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Utility of the Delta-T Theta Probe for Obtaining Surface Moisture Measurements from Beaches

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ABSTRACT

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Recent studies have employed a new device to measure beach "surface" moisture content, the Delta-T Theta probe. A key weakness of the device for this application is that the sensor length (6.0 cm) exceeds the desirable depth for "surface" measurements in the context of coastal-aeolian processes. This study investigated the reliability of the Delta-T Theta probe when modified to restrict measurement depths to 0.5–1.5 cm. Field investigations were conducted at two beaches in Texas and North Carolina to allow assessment of the influence of different sediment sizes. Results demonstrated that sensor output becomes less sensitive as the sensor length is decreased. However, R^2 values reveal very strong relationships between probe output and laboratory-measured moisture content, with virtually all sampling runs exceeding 0.90. Further, although the standard error approximately doubled (from $\pm1\%$ to $\pm2\%$) for the modified versions of the probe, the error remained within the accuracy ranges reported in the literature and did not appear to consistently increase as the sensor length was shortened. Grain size was found to have no consistent influence on sensor performance. Comparisons of multiple runs and multiple probes indicated that it is possible to achieve high levels of repeatability both between runs and between probes, but several instances of significant departures were identified that suggest caution with this application and that other environmental parameters may influence results.

ADDITIONAL INDEX WORDS: *Moisture probe, beach moisture content, instrument calibration, aeolian transport.*

INTRODUCTION

Surface soil moisture has an important influence on a wide range of natural and human systems, including the near-surface energy balance (Abu-Hamdeh, 2003), micro and macro fauna habitat (Colombini, Fallaci, and Chelazzi, 2005; Hayward *et al.*, 2004), and climate and landscape modeling (Cosh *et al.*, 2005). It can also play a very significant role in aeolian sedimentary systems, particularly in coastal environments (Davidson-Arnott, Macquarrie, and Aagaard, 2005; Logie, 1982; Sherman *et al.*, 1998), which motivates the present study. The thickness of the surface layer that is of interest in the context of wind-blown sand transport is generally quite thin, ranging from a few millimeters to a few centimeters (Kalieta, Heitman, and Logsdon, 2005; Namikas and Sherman, 1995), and it has been suggested that one of the greatest challenges in working in coastal-aeolian systems lies in the measurement of moisture content in this shallow layer over suitable ranges of space and time to enable modeling (Mckenna Neuman and Langston, 2006).

The most common approach to measuring surface moisture content of beach sediments involves the scraping and removal of sediment samples from the beach surface (*e.g.*, Jackson and Nordstrom, 1997; Sarre, 1988; Wiggs, Baird, and Atherton, 2004). This technique has two significant limitations. It is destructive of the surface, which precludes repetitive sampling to document temporal variability, and it is time-consuming so that it is difficult to apply over a large area (Atherton, Baird, and Wiggs, 2001). This paper examines the utility of a new device for obtaining rapid, repetitive measurements of surface moisture content that significantly reduces these problems, the Delta-T Theta probe (Figure 1) (Delta-T Devices, 1999).

Atherton, Baird, and Wiggs (2001) found that the Delta-T probe allows rapid and relatively nondestructive measurements of moisture content to be made, whereas Yang and Davidson-Arnott (2005) and Davidson-Arnott *et al.* (2008) successfully used the probe for repetitive measurements across a point grid. A key weakness regarding the Delta-T Theta probe, however, is that the depth of the sensing volume is significantly greater than the depth of bed likely to be involved in individual aeolian transport events. Tsegaye *et al.* (2004) and Yang and Davidson-Arnott (2005) modified the probe to reduce the depth across which the measurement is integrated from 6.0 cm down to 2.0 cm, a much more appropriate depth in the context of wind-blown sand. Yang and Davidson-Arnott (2005) state that the 2-cm sensor length was chosen as a compromise between restricting measurements to as shallow a depth as possible while minimizing the decrease in accuracy and precision resulting from the shortened array. Results from these studies, however, do not document any decrease in either accuracy or precision as probe length is decreased. However, it has been suggested within the literature that it is desirable to restrict moisture measurement to even shallower depths (Namikas and Sherman, 1995; Sarre, 1988). Furthermore,

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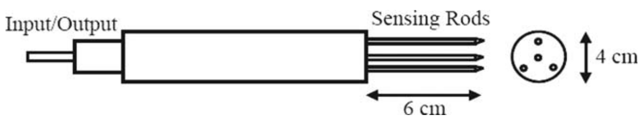

Figure 1. Schematic diagram of the Delta-T Theta probe.

none of these previous studies has reported on the reliability and repeatability of the modified device in any detail.

The primary purpose of the present study is to assess the reliability of the Delta-T Theta probe for measuring very-shallow depth moisture content on beaches. This task is accomplished through a systematic examination of several aspects of probe operation. The specific research questions addressed are:

(i) How does sensor output vary (magnitude, reliability) as sensor rod length is decreased?
(ii) Does sediment grain size influence any variations identified in (i)?
(iii) Does reduction of sensor length affect probe interchangeability?
(iv) How repeatable are the results across multiple runs?

The Delta-T Theta probe may provide a solution that allows workers to monitor spatial and temporal patterns in surface moisture content at very shallow depths on beaches and begin to develop models of this variability. The results of this study will provide a clearer understanding of the capabilities of the Delta-T Theta probe for use in determining surface moisture contents.

BACKGROUND

Initial research into the potential uses of the Delta-T Theta probe to determine soil moisture content was conducted by Gaskin and Miller (1996) and Miller and Gaskin (1998). The basic operation of the probe involves generation of a 100-MHz sinusoidal signal to measure the impedance of the soil material, which is dependent on moisture content. The output is in the form of an analog DC voltage between 0 and 1 V, which is proportional to moisture content. The soil sampling volume consists of a cylinder approximately 4.0 cm in diameter and 6.0 cm in depth, surrounding the center signal rod (Delta-T Devices, 1999; Miller and Gaskin, 1998).

The manufacturer provides calibration relationships for "typical" mineral and organic soils that are indicated to be accurate to approximately $\pm$5% (moisture content by volume). For increased accuracy ($\pm$1%), the manufacturer recommends best-fitting the third-order polynomial that describes probe output using a single, site-specific measurement (a measurement is taken with the probe in the sediment of interest, and the sampled material is then oven dried to determine actual moisture content). However, it seems likely that the dramatic alteration of the probe length may also alter the nature of the output function so that a more detailed calibration process is appropriate. In practice, this issue is not especially significant because previous workers studying beaches have tended to conduct multipoint site-specific calibrations and simply fitted the most appropriate function or functions to the data set (*e.g.*, Atherton, Baird, and Wiggs, 2001; Yang and Davidson-Arnott, 2005).

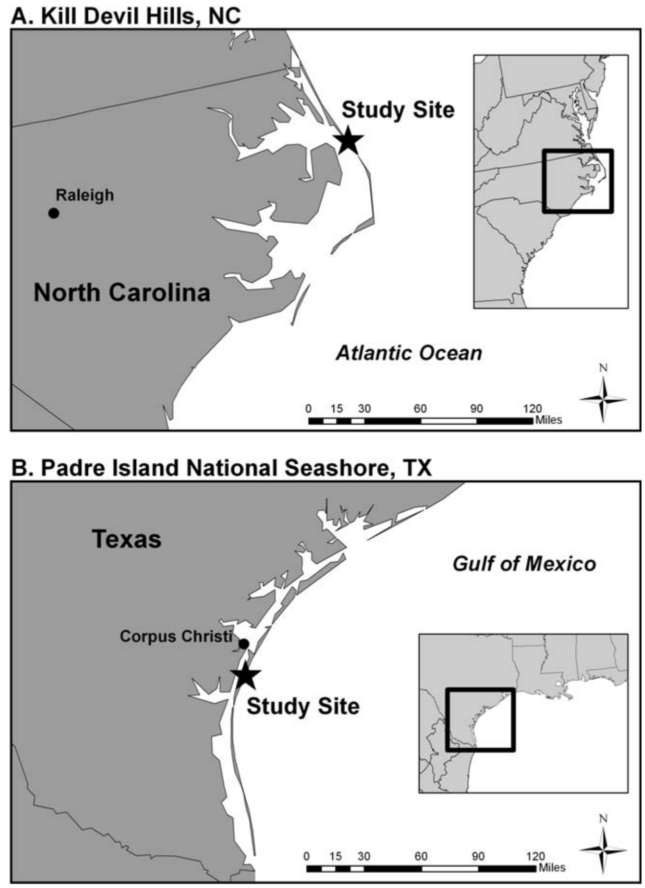

Figure 2. Location map of studies sites. (A) Kill Devil Hill, North Carolina; (B) Padre Island National Seashore, Texas.

METHODS

Study Sites

Field investigations for this study were conducted at sites in Padre Island National Seashore, Texas, from August 2 to 5, 2006, and Kill Devil Hills, North Carolina, from December 27 to 29, 2006 (Figure 2). These research sites were selected to provide different sediment sizes to enhance the applicability of the results of this study.

Padre Island National Seashore occupies a large barrier island that extends 182 km along the southeastern shore of Texas. Sediment is very well sorted and consists of fine to very fine quartz grains with a mean diameter of 0.15 mm. The town of Kill Devil Hills, North Carolina, is located along the northern portion of the Outer Banks barrier islands. Sediment here consists primarily of medium quartz grains with a mean diameter of 0.37 mm, along with a small but varying percentage of shells and shell fragments predominantly located between the high and low tide lines.

Field Methods

The basic procedure used in this study was to take a surface moisture measurement by inserting the probe and recording

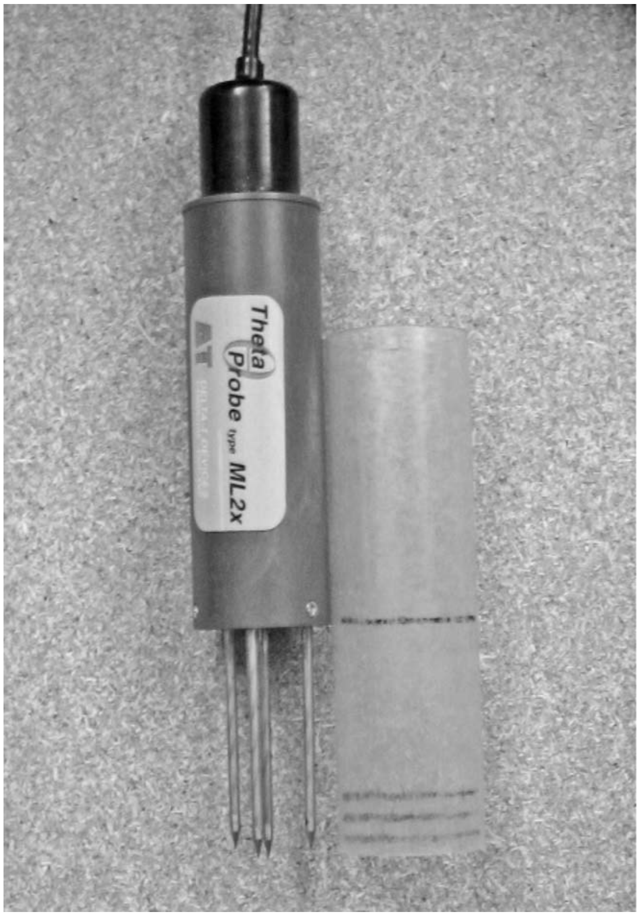

Figure 3. Short core sampling tube utilized to retrieve measured surface moisture samples.

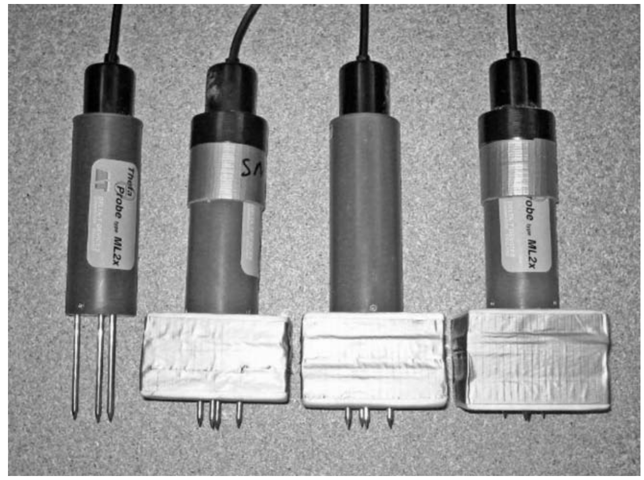

Figure 4. Delta-T Theta probe inserted through varying thicknesses of dielectric foam blocks. The foam blocks reduce sensor length from the manufacturer supplied 6.0 cm to lengths of 1.5, 1.0, and 0.5 cm (right to left).

the voltage output using an HH2 moisture meter (Delta-T Devices, 2005). The sediment that occupied the sensing volume was immediately retrieved using a short core tube of the same diameter and depth as the sensing volume (Figure 3). The sediment sample was then sealed and labeled for subsequent laboratory determination of gravimetric moisture content using the standard oven-drying method. This provided a single paired measurement of sensor output and "true" moisture content. A series of sampling runs were conducted, each composed of 20 such paired measurements that collectively encompassed the full output range of the sensor. The full output range was established prior to each run by taking test measurements in the swash zone (saturated sediment) and loose dune sand (driest sediment). Additional samples were then collected on a trial-and-error basis to represent the full output in 20 approximately equal-sized increments. Between each measurement sample, the sensing rods were wiped cleaned so that any moisture or sand adhering to them would not influence the subsequent measurement. Additionally, it was noted that throughout the course of the day the foam blocks would capture a small amount of moisture. To minimize the influence of moisture held by the foam blocks, after each measurement run the foam blocks were either cleaned or replaced.

Three variables were altered between runs: probe sensor length, different probe units, and sediment size. To assess the influence of sampling depth, we inserted the sensor rods through dielectric foam blocks of varying thickness to reduce sensor rod length (and thus the sampling depth) to 1.5, 1.0, and 0.5 cm (Figure 4). A control run was also conducted using the full 6.0-cm probe as supplied by the manufacturer. Three runs were conducted at each probe length to assess repeatability. Next, an additional run was conducted at each probe length with a second probe to examine probe interchangeability and identify any influence of sensor length on it. Finally, this entire sampling program was replicated at a second site with a markedly different grain size to determine whether grain size had a significant influence on the results.

Lab Procedure

The moisture content of the retrieved sediment samples was determined using the standard gravimetric method (*e.g.*, Hank, 1992; Hillel, 1971). Samples were weighed to 0.001 g, dried in an oven at 65°C for 36 hours, and reweighed to determine the dry sample weight. Moisture content was then determined as

$$w = \frac{w_s - w_d}{w_d} \times 100\%,$$

where moisture content w is expressed as a percentage by weight of a sediment sample, and w_s and w_d are the initial wet sample weight and the dried sample weight, respectively.

Analysis

For each individual experimental run, the Theta probe voltage output was plotted against gravimetric moisture content and third-order polynomial regression was used to determine the best-fit relationship. The third order was used here based on the manufacturer's recommendation, although other functions were also found to provide a good fit and other workers have used other functions previously. Yang and Davidson-Arnott (2005), for example, obtained a good fit with a simple linear function. However, it is worth noting that their data were restricted to moisture contents less than about 10% and did not encompass the full range of possible contents.

The relative strength of the relationship under various experimental treatments was assessed on the basis of the coefficient of determination (R^2), which represents the percentage of the total variance in moisture content that is explained by the voltage output. The standard error (SE) was also calculated for each run as:

$$SE = \sqrt{\frac{1}{n-2}\sum\left(\theta_{\text{measured}} - \theta_{\text{predicted}}\right)^2},$$

where θ_{measured} is the laboratory determined gravimetric moisture content from a field moisture sediment sample, $\theta_{\text{predicted}}$ is the gravimetric moisture content predicted for that sediment sample based on the associated voltage output and the best-fit relationship, and n is the total number of samples (Harnett, 1975). In effect, the SE represents a typical error range expected for the moisture content measurements in units of percentage, and thus provides a second criterion to assess how the utility of the probe changes among the various experimental treatments considered here.

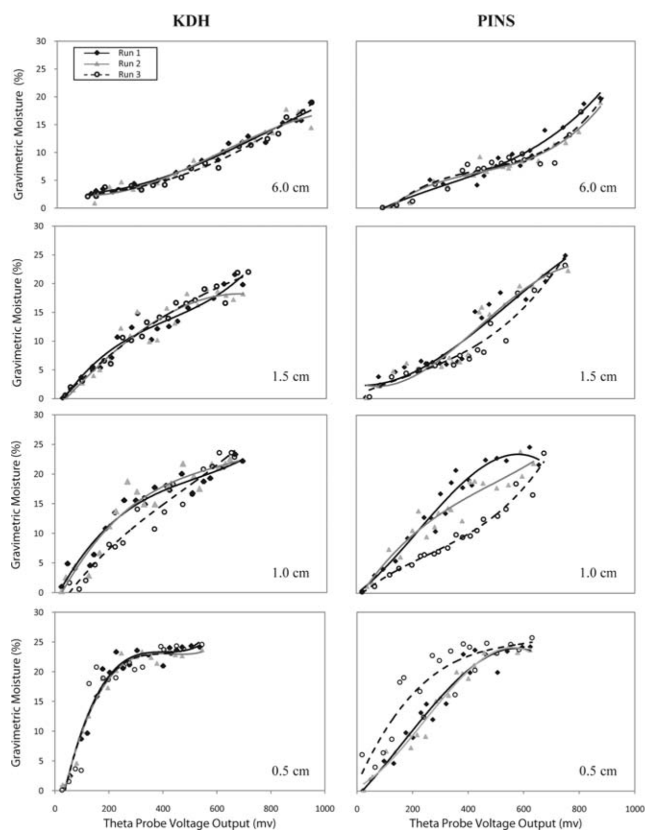

Figure 5. Calibration relationships at sensor lengths 6.0, 1.5, 1.0, and 0.5 cm for KDH and PINS. Symbols show measured values for experimental run 1, 2, and 3 utilizing probe A. Lines represent third-order polynomial calibration relationships.

RESULTS AND DISCUSSION

Influence of Sensor Length/Sampling Depth

The influence of sensor length (*i.e.*, sampling depth) on the relationship between moisture content and probe output is shown in Figure 5. In the case of Kill Devil Hills (KDH), there is negligible increase in between-run scatter as sampling depth is reduced. With the finer sediments at Padre Island (PINS), more variation is apparent between runs; although this is not necessarily problematic because it occurs at the full sensor length to a degree as well as the shorter lengths. Two interrelated trends in probe output are clearly apparent at both sites as sampling depth is decreased. First, the total output range decreases considerably as sensor length is reduced. With the full 6.0-cm sensor length, the maximum output is about 940 mV. This is reduced by about 40% to around 540 mV at the shortest sensor length. Second, this decrease in output range results in a significant increase in the steepness of the curves as sampling depth is decreased. These findings demonstrate that the sensor becomes less sensitive as sampling depth is decreased, which coincides with findings reported by Tsegaye *et al.* (2004).

A quantitative assessment of influence of sensor length/sampling depth is provided in Table 1. Across all sampling depths, the R^2 values indicated very strong relationships with virtually all values exceeding 0.90. With the finer sediments at PINS, there is no consistent trend in R^2 values as sampling depth is decreased. Although the mean R^2 value of 0.92 at the shortest sensor length is slightly lower than the 0.94 found for the full sensor length, the strongest relationship ($R^2 = 0.95$) occurs at the second shortest sensor length. The mean R^2 values from KDH are more clearly indicative of an influence of depth, but it is of minimal magnitude with only a slight drop in R^2 from 0.97 to 0.94. It is worth noting that the R^2 value at the shortest sensor length at KDH is as strong as that for the full sensor length at PINS, indicating that variations in R^2 values between sites may be more significant than that between different sensor lengths/sampling depths.

The SE values indicate expected error on a percentage moisture content basis (Table 1). Both sites show comparable results. The SE is about ±1% with the full sensor length, which is consistent with the manufacturer reported maximum accuracy of ±1% obtainable from a site-specific calibration. The SE approximately doubles for all shortened probe runs but does not appear to consistently increase with decreasing sensor length. In part, this increase in error is likely due to the decrease in output sensitivity noted earlier. Given that the output range is reduced by up to 40% due to shortened probe length, if the absolute magnitude of error (in volts) remains constant, this would represent up to an 80% increase in terms of moisture content (*i.e.*, from about ±1% to about ±1.8%). It is also suspected that an increase in operator error may be part of the cause. It was apparent in the field that inserting the probe

Table 1. *R^2 and SE values for probe A at sensor lengths 6.0, 1.5, 1.0, and 0.5 cm for KDH and PINS.*

Sensor Length (cm)	Experimental Run			Mean	Std. Deviation	Sensor Length (cm)	Experimental Run			Mean	Std. Deviation
	1	2	3				1	2	3		
R^2—KDH						R^2—PINS					
6.0	0.98	0.95	0.98	0.97	0.02	6.0	0.96	0.96	0.89	0.94	0.04
1.5	0.95	0.92	0.97	0.95	0.03	1.5	0.91	0.93	0.94	0.93	0.02
1.0	0.95	0.92	0.94	0.94	0.02	1.0	0.96	0.92	0.97	0.95	0.03
0.5	0.96	0.98	0.89	0.94	0.05	0.5	0.96	0.98	0.81	0.92	0.09
SE—KDH						SE—PINS					
6.0	0.7	1.1	0.8	0.9	0.2	6.0	1.1	0.9	1.1	1.0	0.1
1.5	1.6	1.9	1.1	1.5	0.4	1.5	2.2	1.9	1.6	1.9	0.3
1.0	1.5	2.1	1.9	1.8	0.3	1.0	1.6	1.9	1.0	1.5	0.5
0.5	1.6	1.2	2.6	1.8	0.7	0.5	1.7	1.4	3.2	2.1	1.0

at an angle or failing to insert it fully could cause erroneous results. As the probe length is shortened, the relative magnitude of such errors would be expected to increase. Although the SE does increase with shorter probe length, at ±2% the absolute magnitude of the error is still acceptable for many purposes even at the shortest sensor length tested here. In fact, this error falls within the accuracy range that has been reported in the literature for a site-specific calibration using the full probe length on more complex soils (Cosh *et al.*, 2005; Delta-T Devices, 1999; Tsegaye *et al.*, 2004).

Influence of Grain Size

Although differences between the two sites appear minimal thus far, an analysis of variance was performed on the R^2 and SE values to provide a quantitative assessment of the influence of grain size. It was found that neither the R^2 values nor the SE values differed significantly between sites at the 95% confidence interval. These findings indicate that grain size does not have a significant influence on Theta probe performance, at least over the grain-size range considered here. Qualitatively, however, the shapes of the output curves do appear to differ in some cases (Figure 6).

Figure 6 shows a comparison of the grouped data sets for fine (PINS) *vs.* medium (KDH) sediment. The output curves are nearly identical at the 6.0-cm sensor length, indicating that grain size does not influence the sensitivity of the Theta probe as it is supplied by the manufacturer. As well, at a sensor length of 1.0 cm, the curves are also quite similar with the minimal difference almost entirely attributable to a single run. This suggests that some condition other than grain size (which was constant across runs) was responsible for the departure. Both temperature and salinity have been identified in the literature as environmental factors that may influence probe output (Kaleita, Heitman, and Logsdon, 2005), but the nature and magnitude of any such influence have not yet been clearly documented because findings are often conflicting from one situation to the next. At the other two shortened sensor lengths, larger and more consistent differences in the shapes of the output curves are apparent. Given the previous discussion, however, it does not seem likely that grain size effects are responsible for these differences. Because clear between-site differences are evident at only two of the four sampling depths, it seems more plausible that environmental conditions, such as temperature and salinity, and/or operator inconsistency were responsible.

Repeatability

An important question regarding the utility of the Delta-T Theta probe is the ability of the probe to conduct repeatable moisture measurements. Comparison of the multiple-run sequences shown in Figure 5 indicates that at KDH the repeatability was excellent. At both the longest and shortest probe lengths the output curves are consistently within ±1% of each other (in terms of moisture content predicted for a given measured voltage), which is within the range of expected error. For the 1.5-cm runs, this range expands slightly for moisture contents greater than about 10%, but the curves still remain within the ±2% SE. Finally, two of the curves for the 1.0-cm run agree well, but the third shows consistent differences. Because the latter run was conducted on a different day from the other two, it seems likely that changes in environmental conditions may have been responsible rather than probe inconsistency.

The PINS runs show a larger degree of interrun variability. For the full-length sensor, results are still quite good. At a probe length of 1.5 cm, Run 3 output falls 3%–4% below the

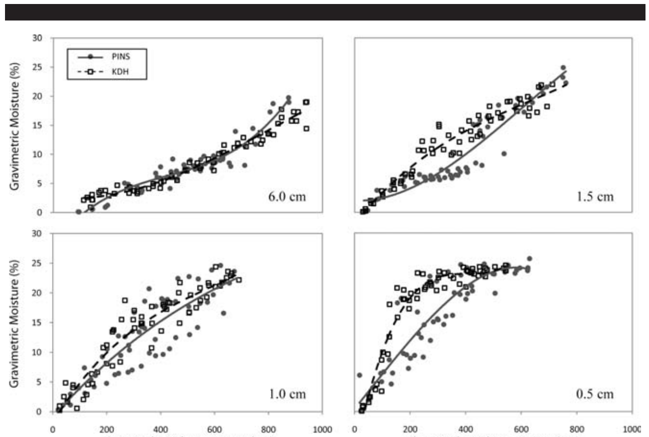

Figure 6. Calibration relationships at sensor lengths 6.0, 1.5, 1.0, and 0.5 cm illustrating differences in grain size between KDH (medium) and PINS (fine). Symbols represent measured values. Lines represent third-order polynomial calibration relationships.

other two runs over most of the output range. This largely results from the presence of a couple of outliers in the intermediate range, and visual examination shows that most of the measurements that comprise Run 3 fall well within the scatter of the other two runs. Hence, operator error on a few of the intermediate measurements could account for the observed differences. At both of the two shortest probe lengths, at least one run consistently departs from the other to a marked degree. Operator error does not seem to be the problem here because of the consistency of the differences throughout the run. Nonetheless, it is worth noting that the KDH runs were all conducted by the same operator, while five different persons participated in the PINS data collection. It also certainly remains possible that the observed inconsistencies were due to changing environmental conditions or probe unreliability.

The KDH results demonstrate that it is possible to get excellent repeatability, even at the shortest probe lengths. However, the PINS results suggest that care and attention to establish calibration relationships is advisable and that further attention to the influence of environmental conditions on probe output is warranted.

Interchangeability

A last issue considered here is that of the influence of probe length/sampling depth on probe interchangeability (Figure 7). Comparison of the multiple-probe sequences shown in Figure 7 indicates that at KDH the interchangeability was excellent. At the three longest sensor lengths, the output curve for probe B falls well within the scatter of the output curves for probe A. At the shortest probe length, the output curve for probe B consistently departs from probe A to a marked degree. Because the latter run was conducted on a different day from the others, it again seems likely that a change in environmental conditions may have been responsible rather than probe inconsistency.

The PINS runs show a larger degree of multiprobe variability; however, the resultant error stills falls within the acceptable limits. For the full-length probe, the output curve for probe B falls within the scatter of the output curves for probe A. For the 1.5- and 0.5-cm probe lengths, the output curves between the probes depart slightly at the middle and high moisture contents, respectively, but the curves still remain within ±2%–3% of each other. Finally, at the 1.0-cm probe length, two of the three runs for probe A consistently depart from that of probe B to a marked degree: however, the output curve for one run at probe A is nearly identical to that of Probe B. At both KDH and PINS, results demonstrate that it is possible to get excellent interchangeability, even at the shortest probe lengths.

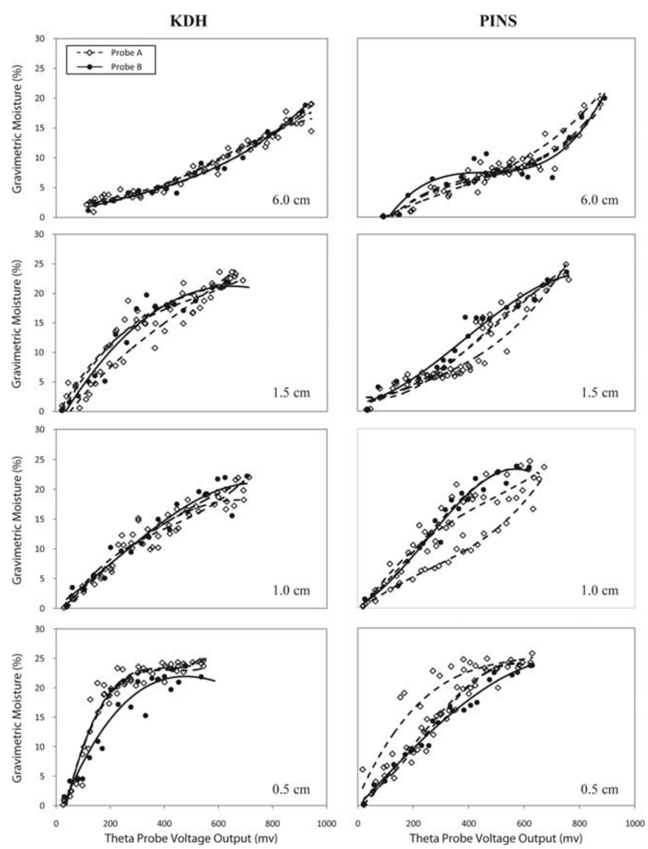

Figure 7. Calibration relationships at sensor lengths 6.0, 1.5, 1.0, and 0.5 cm for KDH and PINS. Symbols show measured values for experimental runs utilizing probe A and probe B. Lines represent third-order polynomial calibration relationships.

FINDINGS AND CONCLUSIONS

Several useful findings emerge from this study. The total output range of the probe decreased considerably as sensor length was reduced, with the practical result that the probe became less sensitive as sampling depth was decreased. However, quantitative assessments indicated that the probe measurements remained robust down to sampling depths as shallow as 0.5 cm. The relationships between probe output and laboratory-measured moisture content remained quite strong, with R^2 values consistently exceeding 0.90. The standard error did increase for shorter sensor lengths; however, the magnitude of error still falls within the accuracy ranges reported in the literature for site-specific calibrations at full sensor length. Analysis of variance indicated that grain size had no significant influence on the probe output, and neither the R^2 values nor the SE values differed significantly at the 95% confidence interval for the two sites considered here. Finally, while it was found that it is possible to achieve both excellent repeatability and interchangeability, several cases of consistent departures were identified both between runs and between probes. Given that repeatability and interchangeability were generally good, it is believed that other environmental parameters (such as temperature and salinity) and/or operator error may have played a role in generating the observed discrepancies. Additional work is needed to investigate these possibilities.

The overall goal of this research was to assess the reliability of the Delta-T Theta probe to conduct simple, fast, and effective measurements of very shallow depth moisture contents on beaches. Through the use of site-specific calibrations, the performance of the modified Delta-T probe demonstrates that it is possible to get excellent reliability even at very-shallow measurement depths.

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