Continuous Moisture Measurement during Pavement Foundation Construction

Research Team
- Mark Baker
- Soheil Nazarian

Research Panel
- Terry Beaudry
- Eddie Johnson
- Kevin Kliethermes, FHWA
- Deepak Maskey
- John Siekmeier, MnDOT
- Eyoab Zegeye Teshale
- Raul Velasquez

1

Objectives

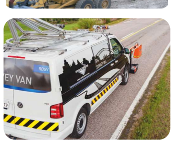
To demonstrate a prototype/breadboard of a device that can continuously measure moisture during pavement foundation construction (similar to Asphalt Rolling Density Meter)

https://www.geophysical.com/wp-content/uploads/2020/01/PaveScanRDM2_0_gallery4.jpg

2

Motivation

Build Earthwork right



Maintain it right
(not the scope of this project)

3

Dealing with Moisture Variation

- **Seasonal Moisture Content Variation**
  - Impacts modulus of soil and hence performance pavement foundation
- **Moisture Content during Construction**
  - Impacts compaction effort and quality of earthwork

4

Moisture Content during Construction

- **Should be measured**
  - just after spreading/mixing before compaction (process control)
  - At the time of modulus testing (acceptance process)
- **Data needs**
  - Primarily spatial even though time sensitive

5

Measurement of Moisture Content

Method	Measurement Principle
Nuclear Magnetic Resonance	Detection of magnetic moment (H)
Capacitance meters	Resonant frequency or impedance
Time-domain Reflectometry	Waveguide Impedance
Ground Penetrating Radar	Propagation of electromagnetic waves
Thermal Sensors	Heat conductivity or heat capacity
Conductivity Sensors	Electrical conductivity
Resistance Measurements	Resistance between two electrodes
Tensiometer Measurements	Pressure differential

6

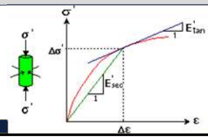
Moisture Content & Quality Management

Moisture Content

- Degree of Saturation
- Gravimetric MC
- Volumetric MC

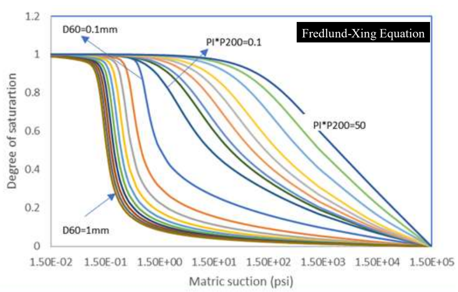
Quality Management

- Modulus
- Stiffness
- Strength



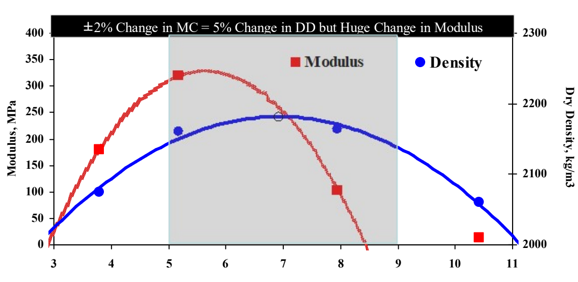
7

Gold Standard

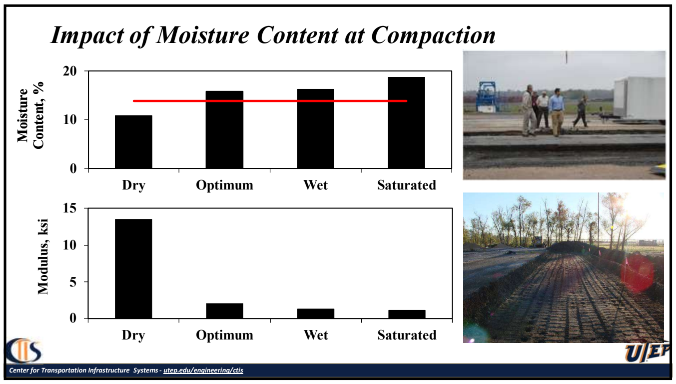


8

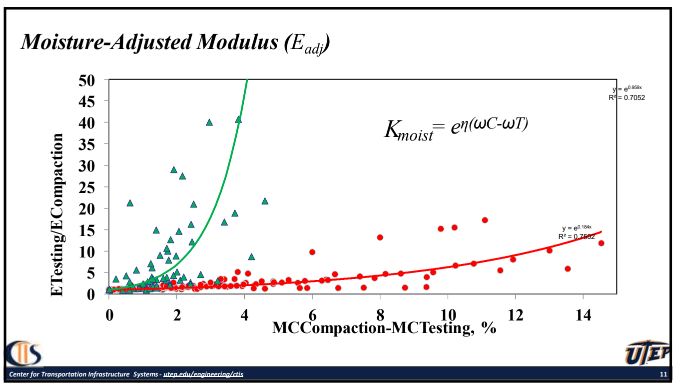
Impact of Initial Moisture Content



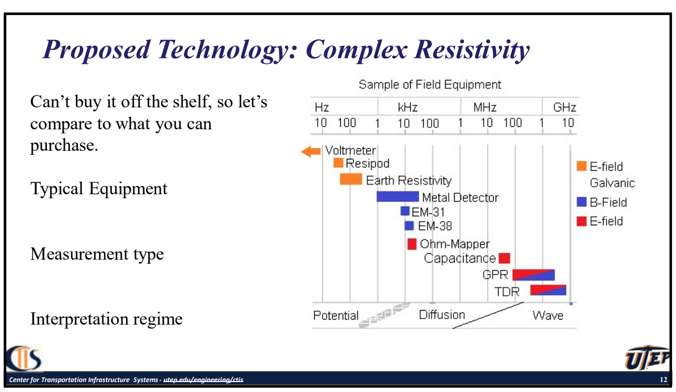
9


Impact of Moisture Content at Compaction
Moisture Content, %
20
10
0
Dry
Optimum
Wet
Saturated
Modulus, ksi
15
10
5
0
Dry
Optimum
Wet
Saturated
Center for Transportation Infrastructure Systems - utep.edu/engineering/ctis

10


Moisture-Adjusted Modulus (E_{adj})
$K_{moist} = e^{\eta(\omega C - \omega T)}$
ETesting/ECompaction
50
45
40
35
30
25
20
15
10
5
0
0
2
4
6
8
10
12
14
MCCompaction-MCTesting, %
R² = 0.7052
Center for Transportation Infrastructure Systems - utep.edu/engineering/ctis
11

11


Proposed Technology: Complex Resistivity
Can't buy it off the shelf, so let's compare to what you can purchase.
Typical Equipment
Measurement type
Interpretation regime
Sample of Field Equipment
Hz kHz MHz GHz
10 100 1 10 100 1 10 100 1 10
Voltmeter
Resipod
Earth Resistivity
Metal Detector
EM-31
EM-38
Ohm-Mapper
Capacitance
GPR
TDR
E-field Galvanic
B-Field
E-field
Potential
Diffusion
Wave
Center for Transportation Infrastructure Systems - utep.edu/engineering/ctis
12

12

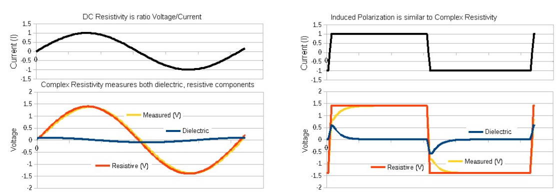
Hypotheses

- Dielectric permittivity and electrical conductivity of in-place geomaterials can be continuously measured and used to estimate moisture content and matric suction, which can then be displayed graphically as a moisture uniformity map.
- More extensive frequency/amplitude sweeps can be used in a slower point-analysis diagnostic mode.

13

Complex Resistivity vs. Traditional Resistivity

- Traditional is V/I, usually a square wave
- CR uses resistive/dielectric measurements:
  or square wave as Induced Polarization
- Also expect amplitude non-linearity in geo-materials



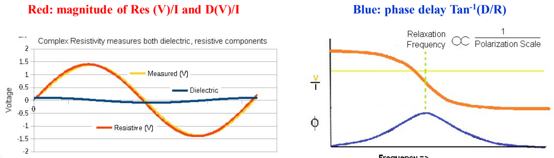
14

Complex Resistivity Concepts

- DC Resistivity gives some intermediate approximation
- Relaxation mechanisms multiple frequencies and scales
- Not all soils behave this nicely, avoid swelling clays
- Multiple polarization scales give multiple relaxation frequencies

Red: magnitude of Res (V)/I and D(V)/I

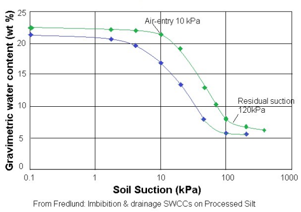
Blue: phase delay Tan^{-1}(D/R)

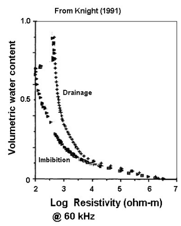


15

Resistivity Responds to Shape of Moisture

- Wetting/drying hysteresis in SWCC has analogous resistivity hysteresis in two unrelated samples with similar pore size.
- Resistivity relaxation at 60 kHz confirms base aggregate relaxation should be in 10-20 kHz range.





16

Test Set Up

- **Laboratory Best Results**
  - Use a 4-electrode (4E) resistivity array, using existing surface contacts with our custom electronics for phase measurement as a function of frequency and amplitude
- **Field Tests**
  - Combinations of multiple current/potential electrode pairs to image lateral/depth variations.
- **Less Accurate/Faster Continuous Measurement**
  - with electromagnetically coupled eddy-currents sensors
  - capacitive-coupled field injection technique

17

Advantages of Complex Resistivity

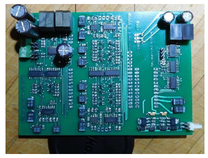
1. Unlike GPR and TDR, frequency range that is most sensitive to polarization at air/water interface can be determined for given pore size.
2. Full saturation is immediately recognizable by loss of polarization signature.
3. Volume of material investigated can be controlled by electrode geometry
4. Same measurements in both lab and field, simplifying material-specific calibration.

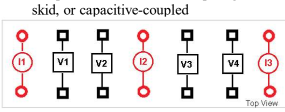
18

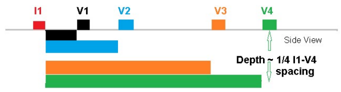
Instrumentation

An equatorial array geometry with multiple sources, giving both spatial variation and depth information with following components :

- Electronics and lab electrode systems
- Array of current and voltage dipoles on cart
- Number/spacing for areal resolution and depth needed
- Software for data collection and interpretation
- A dipole element could be slip-ring conductive wheel, skid, or capacitive-coupled







19

Field Operation

- **Similar to Asphalt Rolling Density Meter**
  - Map area of interest first
  - Site locations for a few calibration samples.
  - Convert field measurements to a continuous map of moisture content and its derivatives.
- **In two construction stages**
  - after material placement, watering, and mixing but before compaction
  - as part of quality control after compaction

20

Calibration

- **Routine**
  - Prepare several moisture-density specimens for Proctor tests to obtain
    - moisture-density curve
    - moisture-complex resistivity curve
    - degree of saturation-complex resistivity curve
    - modulus-complex resistivity curve
      - Using seismic testing
      - Using LWD as per AASHTO TP 123-01
- **More Advanced/Rigorous (future phases)**
  - Develop mixing laws that integrate matric suction pore geometries with CR and stiffness

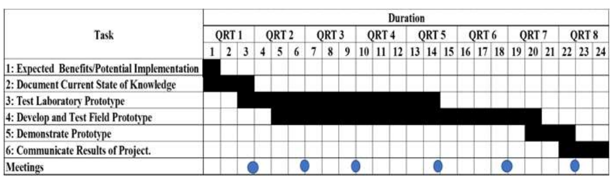
21

Calibration

- **Routine**
  - Prepare several moisture-density specimens for Proctor tests to obtain
    - moisture-density curve
    - moisture-complex resistivity curve
    - degree of saturation-complex resistivity curve
    - modulus-complex resistivity curve
      - Using seismic testing
      - Using LWD as per AASHTO TP 123-01
- **More Advanced/Rigorous (future phases)**
  - Develop mixing laws that integrate matric suction pore geometries with CR and stiffness

22

Tasks



23

Task 1: Initial Memorandum on Expected Research Benefits and Potential Implementation Steps

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

- **Deliverable(s)**
  - A memorandum containing expected research benefits and potential future implementation
- **Objective(s)**
  - provide an initial assessment of research benefits, a proposed methodology, and potential implementation steps with following contents:
    - Project Abstract and Objectives
    - Benefit to Taxpayers of the NRRA Member States\
    - Initial Projection of Expected Benefits
    - Expected Technical
    - Summary of Research Methodology
    - Research Implementation Steps
    - Quantification of Benefits of Project

24

Task 2: Document Current State of Knowledge

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

- **Deliverable(s)**
  - A memorandum containing current state of knowledge, case studies, an extended work plan, and an experimental test plan.
- **Objective(s)**
  - Document current state of knowledge related to field and laboratory methods for moisture content, degree of saturation and matric suction measurements.
  - Include several case studies that demonstrate the technical benefits and the cost savings resulting from more effective moisture monitoring
  - Provide a comprehensive and extended work plan for the smooth and timely execution including:
    - an experimental test plan to test up to ten different geomaterials (from home state of panel).
      - fine-grained soils (CL, CH, ML, or MH),
      - sandy materials (SW, SP, SM, or SC), and
      - coarse-grained materials (GW, GP, GM, or GC)

25

Task 3: Test Laboratory Prototype

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

- **Deliverable(s)**
  - A memorandum containing results of laboratory testing with prototype, a SWOT analysis of outcome, and a firm plan for field implementation.
- **Objective(s)**
  - Laboratory testing on each material using Proctor specimens
    - Conduction of gradation and Atterberg limits tests on soil samples
    - Development of following curves with duplicate tests at OMC, OMC±10% OMC, and OMC±20%OMC
      - moisture-density
      - moisture-CR (using the lab prototype)
      - moisture-modulus (using Free-free- resonant column tests),
      - moisture-LWD modulus (using AASHTO TP 123-01),
      - degree of saturation-CR.
  - Small-scale (24 in. high by 18 in. diameter) specimens
    - Test at least at five horizontal locations at each 6 in. lift
    - Compare moisture contents estimated by the prototype with those from oven drying
  - Statistical and process control analyses to develop a preliminary operational tolerance, overall precision and bias

26

Task 4: Develop and Test Field Prototype

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

- **Deliverable(s)**
  - A memorandum containing detail information about field prototype, results of the preliminary field testing, a SWOT analysis of the outcome, and a firm plan for field demonstration test plan.
- **Objective(s)**
  - Construct a (not ruggedized or professionally packaged) prototype field version of the tool
  - Field testing of the field prototype at local sites to
    - verify the applicability of the results from small-scale and laboratory tests carried out as part of Task 2, and
    - to establish variability of prototype under less controlled condition to delineate the equipment variability (established in Task 2) from site variability by
      - Repeating tests enumerated in Task 2 from geomaterials sampled from five points at windrow before compaction
      - Monitoring increase in density and modulus (with LWD) of the layer with the number of passes at two points
      - Carrying out continuous measurement with prototype along five lines three times
      - Mapping spatial variation of moisture measurements
      - Testing ten points at least three times with the device shortly before and after compaction along with NDG and LWD test at each point
      - Retrieve samples for moisture content from ten points to validate the device's results.
  - Analyze field data to ensure that the goals listed above are met.

27

Task 5: Demonstrate Prototype

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

- **Deliverable(s)**
  - A memorandum containing detail information about field demonstration, results of field demonstration, and documentation of strengths and shortcomings of device
- **Objective(s)**
  - Demonstrate to NRRA partners at a site either at MnROAD or any other location selected by the panel.
    - concurrently with one of annual meetings of NRRA
    - with an extensive presentation to obtain feedback for future modifications and improvements of the prototype.

28

Task 6: Communicate Results of Project

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

- **Deliverable(s)**
  - A project final report containing the results of all activities described in Tasks 2 through 6, and a recommendation for improvements and implementation
- **Objective(s)**
  - print-ready and web-publishable final report accompanied by:
    - An implementation plan for improving and deploying the products of the research;
    - A draft specification for compaction of geomaterials and supporting test methods in standard AASHTO format;
    - An informational webinar to members of NRRA

29

Thank You for Your Attention!!

30