Analysis of Sensor Array for Measuring Soil Resistance Forces

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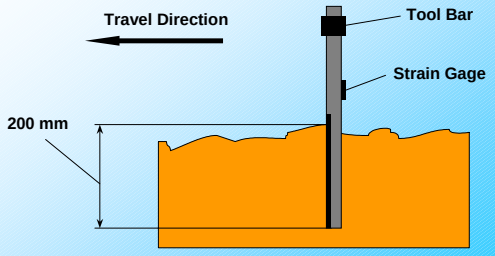
Background

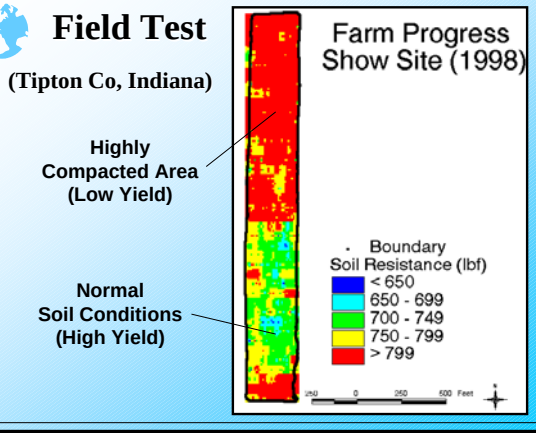
- Soil compaction is one of the factors often limiting crop yield
- Measurement of soil cone penetration is the most popular way to estimate the level of soil compaction today
- The instrumentation for measurement of soil mechanical impedance on-the-go has potential to be useful for site-specific soil management

Previous Design



Field Test

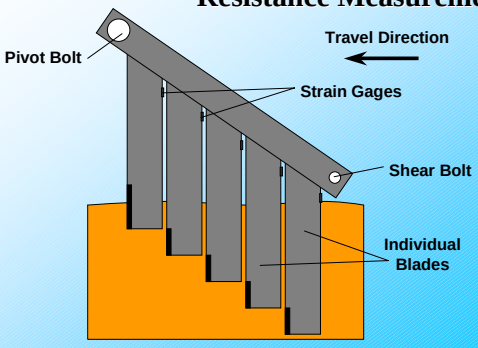
(Tipton Co, Indiana)



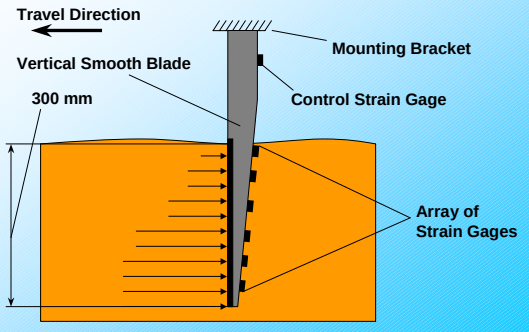
Objectives

- Develop and test a prototype system for estimation of soil impedance by measuring the degree of bending of a vertical smooth blade while it is pulled through the soil
- Use an array of strain gages to differentiate soil resistance at various depths
- Use GPS and standard mapping software to create multilayer soil resistance field map

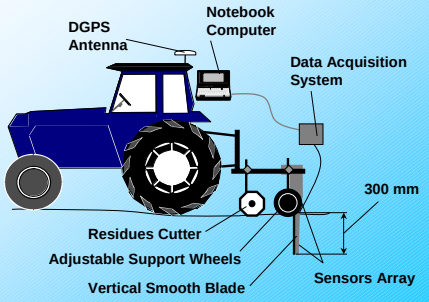
Differential Soil Mechanical Resistance Measurement



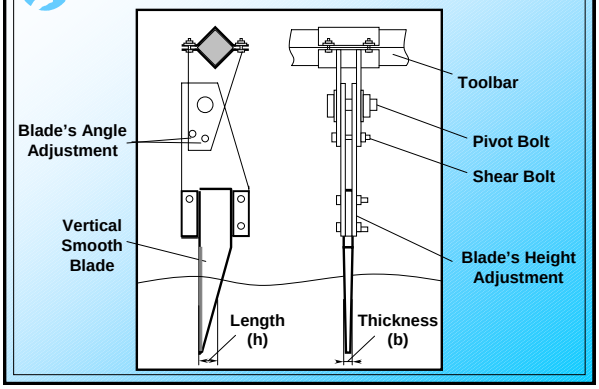
Vertical Smooth Blade



System for Measuring Soil Mechanical Resistance On-the-go



Mounting of the Vertical Smooth Blade



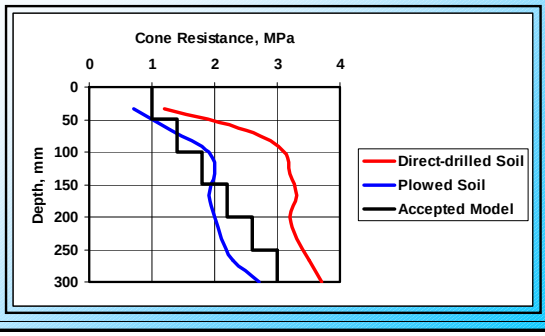
Analytical Solution

$$\varepsilon = \frac{6}{E}\frac{Yab_p}{b_\varepsilon h_\varepsilon^2} p$$

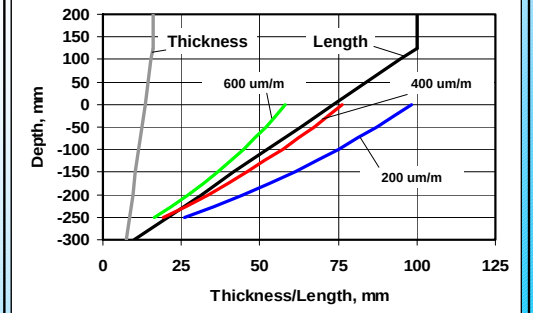
ε - strain, um/m
p - superposed pressure, MPa
E - module of elasticity (207 GPa)
a - distance between sensors (50 mm)
b - thickness of the blade (16 mm)
h - length of the blade, mm
Y - arm of the bending moment, mm

$$\begin{Bmatrix} \varepsilon_1 b_{\varepsilon 1} h_{\varepsilon 1}^2 \\ \varepsilon_2 b_{\varepsilon 2} h_{\varepsilon 2}^2 \\ \varepsilon_3 b_{\varepsilon 3} h_{\varepsilon 3}^2 \\ \varepsilon_4 b_{\varepsilon 4} h_{\varepsilon 4}^2 \\ \varepsilon_5 b_{\varepsilon 5} h_{\varepsilon 5}^2 \\ \varepsilon_6 b_{\varepsilon 6} h_{\varepsilon 6}^2 \\ \varepsilon_7 b_{\varepsilon 7} h_{\varepsilon 7}^2 \end{Bmatrix} = \frac{6}{E} \begin{bmatrix} Y_{11} & 0 & 0 & 0 & 0 & 0 \\ Y_{12} & Y_{22} & 0 & 0 & 0 & 0 \\ Y_{13} & Y_{23} & Y_{33} & 0 & 0 & 0 \\ Y_{14} & Y_{24} & Y_{34} & Y_{44} & 0 & 0 \\ Y_{15} & Y_{25} & Y_{35} & Y_{45} & Y_{55} & 0 \\ Y_{16} & Y_{26} & Y_{36} & Y_{46} & Y_{56} & Y_{66} \\ Y_{17} & Y_{27} & Y_{37} & Y_{47} & Y_{57} & Y_{67} \end{bmatrix} \begin{Bmatrix} p_1 a_1 b_{p1} \\ p_2 a_2 b_{p2} \\ p_3 a_3 b_{p3} \\ p_4 a_4 b_{p4} \\ p_5 a_5 b_{p5} \\ p_6 a_6 b_{p6} \end{Bmatrix}$$

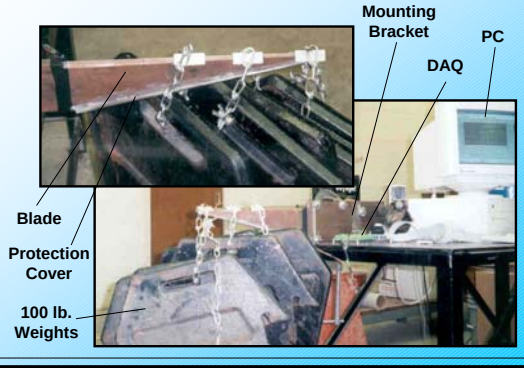
Soil Mechanical Resistance
(Typical Curves)



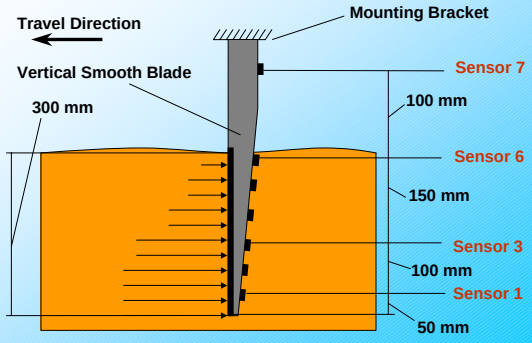
Design of the Vertical Smooth Blade
(Geometry)



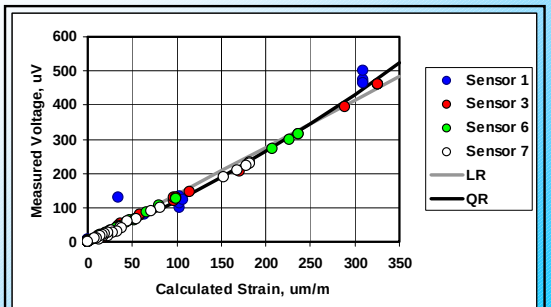
Laboratory Calibration



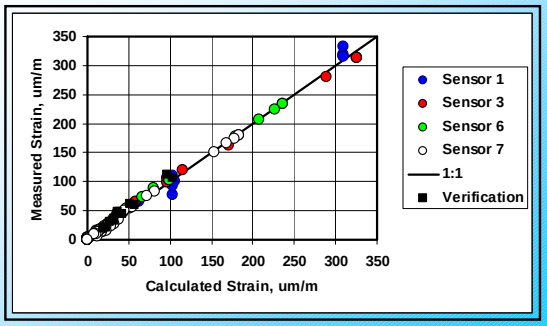
Vertical Smooth Blade



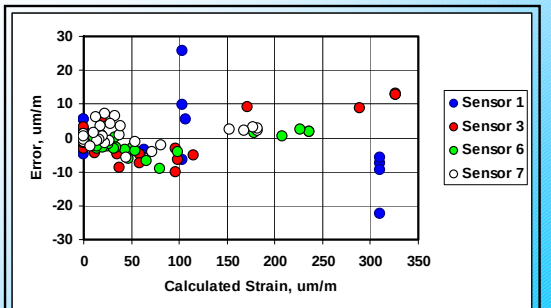
Laboratory Calibration of Strain Gages



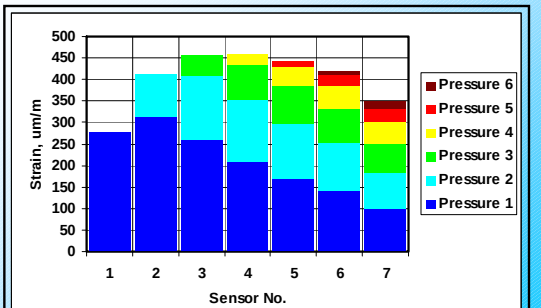
Calculated versus Measured Strain



Error Distribution



Superposition of Resistance Forces



Analytical Solution

$$\varepsilon = \frac{6}{E}\frac{Yab_p}{b_\varepsilon h_\varepsilon^2} p$$

ε - strain, um/m
p - superposed pressure, MPa
E - module of elasticity (207 GPa)
a - distance between sensors, mm
b - thickness of the blade, mm
h - length of the blade, mm
Y - arm of the bending moment, mm

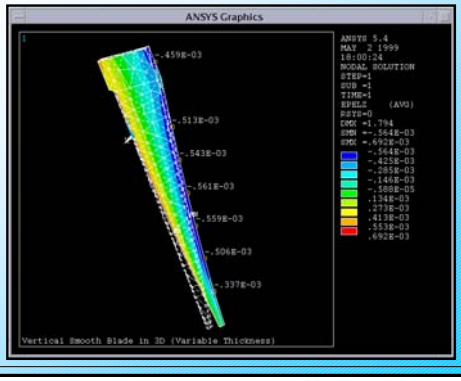
$$\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\\ \varepsilon_4\end{Bmatrix} = \frac{6}{E}\begin{bmatrix} \frac{Y_{11}a_1b_{p1}}{b_{\varepsilon1}h_{\varepsilon1}^2} & 0 & 0 \\ \frac{Y_{12}a_1b_{p1}}{b_{\varepsilon2}h_{\varepsilon2}^2} & \frac{Y_{22}a_2b_{p2}}{b_{\varepsilon2}h_{\varepsilon2}^2} & 0 \\ \frac{Y_{13}a_1b_{p1}}{b_{\varepsilon3}h_{\varepsilon3}^2} & \frac{Y_{23}a_2b_{p2}}{b_{\varepsilon3}h_{\varepsilon3}^2} & \frac{Y_{33}a_3b_{p3}}{b_{\varepsilon3}h_{\varepsilon3}^2} \\ \frac{Y_{14}a_1b_{p1}}{b_{\varepsilon4}h_{\varepsilon4}^2} & \frac{Y_{24}a_2b_{p2}}{b_{\varepsilon4}h_{\varepsilon4}^2} & \frac{Y_{34}a_3b_{p3}}{b_{\varepsilon4}h_{\varepsilon4}^2} \end{bmatrix}\begin{Bmatrix}p_1\\ p_2\\ p_3\end{Bmatrix}$$

Analytical Solution

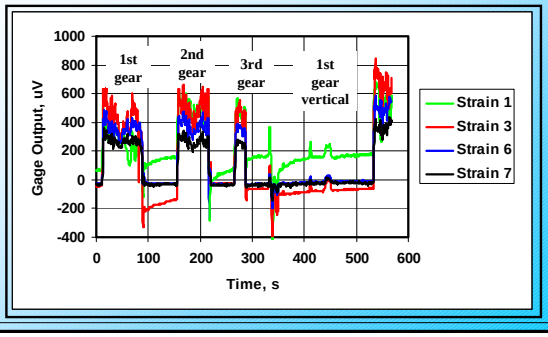
$$\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\\ \varepsilon_4\end{Bmatrix} = \begin{bmatrix}93 & 0 & 0\\ 87 & 78 & 0\\ 47 & 80 & 54\\ 32 & 63 & 68\end{bmatrix}\begin{Bmatrix}p_1\\ p_2\\ p_3\end{Bmatrix}$$

$$\begin{Bmatrix}p_1\\ p_2\\ p_3\end{Bmatrix} = \begin{bmatrix}0.0108 & 0 & 0\\ -0.0119 & 0.0127 & 0\\ 0.0081 & -0.0187 & 0.0184\end{bmatrix}\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\end{Bmatrix}$$

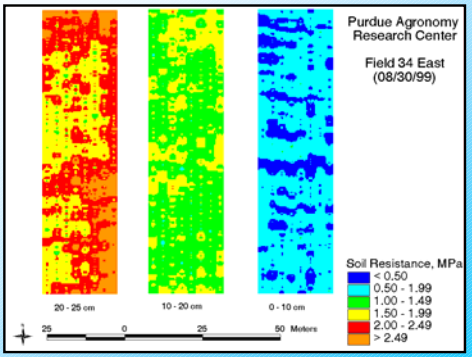
Numerical Solution



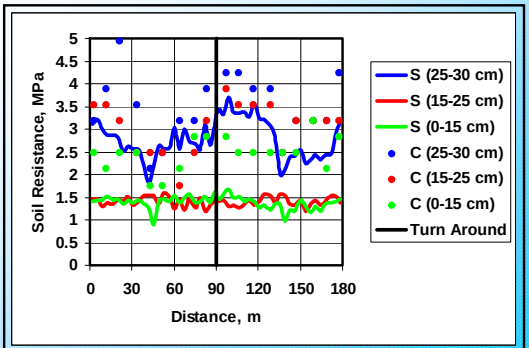
Initial Field Test



Field Test



Individual Field Pass



Conclusions

- Vertical smooth blade can be used for differential soil resistance measurement
- Analytical and numerical solutions showed similar results, and laboratory calibration was done with R^2=0.99
- Field test showed that vertical blade allowed measurement of integrated soil impedance
- Determination of top soil resistance is the most problematic (sensitivity is below 40%)

Future Development

- Investigation of higher range strain gage measurements
- Modification of crop residue cutting mechanism
- Improvement of data acquisition system (reduce noise)
- Additional field experiments (compacted versus loose soil)
- Comparison of field data against high density cone penetrometer readings

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