to high tides and sea level rise. Structural performance and load bearing capacity of the pavement system are affected by the reduced strength of subgrade soil due to the presence of water. However, these effects are not visible and may lead to the failure of road infrastructure under traffic loads. Evaluating the structural performance of pavements under flooded conditions could help to prevent the structural failure.

The evaluation of post-event condition of roadways and flooded transportation infrastructure have been limited to few recent studies such as hurricane Katrina in Louisiana (Chen and Zhang, 2011) and hurricane Sandy in New York and New Jersey (Kaufman et al, 2012). The impact of such events is even more visible on low-volume and gravel roads. The local highway agencies need a decision support system to evaluate the performance of affected infrastructure and decide for remedial and repair strategies.

The scope of this paper is to utilize remote sensing data to estimate moisture levels in the pavement infrastructures and strength of the roads. It is noteworthy that FHWA initiated an international effort to address the vulnerability of roadway structure after flooding (FHWA, 2012). The scope of this paper aligns with the FHWA Flooded Pavement Assessment and considers the following objectives (FHWA, 2012):

- Identify when emergency or other vehicles can safely be allowed on roads of different types, and on different soils, that have been or are flooded to various degrees (i.e. depths and durations).
- Determine the best times to allow heavy maintenance equipment on the roads (e.g. in terms of the tradeoff between the user costs of road closure versus costs of increased road damage).

- Determine the effects of floods on long-term pavement performance.
- Develop guidelines for use by highway agencies on how to assess flooded pavements for both short term and long-term impacts.

That research was planned to be performed in two phases. Phase I included an extensive review of methods, equipment, and instrumentation that could be used to evaluate the short- and long-term structural capacity of flooded pavements. The outcomes of Phase I were implemented in the work plan for Phase II of the study to propose the procedures, methods, and algorithms to evaluate the conditions of pavement structures under flooding and inundation events. The analytical procedures and the decision support system developed as a part of FHWA study could help the coastal communities to predict the optimum time to resume the transportation infrastructure operation (FHWA, 2012).

Satellite data and remote sensing products have served as a valuable source of information regarding the condition of surface earth layers at several spatial and temporal resolutions since the 1970's (Schowengerdt, 2006). Combining these sources of data with the knowledge of pavement structural performance under various environmental conditions could be an alternative methodology in evaluating the resilience of transportation infrastructure network. The following sections include more details regarding the impact of moisture variation on the strength of pavement foundation layers and the integration of satellite data in that evaluation process.

METHODOLOGY

According to the Mechanistic-Empirical Pavement Design Guide (MEPDG), the effects of the environmental factors on the Resilient Modulus (MR) of pavement structures can be evaluated using an environmental factor as follows:

$$MR = F_{env} \times MR_{opt} \tag{1}$$

where F_{env} is the composite environmental adjustment factor and MR_{opt} is the resilient modulus at optimum conditions and at any stress level. Witczak et al. (2000), as part of the development of the MEPDG, proposed the following equation:

$$\log(F_{env}) = log\left(\frac{M_R}{M_{Ropt}}\right) = a + \frac{b-a}{1+e^{\left(ln\frac{-b}{a}+k_m \times \left(S-S_{opt}\right)\right)}} \tag{2}$$

where MR = modulus at a degree of saturation S; MR_{opt} = modulus at the maximum dry density and optimum moisture content; S_{opt}= degree of saturation (in decimal) at the maximum dry density and optimum moisture content; a = minimum of $log(MR/MR_{opt})$ (-0.3123 and -0.5934 for coarse- and fine-grained materials, respectively); b = maximum of $log(MR/MR_{opt})$ (0.3010 and 0.3979 for coarse- and fine-grained materials, respectively); k_m = regression parameter (6.8157 and 6.1324 for coarse- and fine-grained materials, respectively). Cary and Zapata (2010) further studied the impact of moisture variation and proposed a more specific form of Eq. 2 by incorporating additional geomaterial properties including the percent finer than No. 200 sieve (w, in decimals) and plasticity index of the geomaterials (PI, in percent) as follows:

$$\log(F_{env}) = (\alpha + \beta \times e^{-wPI})^{-1} + \frac{(\delta+\gamma\times wPI^{0.5})-(\alpha+\beta\times e^{-wPI})^{-1}}{1+e^{\left(ln\left(\frac{-(\delta+\gamma\times wPI^{0.5})}{(\alpha+\beta\times e^{-wPI})^{-1}}\right)+(\rho+\omega\times e^{-wPI})^{0.5}\times\left(\frac{S-S_{opt}}{100}\right)\right)}} \qquad (3)$$

where $\alpha = -0.600$, $\beta = -1.87194$, $\delta = 0.800$, $\gamma = 0.080$, $\rho = 11.96518$, and $\omega = -10.19111$. Their equation appears to be empirical and requires the determination of resilient moduli at optimum conditions. Toward development of modulus-moisture equations, some other studies such as Oh and Fernando (2011), Siekmeier (2011) and Mohammad et al (2002) reported the modulus as a function of soil suction, moisture level, and stress conditions. Those equations are based on the MEPDG guidelines and account for principles of unsaturated soil mechanics.

In order to further simplify Eq. 3, Nazarian et al. (2015) suggested that assuming a *wPI*=0 in Eq. 3 could represent a wide range of geomaterials. Replacing all other constants in Eq. 3, the following equation could be employed in estimating the environmental factor:

$$\log \mathrm{F}_{env} = \left[(-0.40535) + \frac{1.20693}{1+\mathrm{e}^{\left[0.68184+1.33194\times(\frac{\mathrm{S}-\mathrm{S}_{\mathrm{opt}}}{100}\right]}}\right] \qquad (4)$$

The degree of saturation (S) can be estimated using the following equation:

$$S = G_s \frac{\omega}{e} \qquad (5)$$

where S is degree of saturation, G_s is specific gravity, ω is volumetric moisture content, and e is void ratio. The following sections include a discussion of extracting soil moisture (ω) during a major extreme event using large-scale satellite data and exploring the feasibility of applying those environmental factors to evaluate the strength of road foundation layers.

Remote Sensing Products

Four remote sensing products were used in the hydrologic analysis of this study to obtain estimates of near-surface soil moisture, water table depth, precipitation, and surface inundation during the period of analysis. Near-surface soil moisture estimates (0-5 cm depth) were obtained using NASA's Soil Moisture Active Passive (SMAP) measurements (Panciera et al., 2014). The SMAP satellite was launched in January 2015 and produces global volumetric soil moisture maps [in cm^3/cm^3] with an unbiased root mean squared error no greater than $0.04\ cm^3/cm^3$ (Kerr et al., 2010; Entekhabi et al., 2014). This work used the SMAP Level-3 daily global product at a 9 km spatial resolution.

NASA's Gravity Recovery and Climate Experiment (GRACE) was used to estimate water table depth. The GRACE product provides groundwater storage in percentage of storage filled, for which 100 percent storage indicates the subsurface storage is filled. GRACE has been previously used to assess regional flood potential (Reager et al., 2015) and model flood inundation (Lucey et al., 2017). The GRACE satellite takes measurements at a 0.125-degree spatial resolution on a 7-day time interval. The GRACE sensor also provides an estimate of percent soil moisture or percent of subsurface pore-space filled with water within the top 5 cm. GRACE observations in this study were extracted for the period of July 31, 2017, to August 28, 2017, which was the same period that hurricane Harvey struck the coast of Texas in the United States.

The hourly North American Land Data Assimilation Product (NLDAS-2) was used to estimate total precipitation during the study period. NLDAS-2 is a gridded product that uses Stage II/IV gauge observations of hourly precipitation forcing to derive a 1/8 degree. To aggregate to daily precipitation total (from mmhr^{-1}), total hourly precipitation was used. Kwak et al. (2014) developed a technique to determine flood risk and inundation using Moderate Resolution Imaging Spectrometer (MODIS), and a digital elevation model. This method is considered a feasible approach for detection of instant inundation. Various MODIS daily optical images at a spatial resolution, depending on the wavelength band, including 250, 500, and 1000 m. Surface inundation and flood risk can be calibrated using observations provided by National Oceanic and Atmospheric Administration's National Weather Service River Observations and Forecast database (NOAA-NWS).

Reichle et al. (2018) recently released the data product for level 4 surface and root zone soil moisture data of the SMAP project. That data estimates the soil surface conditions based on a combination of SMAP observations and the NASA Goddard Earth Observing System, Version 5 (GEOS-5) Land Data Assimilation System (LDAS). The impact of hurricane Harvey on the soil surface and root zone moisture conditions were evaluated using the later data set. Figure 1 shows the root zone volumetric moisture content before and after the hurricane. There is a significant change in volumetric soil moisture (from 0.28 m^3/m^3 before hurricane to 0.48 m^3/m^3 during the hurricane).

Figure 2 illustrates the volumetric surface soil moisture content (cm^3/cm^3) within the study area during the period of hurricane impact. The highlighted area on August 27 and September 01 represents the inundated regions due to Harvey. Some blocks of data are missing due to the resolution of the SMAP data as well as the uncertainty of data extraction and interpretation process. The surface soil moisture estimates the volumetric moisture content within the range of 0 – 5 cm from the top soil surface.

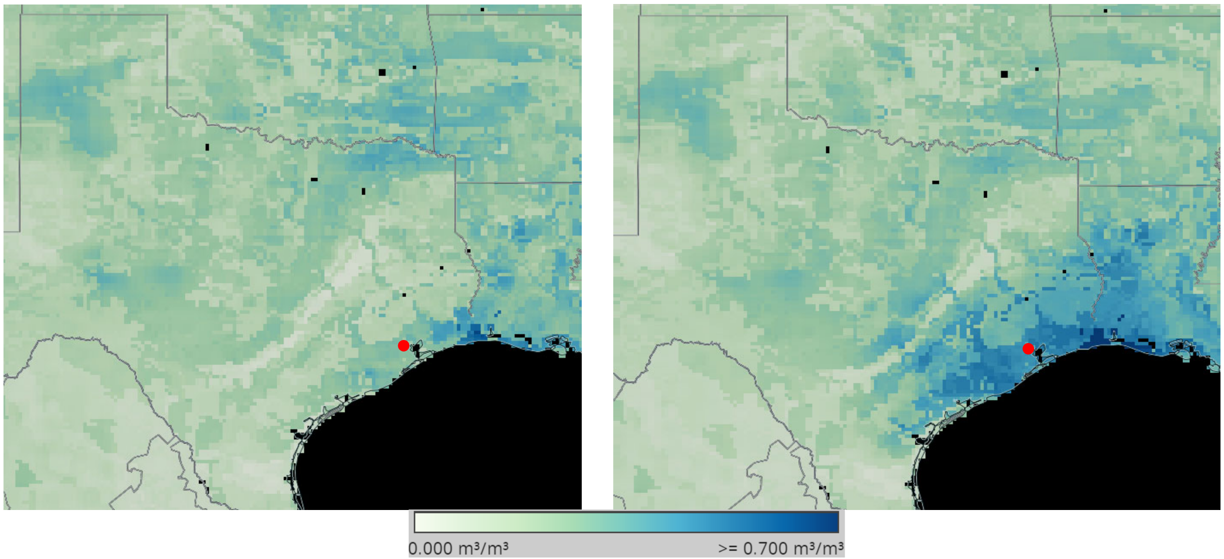

Figure 1 – Comparison of SMAP Root Zone Volumetric Soil Moisture (m^3/m^3) within the Coast of Texas before and during Hurricane Harvey.

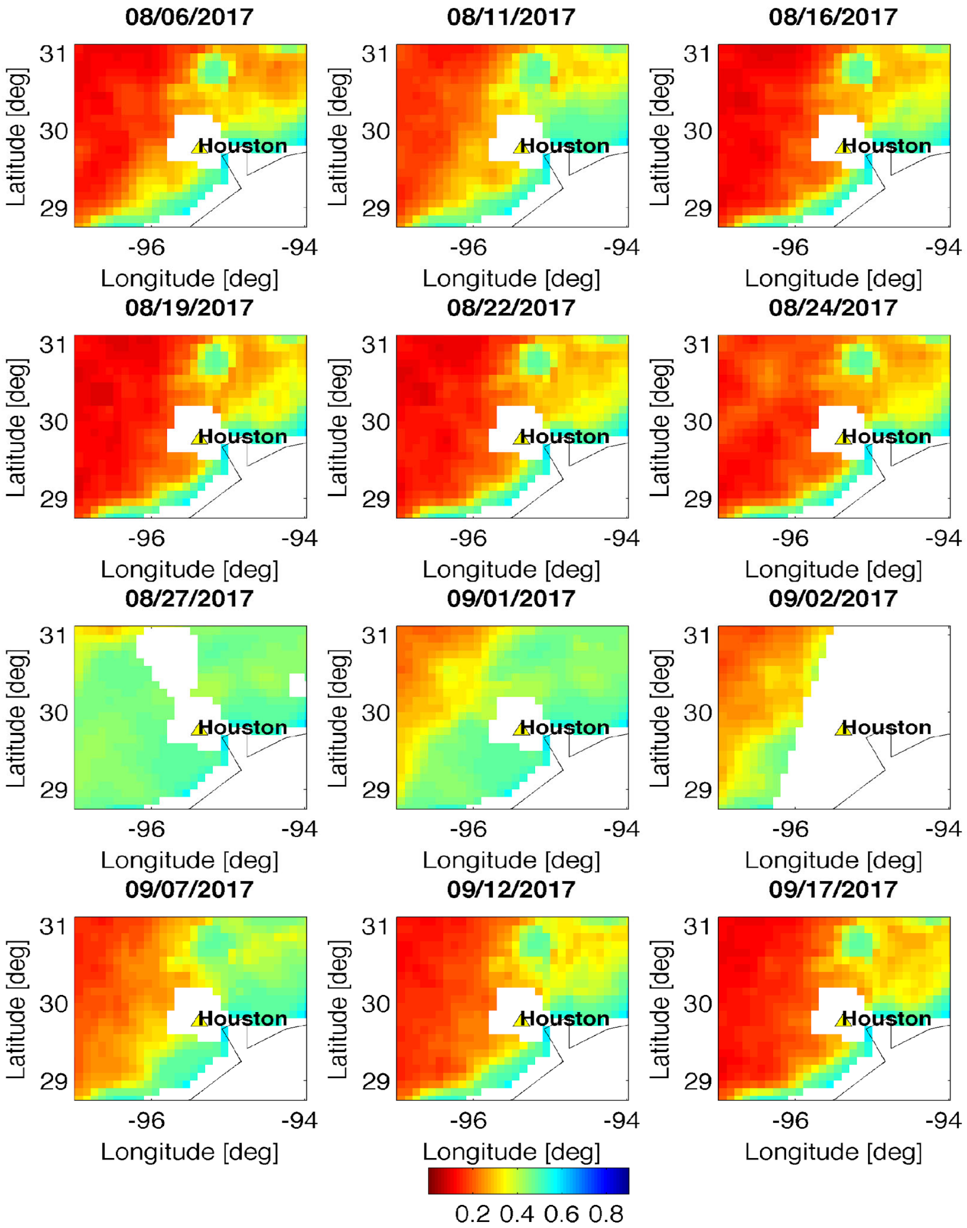

Figure 2. Variation of Volumetric Surface Moisture Content (cm^3/cm^3) throughout the Study Area during the Storm Surge.

In order to further investigate the feasibility of using SMAP data in evaluating the resilience of transportation infrastructures, the strength of road foundation was estimated using the SMAP soil moisture data. Figure 3a illustrates the variation of estimated soil degree of saturation before, during, and after the inundation period within the study area—variation includes standard deviation of all locations within our bounding box shown in Figure 2. As expected, there is a sudden increase in the saturation level upon the start of hurricane. Although due to the limited resolution of the satellite data in estimation of moisture content, the range of variability in the observations is rather high, the impact of inundation is clearly visible in this graph. In order to estimate the impact of such environmental factor on the stiffness of pavement foundation soil layers, Eq. 2 for both fine- and coarse-grained geomaterials were applied to the observed data. As indicated in Eq. 2, the environmental factor (F_{env}) represents the ratio of soil layer modulus with respect to optimum conditions (that is derived in the laboratory environment for each soil type).

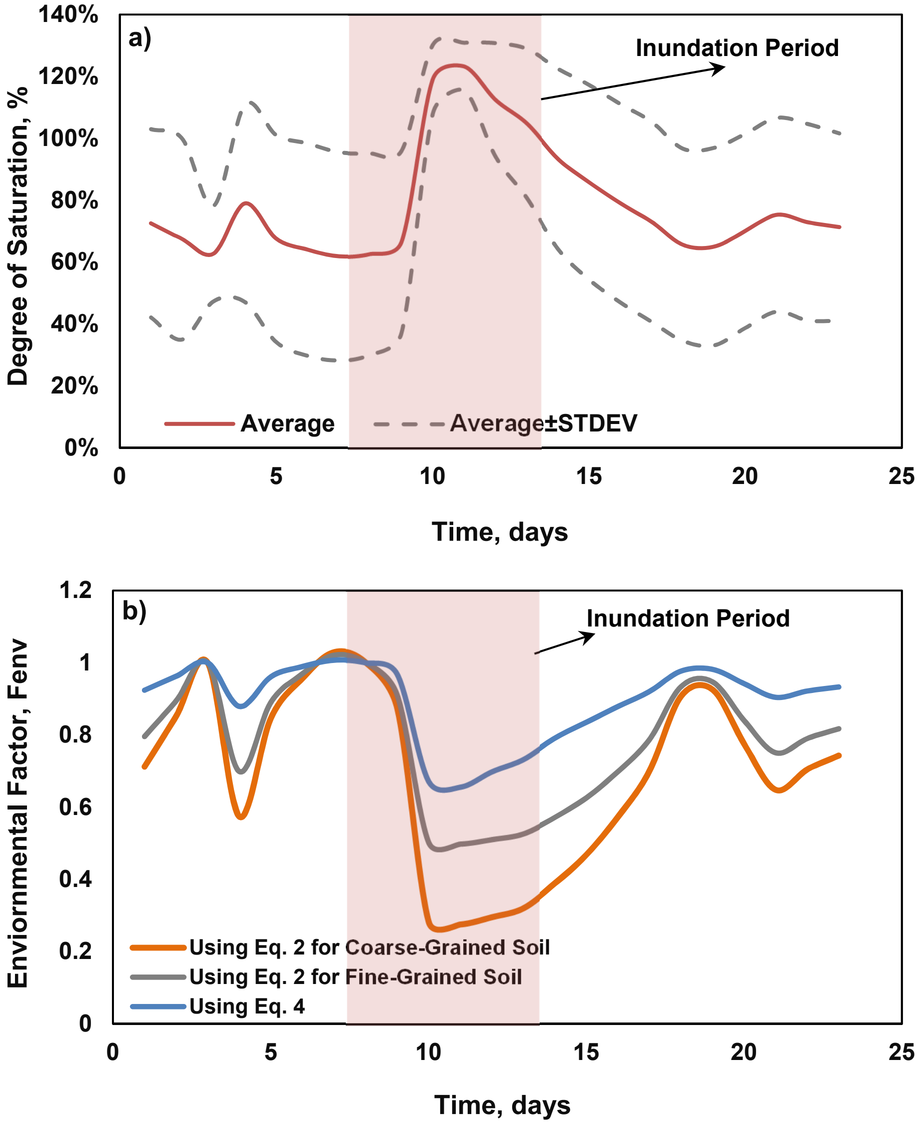

Figure 3. a) Variation of Soil Degree of Saturation based on Satellite Data, and b) Variation of Pavement Foundation Modulus for Different Soil Types before, during (red shaded region), and after Hurricane Harvey

The inundation period, caused by the hurricane flooding, resulted in a significant loss in the magnitude of environmental factor showing a drop in overall foundation strength in terms of modulus. The correlation between modulus and moisture has been extensively investigated in the literature (Khoury et al, 2010, Nazarian et al, 2014, Mazari et al. 2016). Even though the overall trend of variation in environmental factor is consistent between different curves in Figure 3b, the difference in these curves reflects the impact of soil type and grain-size on the moisture damage. It should be noted that the inundation period happened between the dates of August 24, 2017, through September 09, 2017 during the impact period of hurricane Harvey. The stiffness of geomaterial foundation layer could be impacted up to more than 60 percent compared to the optimum conditions (Nazarian et al. 2015). Such significant change in strength of soil layers would have a noticeable impact on the serviceability of road network during inundation period. Evaluating the strength of pavement structure after an extreme weather event could be a major rehabilitation or reconstruction requirement.

CONCLUSION

A series of remote sensing products and satellite data were employed to extract the soil moisture conditions during an extreme weather event. The feasibility of evaluating transportation infrastructure foundation using the satellite data was investigated through a case study. Impact of moisture variation on strength of geomaterial pavement layers were estimated using the experimental equations in the literature. Those models suggest that the stiffness of geomaterial layers declines when subjected to increased moisture levels, considering the impact of geomaterial type and grain size. A 40 percent increase in degree of saturation of geomaterial layer could potentially decrease the stiffness up to 70 percent. Such a decline in the strength of pavement foundation layers affects the resilience of road structure while recovering from an extreme flooding. More detailed analyses of satellite data and their application in evaluating the resilience of transportation infrastructure geomaterial layers is desirable for future studies.

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