Seismic and Electromagnetic Waves for Characterizing Fill and Backfill of Transmission Utilities

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Topics

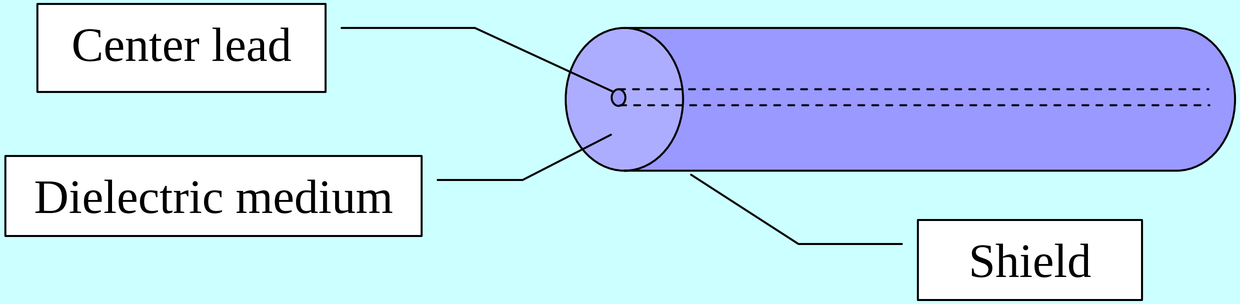
- Backfill Characteristics for Energy Trans. Lines
- TDR test for water content and dry density (Xiong Yu)
- TDR for accurate soil conductivity (resistivity) measurements (Teresa Dallinger)
- TDR test for soil type identification (Carlos Zambrano)
- Automating soil type identification (Pao-Tsung Huang and Sochan Jung)
- TDR probe for cross-hole measurement of soil modulus (Xiong Yu)
- Summary and conclusions

Backfill Characteristics for Energy Trans. Lines

- Energy Transmission Lines (ETLs) include:
  - Pipelines for oil, gasoline, gas, steam, etc.
  - Electrical power lines
- Frequently, these lines are buried
  - Protection from weather
  - Reactions to inertial forces from flowing liquids
  - Security
- Performance of the ETLs depend on
  - Soil backfill dry density & water content to control settlement
  - Soil Stiffness for pipes to control movement of the pipes
  - Soil Conductivity (Resistivity) to control corrosion for pipes, loss of energy power lines, even for above ground lines.

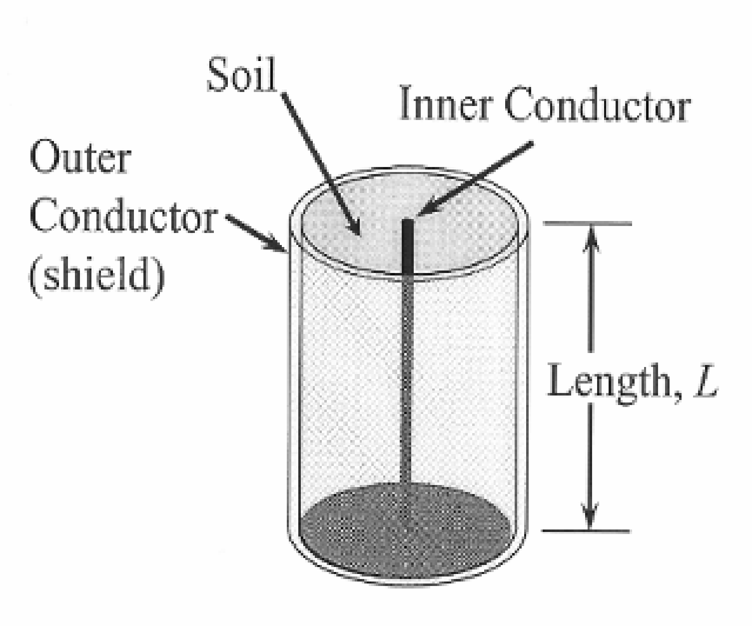
TDR Method

- One-Dimensional Electromagnetic Wave Propagation in a soil cable

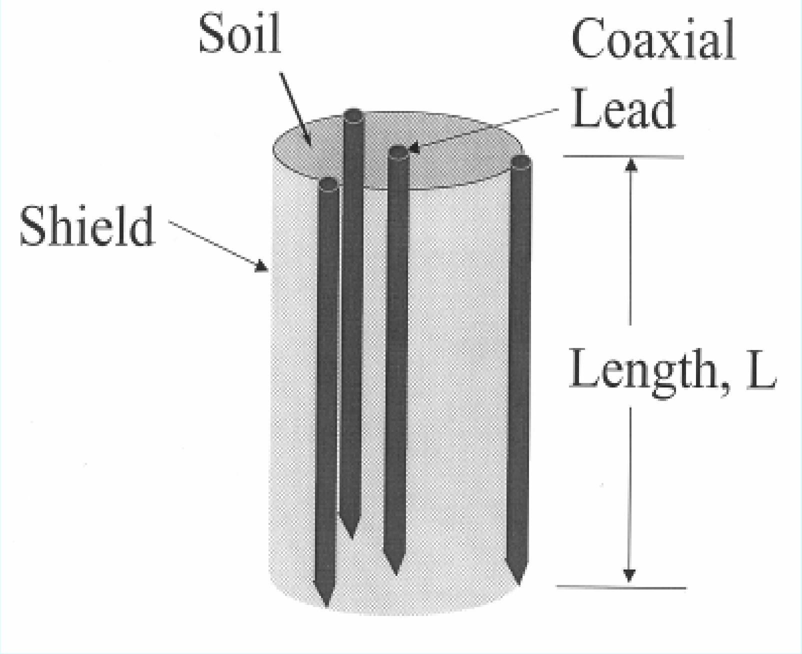


  - A step D.C. voltage is applied to one end of the cable
  - Voltage travel speed is related to the apparent dielectric constant, $\sqrt{K_a}$, of the “insulating” material between the center lead and the outer shield (similar to shear wave velocity related to shear modulus, $\sqrt{G}$)

Compaction Mold as a Soil Cable



Spikes Driven into Soil as a Soil Cable

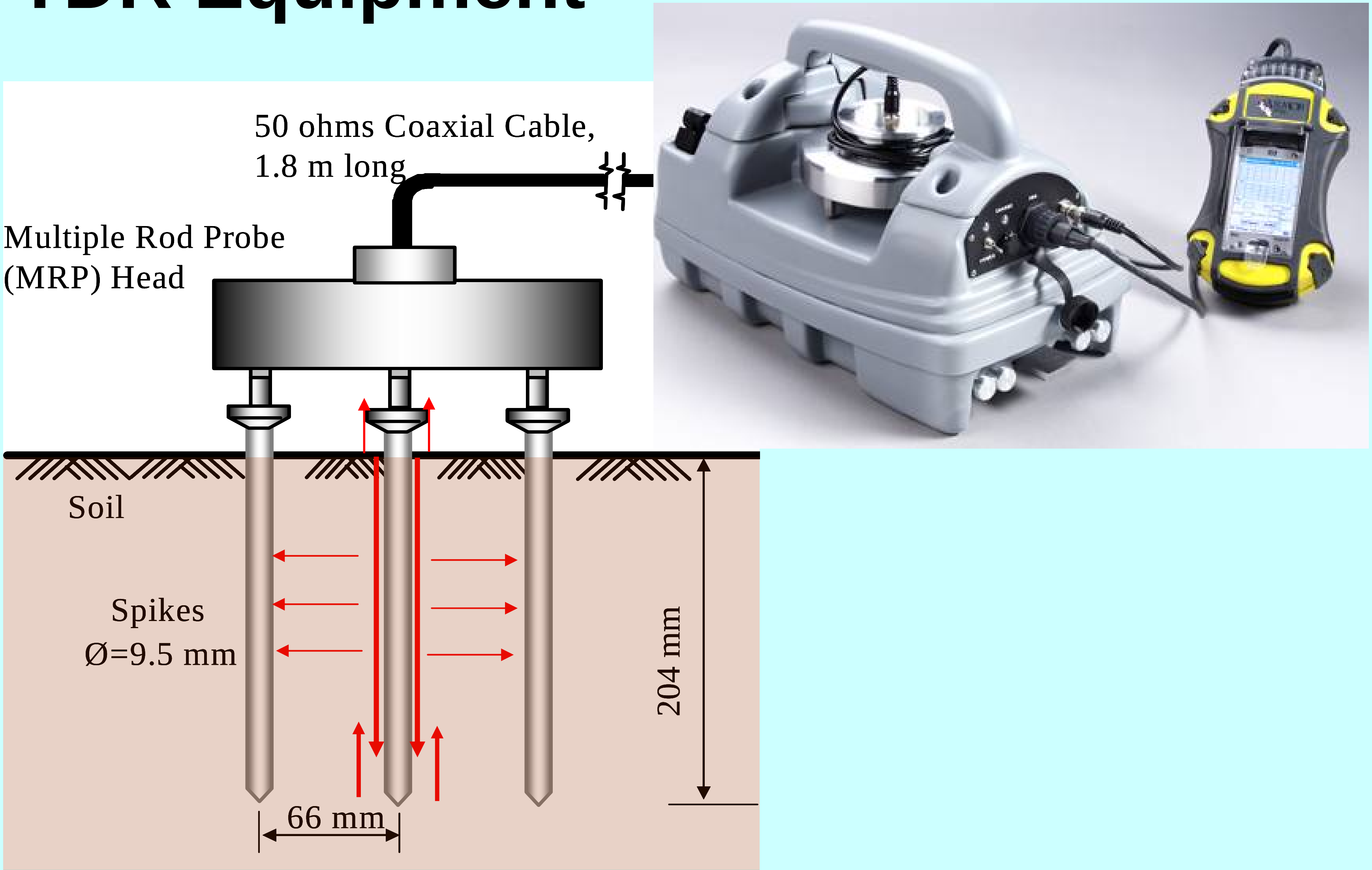


Probe Head

Mold Probe

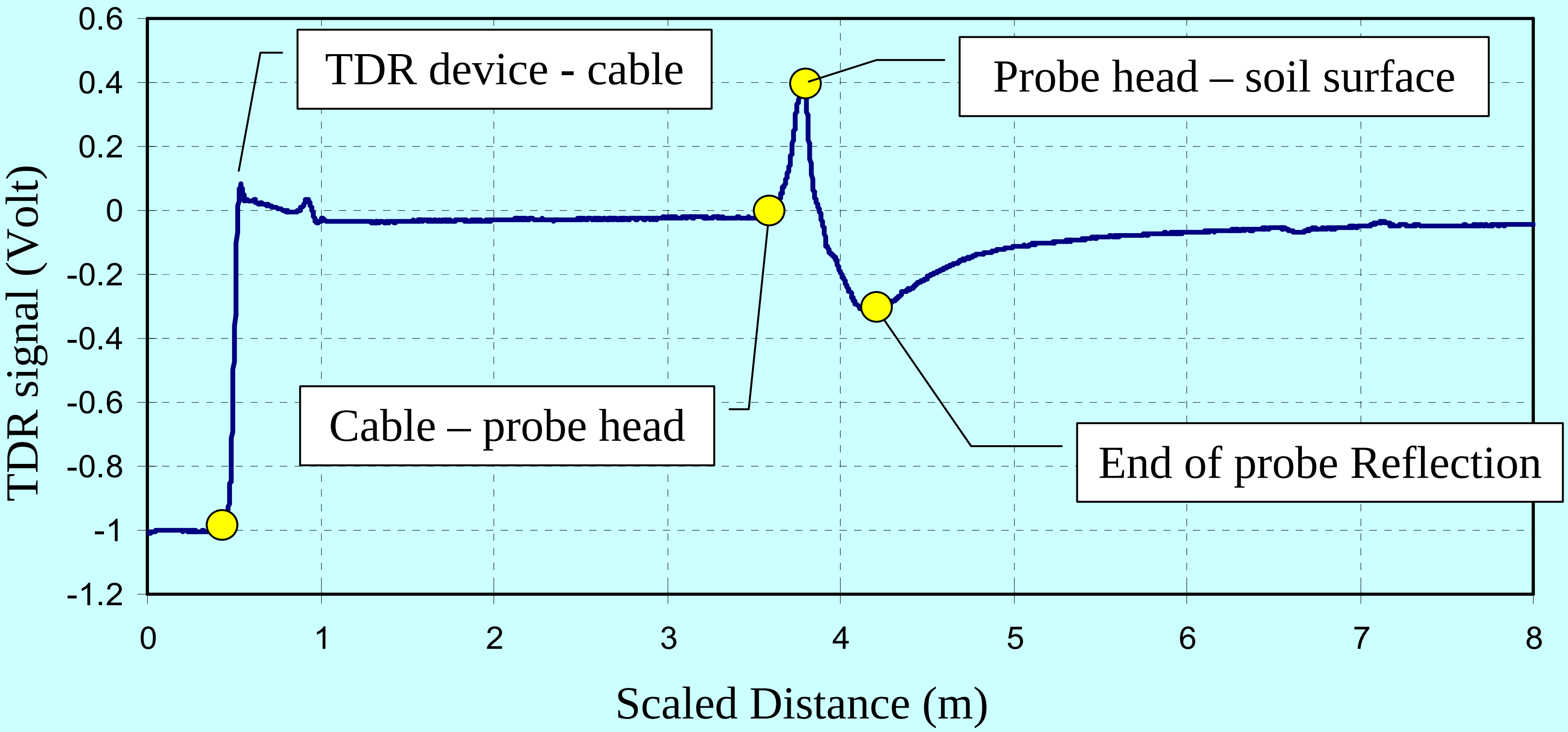
Multiple Rod Probe

TDR Equipment

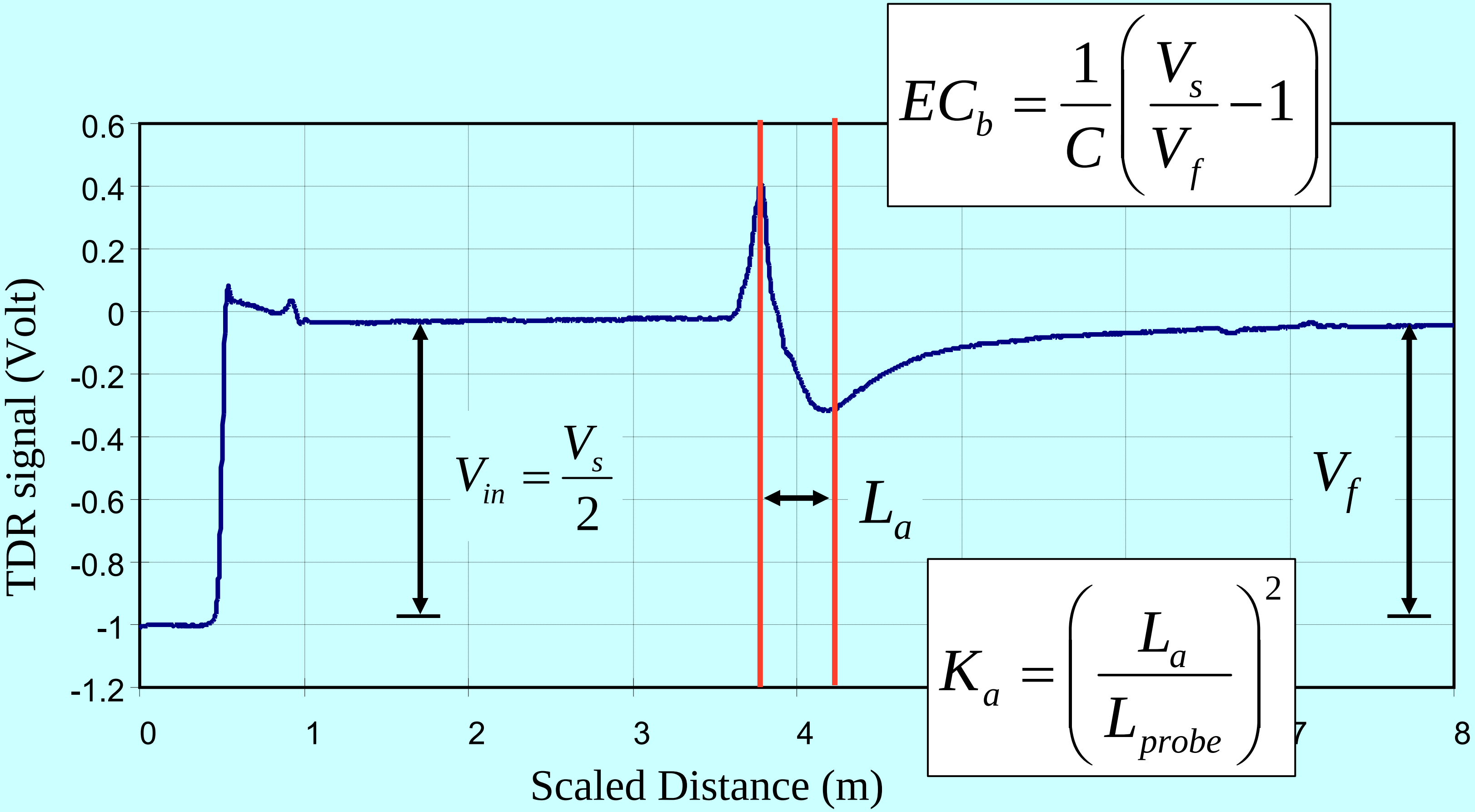


The TDR curve – plot of Voltage vs Scaled Distance

TDR Device provides a step D.C. voltage with a very fast rise time.
When voltage encounters a “impedance mismatch ” (●), a reflection occurs.



The TDR curve – Calculation of Apparent Dielectric Constant, K_a, Electrical Conductivity, EC_b



$$EC_b = \frac{1}{C}\left(\frac{V_s}{V_f} - 1\right)$$

$$V_{in} = \frac{V_s}{2}$$

$$K_a = \left(\frac{L_a}{L_{probe}}\right)^2$$

Water Content and Dry Density

Yu and Drnevich (2004 and ASTM D 6780) established semi-empirical linear relationships

Calibration Equations

$$\sqrt{K_a}\frac{\rho_w}{\rho_d} = a + bw$$

$$\sqrt{EC_b}\frac{\rho_w}{\rho_d} = c + dw$$

$$\sqrt{EC_b} = f + g\sqrt{K_a}$$

Water Content and Dry Density Equations

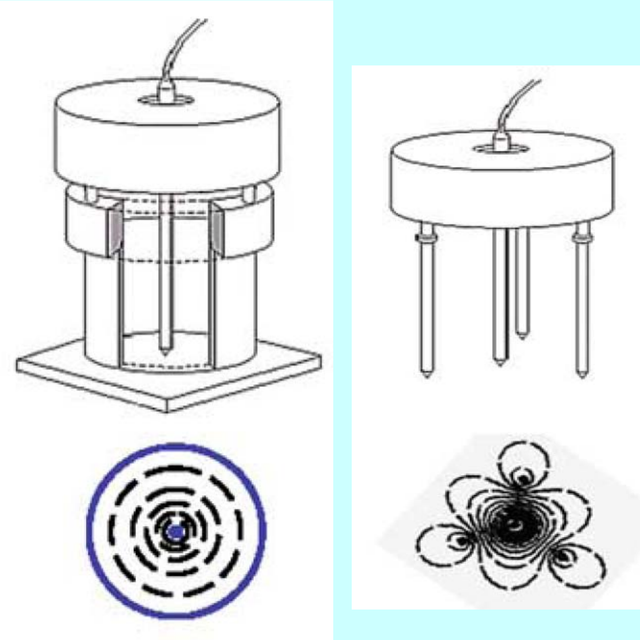
$$w = \frac{c\sqrt{K_a} - a\sqrt{EC_b}}{b\sqrt{EC_b} - d\sqrt{K_a}}$$

$$\rho_d = \frac{d\sqrt{K_a} - b\sqrt{EC_b}}{ad - cb}\rho_w$$

TDR measures water content and dry density

- Important for backfills to control settlement
- Related to stiffness of backfill materials
- Works for most soils except for highly conductive soils such as fat clays at high water contents

Probe Geometry Corrections to Conductivity Measurements – Dallinger (2006)



Probe Configuration	n_f / n_d
PMTDR and MDI-PDA (default values)	2.46
4-in. mold (coaxial) with 5/16-in. center spike	2.45
6-in. mold (coaxial) with 3/8-in. center spike	2.27
MRP with four 3/8-in. spikes inside 6-in. mold	2.32
MRP with four 3/8-in. spikes inside 11-in. mold	2.14
MRP with four 3/8-in. spikes with semi-infinite boundary (field conditions)	2.02

Applying corrections to Electrical Conductivity in the field

$$EC_{b,corrected} = EC_{b,PMTDR-SM} \frac{\left(n_f / n_d\right)_{PMTDR-SM}}{\left(n_f / n_d\right)_{actual}}$$

Notes on Conductivity Measurements

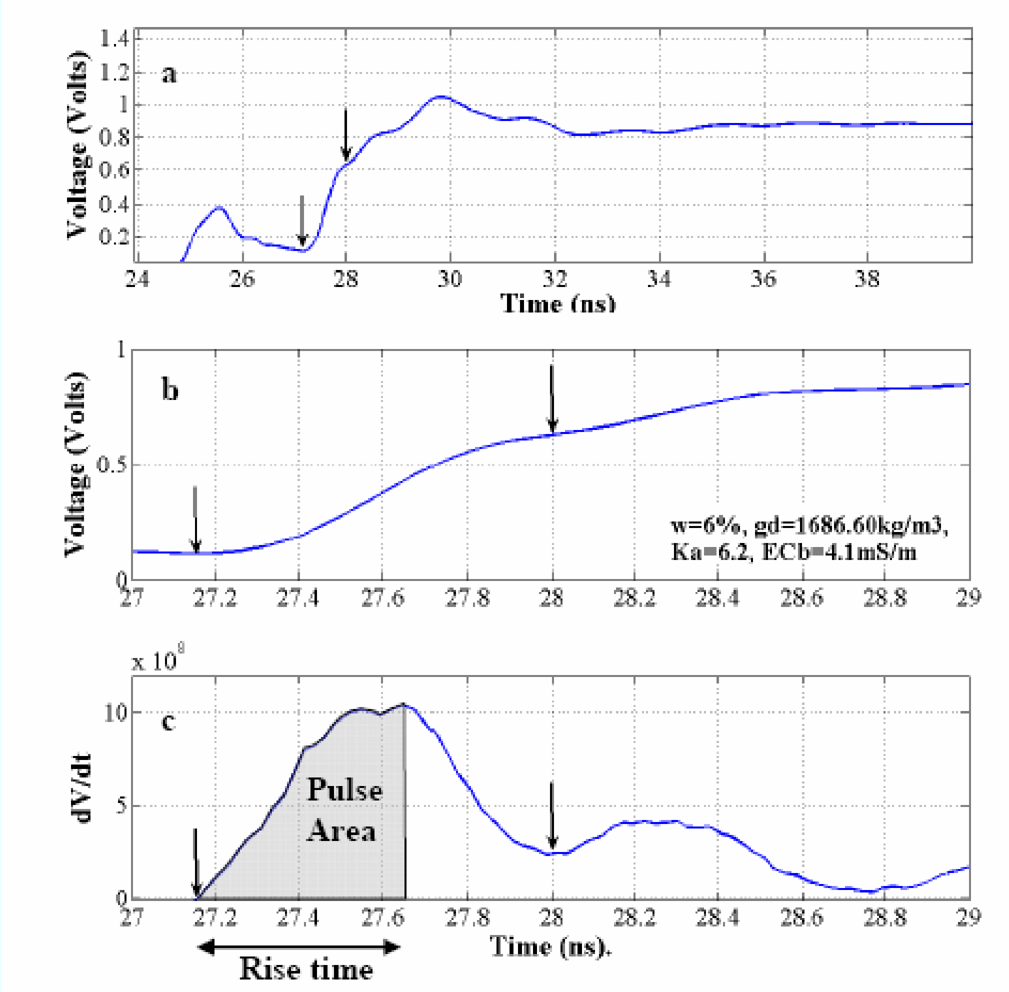
- Can be made on all soils, even fat clays at high water contents
- Reasonably accurate measurements with probe geometry corrections
- Useful for Corrosion Classification of soil

Classification	Soil Resistivity (Ohm-cm)	Soil Conductivity (mS/m)
Noncorrosive	>10,000	< 10
Mildly corrosive	2,000 - 10,000	10 - 50
Moderately corrosive	1,000 - 2,000	50 - 100
Corrosive	500 - 1,000	100 - 200
Very corrosive	< 500	> 200

$$\text{Resistivity} = \frac{1}{\text{Electrical Conductivity}}$$

Ref. Liu, Henry, Pipeline Engineering, Lewis Publishers, 2003, pg. 327.

Pulse Area Method for Soil Identification (Carlos Zambrano)



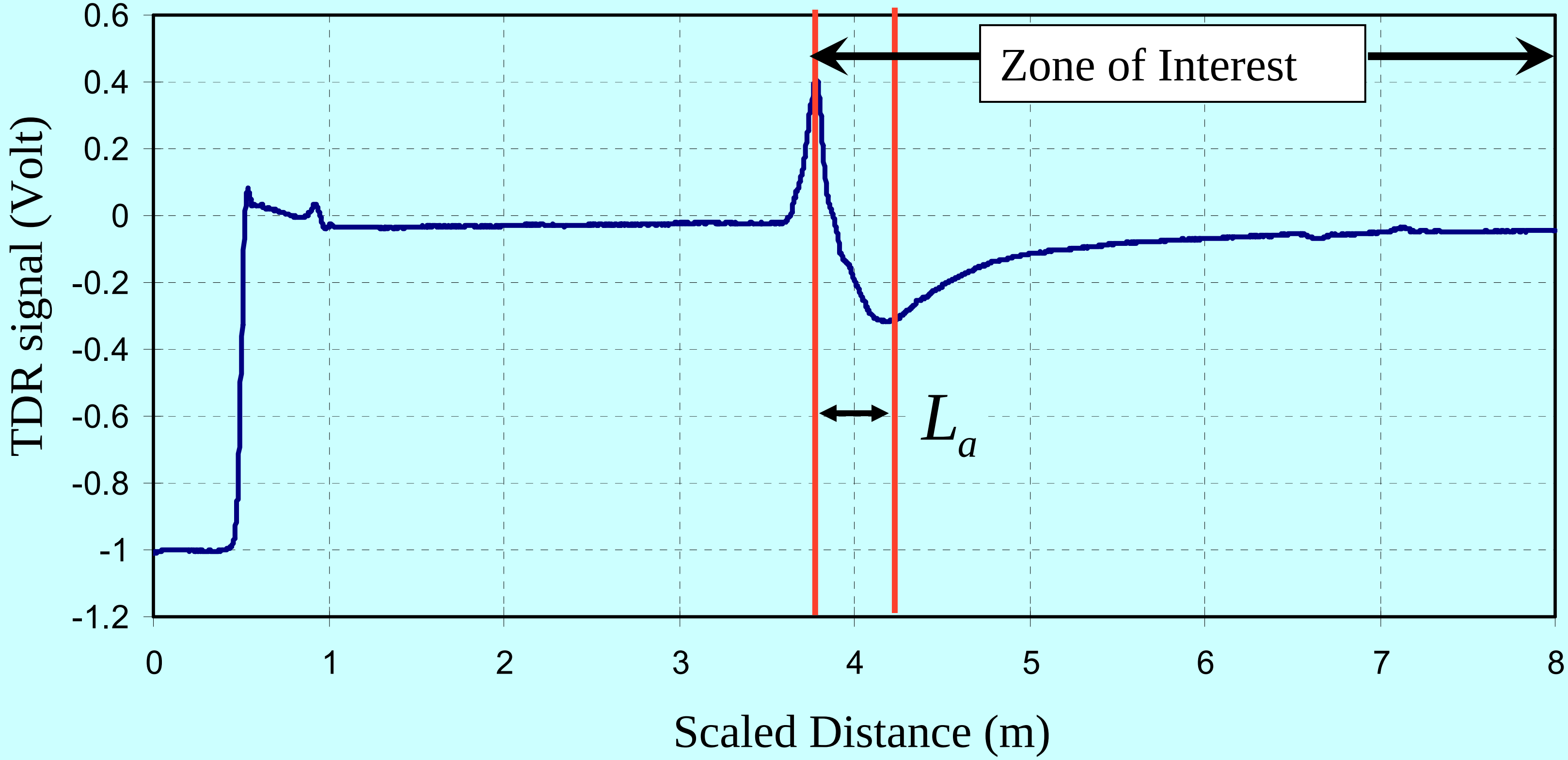
TDR curve for Ottawa sand, *w* = 6%

Zoom in on portion between arrows

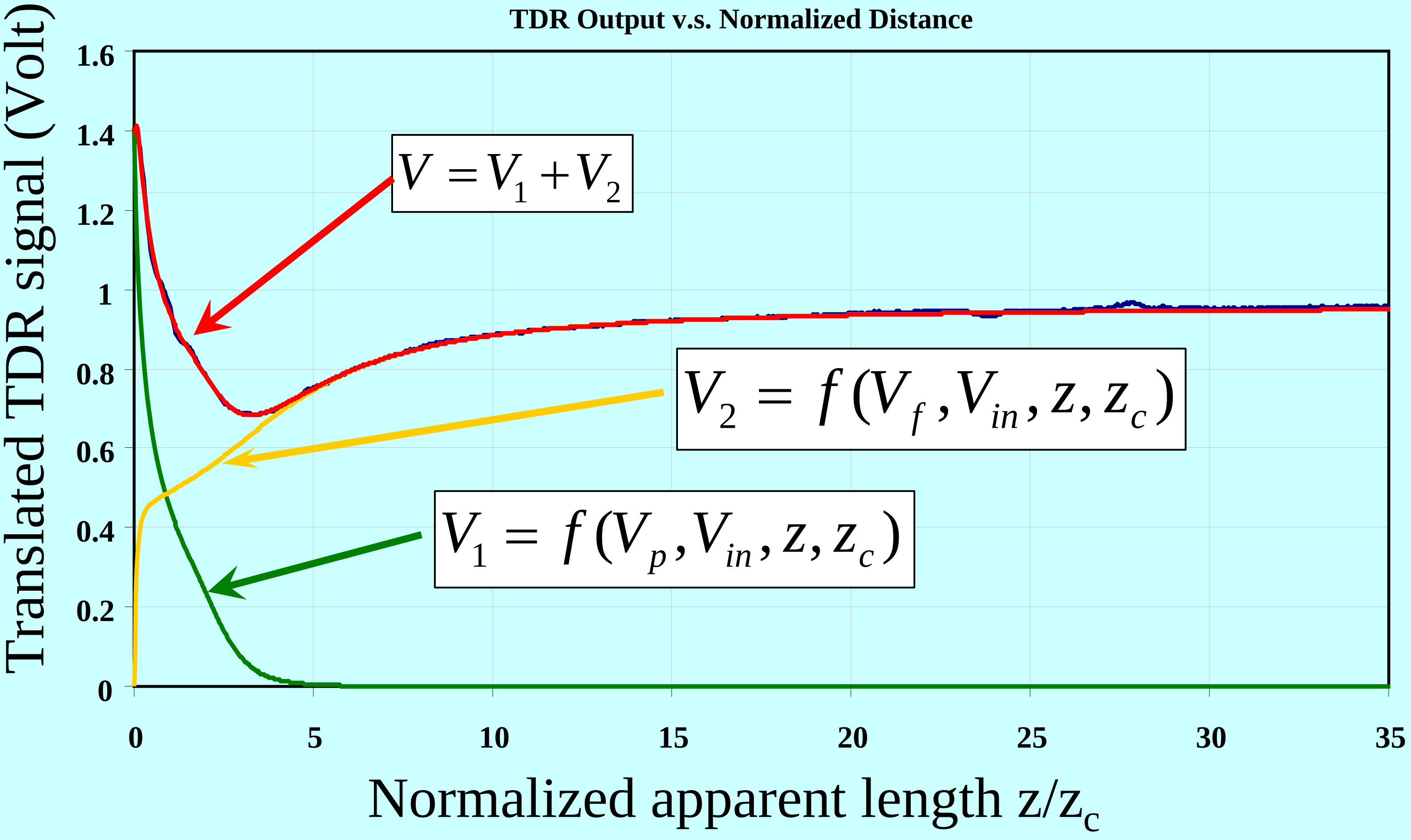
Derivative of TDR curve. Pulse Area is soil type dependent

(Source: Zambrano, 2006)

The TDR curve – Fitting over Zone of Interest



Curve fitting of TDR voltage - Pao-Tsung Huang and Sochan Jung (2007)



Fitting functions

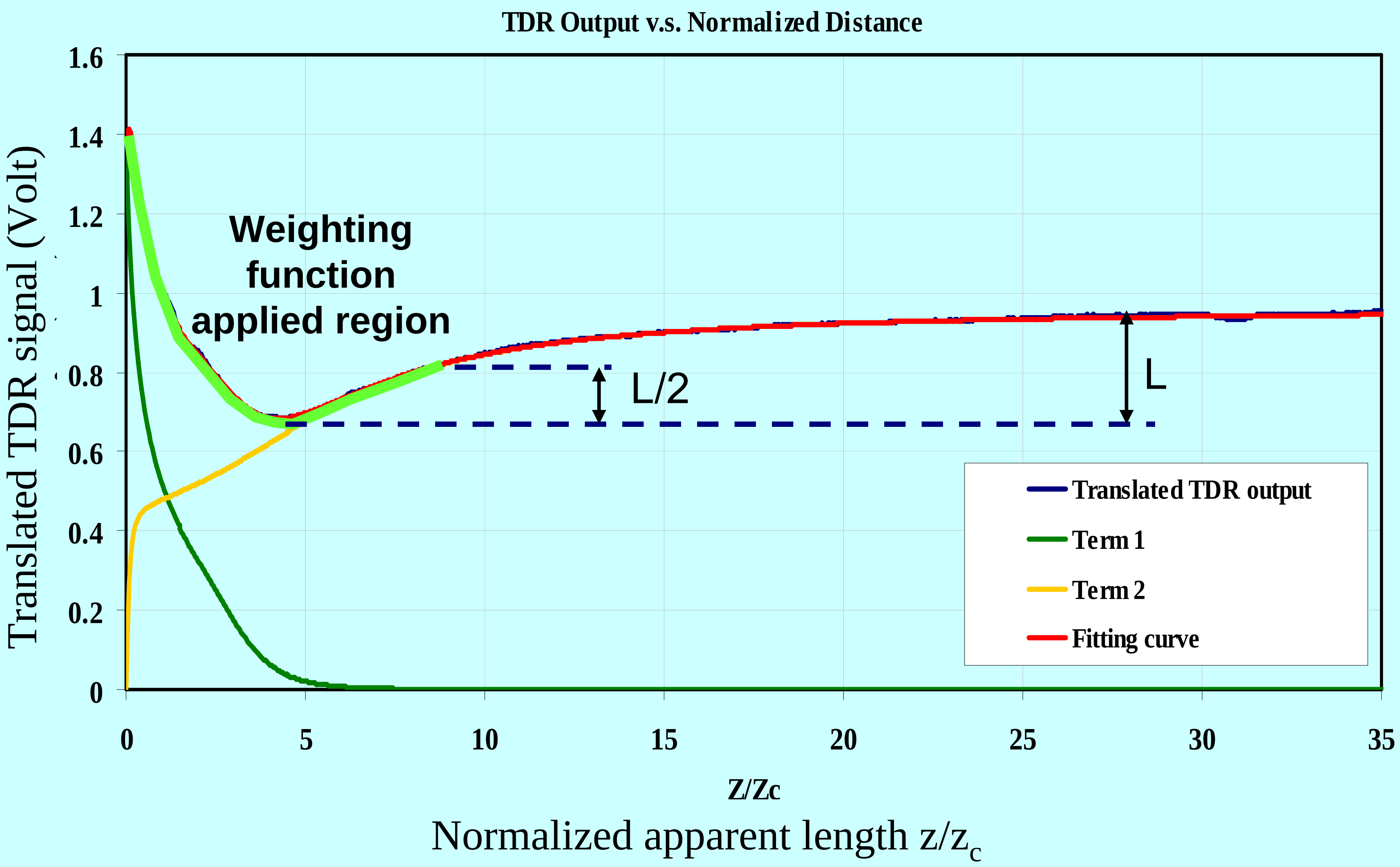
Initial Part of Curve

$$V_1 = \frac{V_p - V_{in}}{1 + \alpha\left(\frac{z}{z_c}\right)^{\beta} + \gamma\left(\frac{z}{z_c}\right)^{\delta}} - V_2(0^+)$$

Final Part of Curve

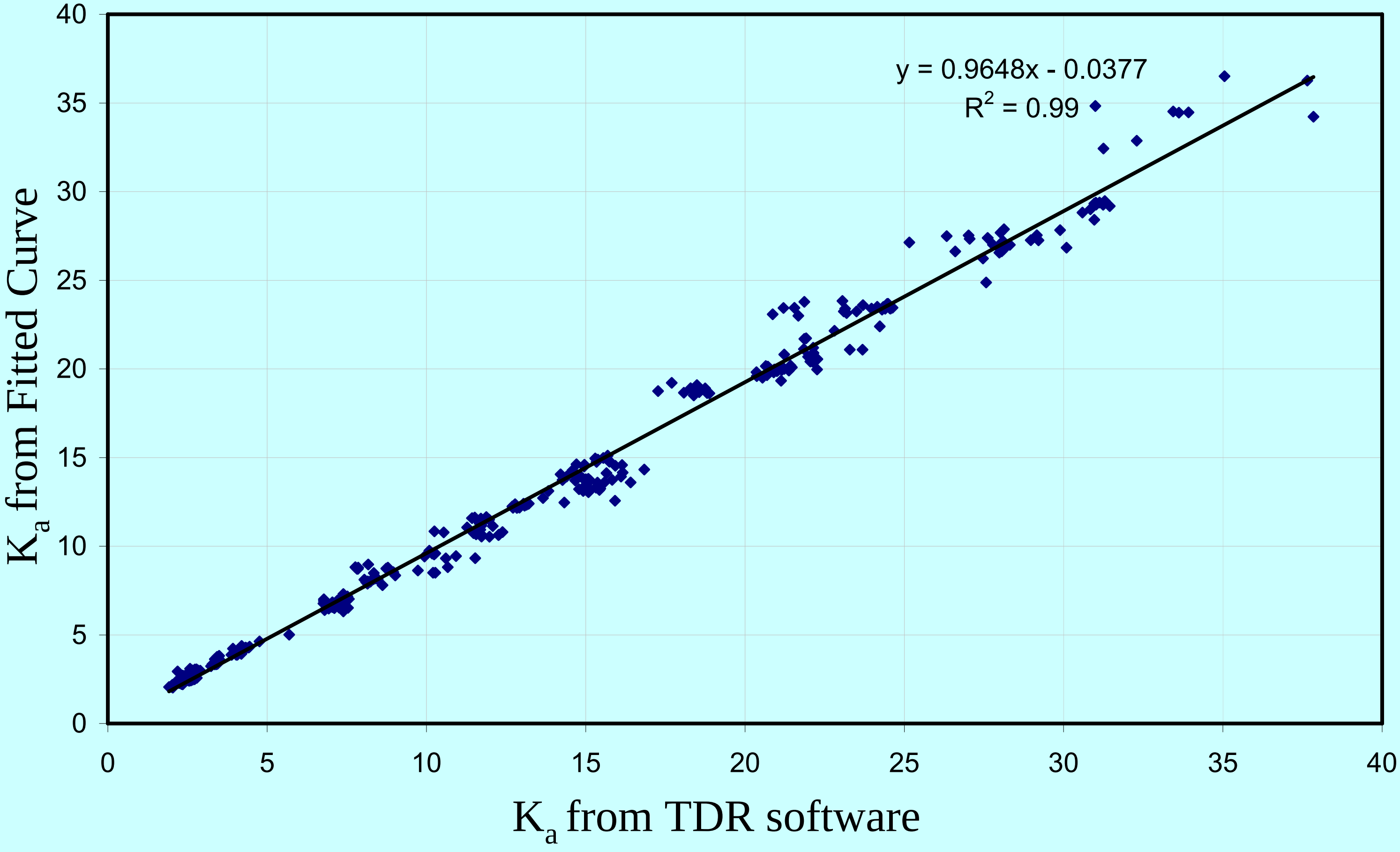
$$V_2 = \left[\frac{1}{2} - \frac{1}{\pi}\tan^{-1}\left(\frac{1 - \left(\frac{z}{z_c}\right)^{\theta}}{\chi\left(\frac{z}{z_c}\right)^{\lambda}}\right)\right] \times \left(V_f - V_{in}\right)$$

Weighting Functions

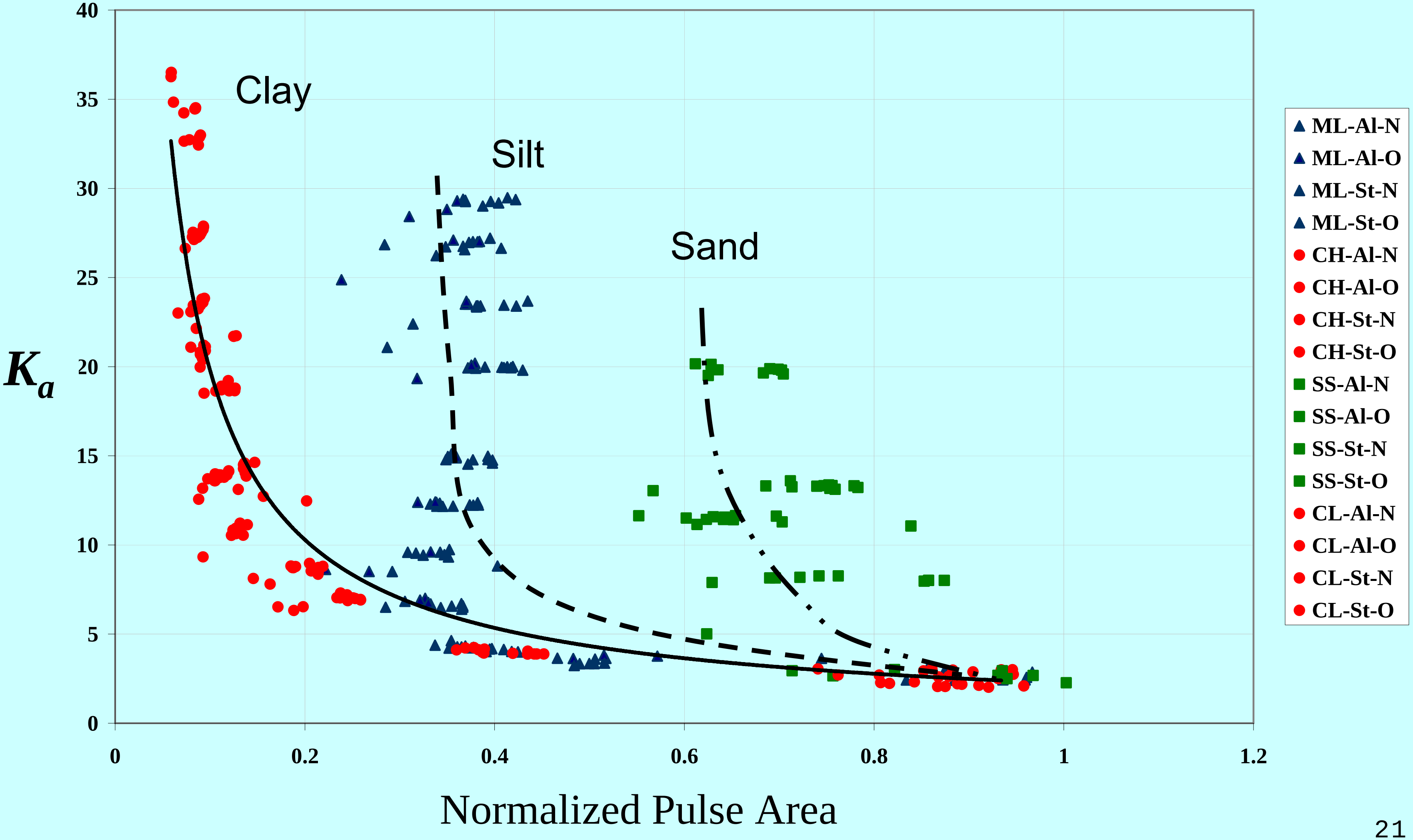


Results

Comparison of K_a calculated from TDR software with calculation using the fitting function.



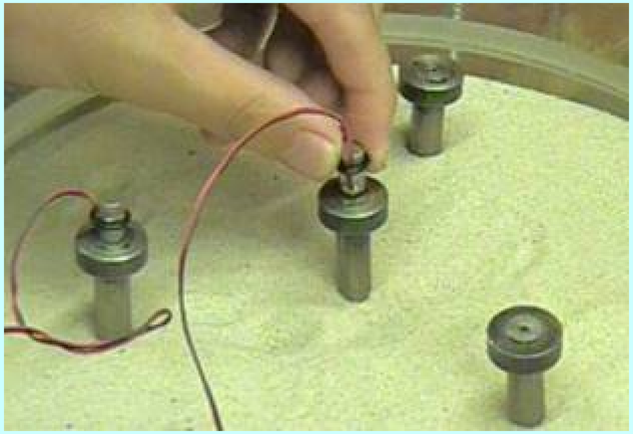
Results – Use of the fitting functions to calculate Pulse Area



Notes of Soil Type Identification

- Normalized Pulse Area is Pulse Area of the reflected signal divided by the Pulse Area associated with the input pulse.
- K_a and Normalized Pulse Area are independent of calibrations
- K_a values must be larger than 10 (water contents in range of optimum are almost always give $K_a > 10$)
- Useful for
  - ☐ Checking that backfill type meets specifications
  - ☐ Calibration factors for TDR measurements of water content and dry density

Seismic Wave Measurement System



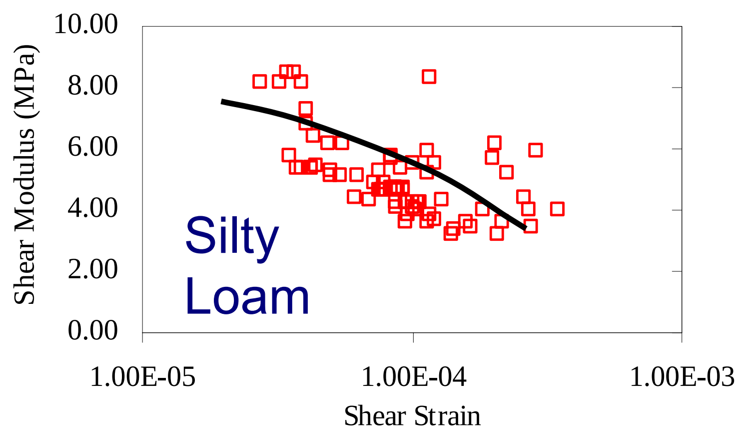
- Attach accelerometers to several TDR spikes
- Impact other spikes with instrumented hammer
- Measure acceleration-time history on spikes
- Determine travel time
- Calculate strain amplitude from particle velocity and wave propagation velocity

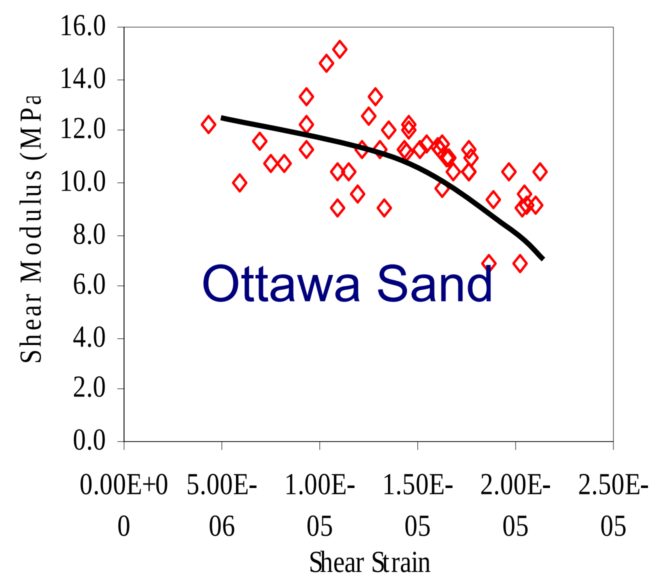
Ref. Yu and Drnevich, ICSMGE, Osaka, Japan, 2005.

Conclusions

- TDR method makes use of a step d.c. voltage where a wave front propagates down a probe embedded in the soil and reflects back from the end of the probe
- The velocity of propagation is related to the apparent dielectric constant of the soil, K_a
- The residual voltage after propagation is related to the electrical conductivity of the soil, EC_b
- Probe geometry affects the measured value of electrical conductivity and accurate corrections are now available

Seismic Test Results





- Impacted spike act as a rigid penetrometer and instrumented spikes act as wave guides

Magnitude of hitting force determines strain amplitude

Results are consistent with values published in the literature

Ref. Yu and Drnevich, ICSMGE, Osaka, Japan, 2005.

Notes on Soil Stiffness Measurements

- Made on same soil volume where electrical conductivity, water content and dry density are determined
- Provide modulus degradation with strain
- Important for pipeline support for liquid inertia forces

Conclusions, Cont’d.

- Conductivity is important for corrosion classification of backfills
- Pulse area is an appropriate way to identify soil types.
- Curve fitting works well in obtaining K_a and Pulse Area
- The TDR Probe can be used as a waveguide for transmitting shear waves from one probe spike to adjacent spikes
- Measurements with TDR probes provide useful information for transmission line backfills

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