Image Analysis and Hardware Developments for the Vision Cone Penetrometer (VisCPT)

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ABSTRACT

The vision cone penetrometer (VisCPT) fits a traditional cone penetrometer (CPT) with a camera to obtain continuous in situ soil images. A previously developed image analysis method determines several textural indices for each captured image. The textural index profiles can identify thin soil layers and lenses that may be undetected by the CPT. A newly redesigned VisCPT having a much higher resolution camera than in previous VisCPTs has been developed. The larger resolution expands the range of soil sizes that can be optically characterized by the system. Updated hardware and image analysis techniques will enhance the capabilities of the VisCPT for generating accurate soil profiles.

INTRODUCTION

The cone penetrometer (CPT) is an accurate in situ soil test that generates nearly continuous soil profiles through correlations between tip resistance, side friction, and pore pressures with soil types (Robertson et al. 1986, Kulhawy and Mayne 1990, Schneider et al. 2008, Abbaszadeh Shahri et al. 2015). The CPT holds many advantages over the Standard Penetration Test (SPT). However, unlike the CPT, the SPT affords the ability to gather soil samples for visual inspection and laboratory index testing. In response to this, the Vision Cone Penetrometer (VisCPT) was developed. The VisCPT captures video footage of soil during CPT advance. Image analysis is performed on the continuous stream of images. This analysis is able to detect thin soil strata not revealed in traditional CPT logs (Ghalib et al. 2000, Hryciw et al. 2009). A new version of the VisCPT has recently been fabricated. This paper describes the hardware improvements and investigates the potential to improve the existing image analysis method. With such improvements, the range of soil particle sizes that the VisCPT can optically characterize will be significantly expanded.

EARLIER VISION CONE PENETROMETERS (VISCPTS)

The original VisCPT shown in Fig. 1 (top) was developed by Raschke and Hryciw (1997). It equipped a traditional CPT device with two black and white charge coupled device (CCD) cameras. The camera closer to the penetrometer tip captured lower-magnification images, while the second camera captured higher-magnification ones. The lower-magnification camera's field of view was 14 mm (vertical), while the higher-magnification's was 2 mm (vertical). Both cameras had a resolution of only 768 x 494 pixels. The second generation VisCPT, shown in Fig. 1 (bottom), replaced the two previous cameras with one micro digital color CCD camera (Shin 2005). The device consisted of an electronic piezocone and a vision module containing the camera. The camera captured images with a 720 x 480 pixel resolution and a 10 mm field of view (vertical).

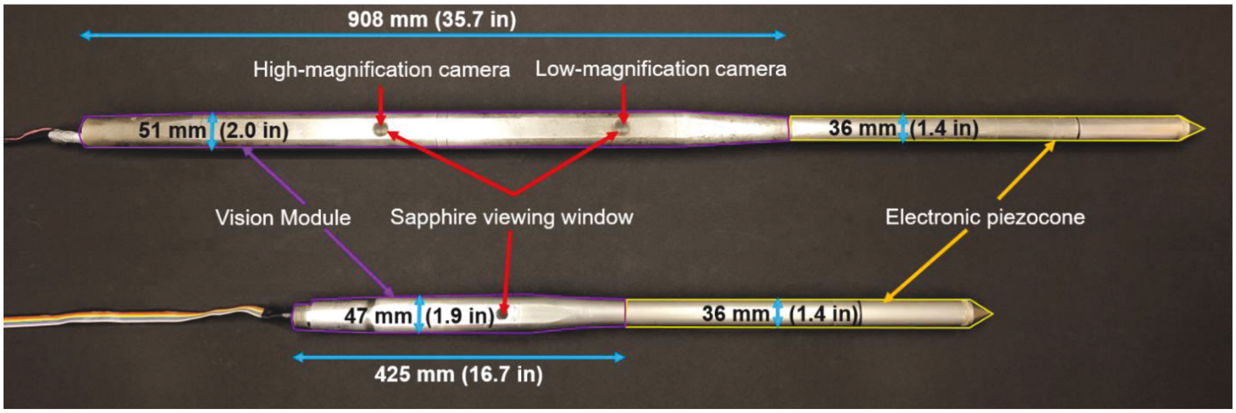

Figure 1. Earlier Vision Cone Penetrometers (VisCPTs). Top: Original VisCPT (1997), Bottom: Second generation VisCPT (2005).

One significant design feature of the first two generations of the VisCPT was the large diameter difference between the piezocone and the vision module. These larger diameters were necessary to house the internal video components that were commercially available at the time.

As the VisCPT is advanced into the ground at the standard rate of 2 cm/sec (0.8 in/sec), continuous images of the passing soil are captured through a sapphire viewing window. These images were analyzed using the Spatial Gray Level Dependence Method (SGLDM) proposed by Haralick et al. (1973). The SGLDM defines 14 textural indices based upon the spatial distributions of grayscale pixel intensity values in an image. As such, these indices will vary with particle size, soil colors, and image magnification. Ghalib et al. (2000) found that three of the indices: *Energy*, *Contrast*, and *Local Homogeneity* were most useful for delineating in situ soil layers. These textural indices could be plotted alongside the traditional CPT tip resistance, side friction, and pore pressure logs. They exhibited a higher resolving capability of thin soil layers than did traditional CPT logs. Details of the SGLDM and the descriptions and mathematical definitions of each textural index are found in Ghalib et al. (2000).

THE NEW VISCPT

The introduction of smaller, board-based microcameras warranted a redesign of the VisCPT. The new VisCPT camera module contains a high-speed digital interface. This allows high resolution images to be transmitted quickly enough to be viewed in real time and to be stored for later analysis. The interface uses a differential cable and an error correcting protocol to guarantee transmission. The highest resolution soil images are transmitted with the cone stationary using lossless compression. Lower resolution images are transmitted and stored with each depth pulse allowing less detailed analysis in real time. The camera itself has a long focal length and views the soil using a right-angled mirror through a sapphire viewing window. The long focal length enables the camera to view the passing soil with a small angle of view, therefore minimizing fisheye effects in the captured images. The exact value of the VisCPT camera's focal length is still to be determined. Careful control of lighting and aperture keep the image in focus even when thermal expansion and contraction of the physical components change the optical path. Also, this keeps soil in focus even if the viewing window is not in direct contact with the soil.

A 3D-printed prototype of the third generation VisCPT has been built and has undergone laboratory testing. The prototype is shown in Fig. 2(a); its cross-section is illustrated in Fig. 2(b). The prototype has an octagonal cross-section, with a 15.9 mm (0.63 in)-diameter sapphire viewing window centered on one of the flat sides. One end of the prototype connects to a 1500 mm^2 (2.3 in^2) electronic CPT piezocone. The other end connects with a CPT rod. An e-Con Systems See3CAM_80 13 Megapixel UVC USB camera is used. This high resolution camera enables characterization of soils into the silt range. For lab bench calibration testing, the VisCPT prototype was connected to a BK Precision 1735A DC power supply that controlled the illumination of the soil through the sapphire window. Figure 3 shows the lab testing system. The octagonal vision module shown in Fig. 2(b) can contain a 1500 mm^2 (2.3 in^2) inscribed circle, which is the same area as the piezocone. Thus, there will be a similar cross-section between these two components of this VisCPT. This level of uniformity was not possible with the earlier VisCPTs.

Investigating Previous and New VisCPT Image Analysis Methods: The new UVC USB camera has a resolution of 13 Megapixels, which is almost 38 times greater than that of the second generation VisCPT. Thus, the new VisCPT required a re-evaluation of the image analysis capabilities for distinguishing particle sizes. To this end, controlled laboratory tests were conducted. A glacial sand termed 2NS by the Michigan Department of Transportation (MDOT, 2010) was sieved for its constituent size fractions. Multiple images of each size fraction were captured by the new VisCPT. *Energy*, *Contrast*, *Local Homogeneity*, as well as two other textural indices, *Contrast* and *Correlation*, were determined. In addition, another image analysis technique utilizing the Haar Wavelet Transform (HWT) was considered.

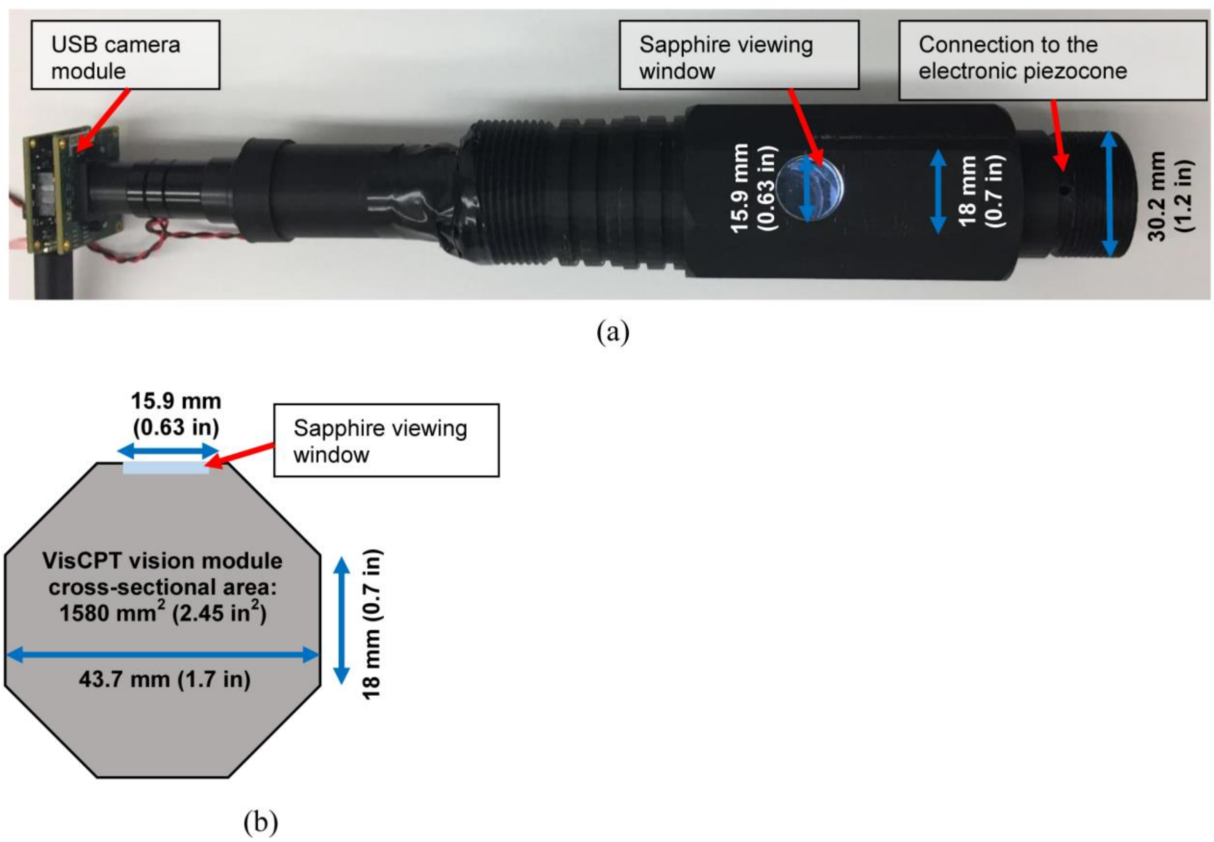

Figure 2. 3D-printed prototype of the third generation VisCPT vision module. (a) Vision module, (b) Schematic of the module's cross-section.

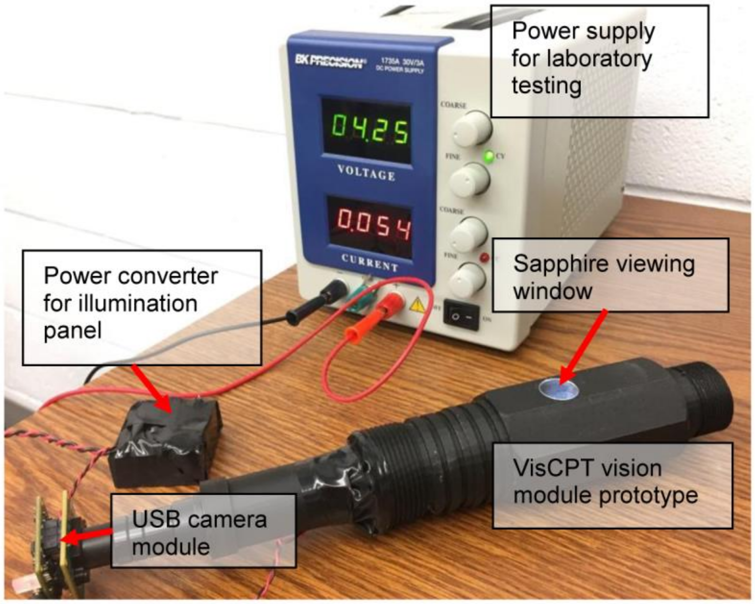

Figure 3. Prototype of the new VisCPT.

The HWT image analysis method has been used to estimate particle sizes of coarse-grained soils in SedImaging and FieldSed tests (Ohm and Hryciw 2014, Ventola and Hryciw 2019). The method analyzes the spatial grayscale intensity distributions across small, overlapping areas throughout an image of a sedimented soil. For each area, the method determines a wavelet index, *CA*. The *CA* is a function of the spatial grayscale distribution and therefore, the sizes of the particles within the area. In general, larger soil particles yield larger *CA* values. A comprehensive definition of *CA* is provided in Hryciw et al. (2015). The *CA* has been related to the average sieve-defined diameter of a soil particle in pixel units, *pixels per particle diameter* (*PPD*), through an empirical correlation having the form

$$PPD = \left(\frac{CA}{a}\right)^{b} \qquad [1]$$

where a and b are empirical constants with values of 2.4 and 5.1 respectively for saturated, multi-colored coarse-grained sand (Jung et al. 2008, Hryciw et al. 2009). Of course, the *PPD* is related to both the actual soil particle size and camera magnification, *MAG* [pix/mm]. Once the *PPD* for an analysis area is calculated using Eq. 1, the sieve-equivalent particle size, d [mm] for that area is computed by

$$d = \frac{PPD}{MAG} \qquad [2]$$

Laboratory images collected with the new VisCPT prototype enabled a comparison of the Haralick textural indices to the HWT-based results, with the potential to utilize or combine the two methods.

IMAGE CAPTURE WITH THE NEW VISCPT SYSTEM

To investigate the two image analysis methods with the new VisCPT, soil images with resolutions of 4208 x 3120 pixels were captured using the system in Fig. 3. The voltage from the power supply was varied to study the effect of image brightness on the indices. To determine the appropriate voltage, dry 2NS soil particles of different size ranges were photographed at a series of voltages. Table 1 summarizes the different particle sizes used for this investigation. All soil images were captured at the same camera magnification (246.6 pix/mm) and with the same camera settings (e.g. sharpness, white balance, exposure, etc.). Five different images for each size range were captured; a total of 40 soil images at each voltage were obtained. Nine different voltages ranging from 3.75 Volts to 7.00 Volts were analyzed. Through a comparison (not detailed here) of voltages/illuminations and the resulting textural indices, 4.25 Volts was determined to provide the ideal illumination for this investigation. Figure 4 shows one of the five soil images captured for each size range using 4.25 Volts. The images in Fig. 4 are 2048 x 2048 pixels. This image size was used throughout this investigation.

Table 1. 2NS sand particle size ranges used in this study.

Sample	Sieve Size Range[1]	Particle Size Range [mm] (Midpoint)	Midpoint *PPD* [pix]
a	#10-#12	1.7 – 2.0 (1.85)	456.2
b	#18-#25	0.71 – 1.00 (0.86)	210.8
c	#30-#35	0.5 – 0.6 (0.55)	135.6
d	#50-#70	0.212 – 0.300 (0.256)	63.1
e	#70-#100	0.150 – 0.212 (0.181)	44.6
f	#100-#170	0.09 – 0.15 (0.12)	29.6
g	#200-#270	0.053 – 0.075 (0.064)	15.8
h	#270-#400	0.038 – 0.053 (0.046)	11.2

[1] Sieve size ranges were gathered in accordance with ASTM (2014) C136/C136M-14

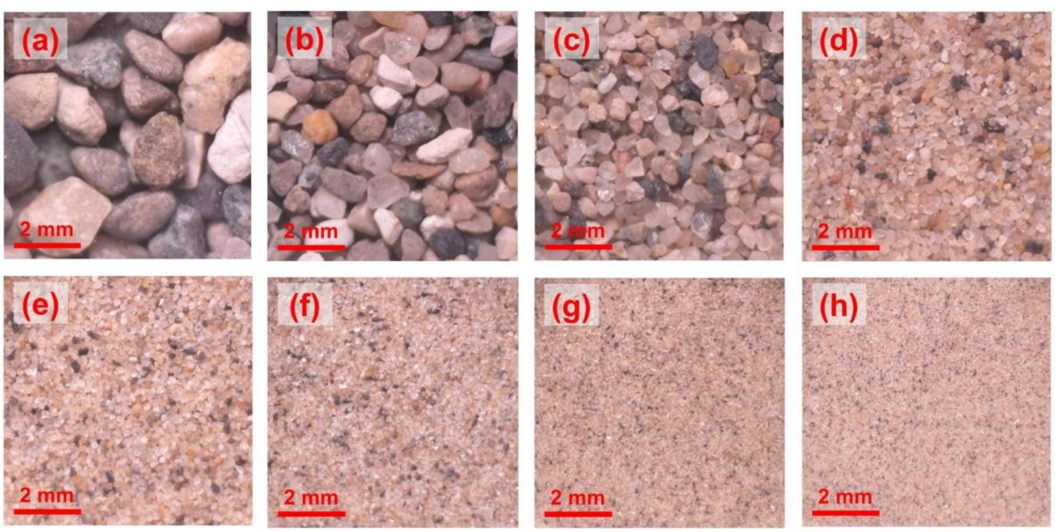

Figure 4. Photos of each 2NS sample from Table 1.

TEXTURAL INDICES IMAGE ANALYSIS FOR THE NEW VISCPT SYSTEM

Five Haralick textural indices: *Contrast*, *Correlation*, *Homogeneity*, *Variance*, and *Energy* were computed for the 40 images of various-sized soil particles from Table 1 and Fig. 4. In Fig. 5, the Haralick textural indices were plotted versus the known midpoint *PPD* value for each image. *Contrast, Correlation, Homogeneity,* and *Variance* all exhibit clear trends with *PPD*; *Contrast* has an inverse relationship with *PPD*, while *Correlation*, *Homogeneity*, and *Variance*

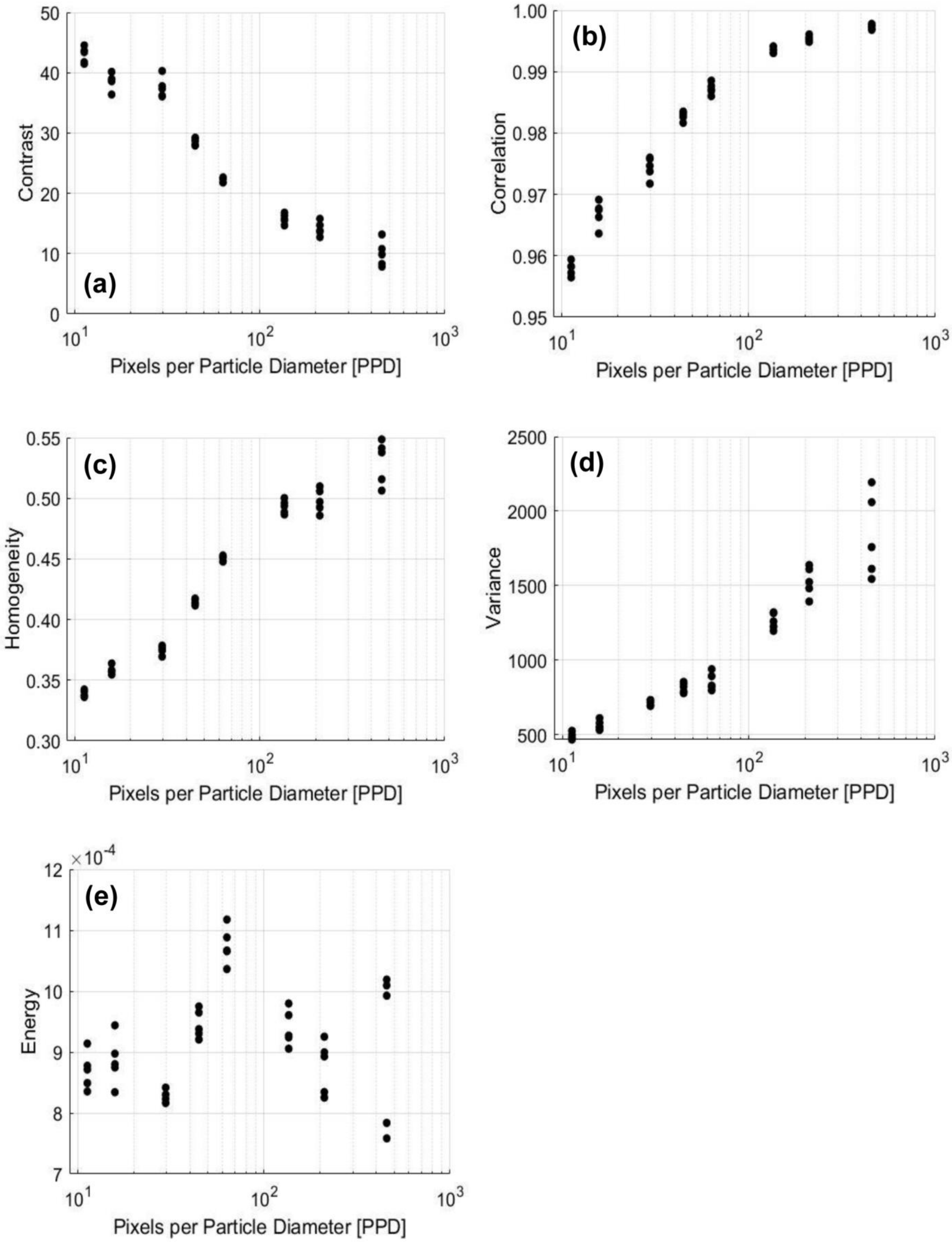

Figure 5. Various Haralick textural indices versus Pixels per Particle Diameter *(PPD)*: (a) *Contrast* vs. *PPD*, (b) *Correlation* vs. *PPD*, (c) *Homogeneity* vs. *PPD*, (d) *Variance* vs. *PPD*, (e) *Energy* vs. *PPD*.

all have direct relationships with *PPD*. Furthermore, there is very high reproducibility between the five different soil images taken at each *PPD*. Figure 5 shows that *Contrast*, *Correlation*, *Homogeneity*, and *Variance* are promising textural indices that will eventually be used to characterize particles over a size range spanning nearly two orders of magnitude, from the silt range to medium sand.

In contrast to the other indices, *Energy* (Fig. 5(e)) appears to have no correlation with *PPD*. Unlike the conclusions reached by Ghalib (2000), it appears that *Energy* cannot be used to determine soil particle sizes. The reason for the discrepancy between Fig. 5(e) and Ghalib (2000) likely lies in the VisCPT camera magnification. Ghalib (2000) was using the earlier generations of the VisCPT, which utilized significantly lower magnification cameras. As such, Ghalib was reporting *PPD* values for sands between 1 and 30 pixels; the *PPD* values reported with the new VisCPT range between 10 and 500 pixels Therefore, the correlation Ghalib (2000) reported between *Energy* and *PPD* is not appropriate for the larger *PPD*s shown in Fig. 5.

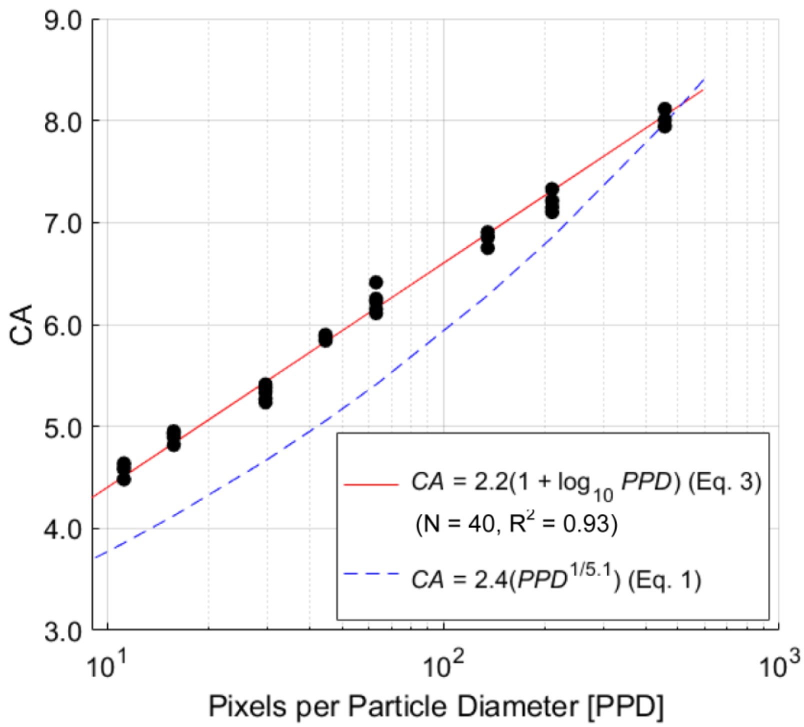

Figure 6. HWT-based wavelet index, *CA* versus Pixels per Particle Diameter (*PPD*).

HWT IMAGE ANALYSIS WITH THE NEW VISCPT SYSTEM

The same 40 images used to compute the textural indices were also analyzed with the HWT-based analysis method. The wavelet indices, *CA,* for all of the images are plotted versus their known midpoint *PPD* in Fig. 6. There is clearly a well-defined positive correlation between *CA* and *PPD*. A best-fit line for the data is:

$$CA = 2.2\left(1 + \log_{10} PPD\right) \qquad [3]$$

Figure 6 also shows the earlier non-linear relationship between *CA* and *PPD* given by Eq. (1). Hryciw et al. (2015) had shown that this relationship should theoretically be linear. At that time, the use of low resolution cameras or the analysis of areas in an image that were too small caused the non-linearity. The new data captured for this paper by the higher resolution VisCPT camera and analysis of larger areas in an image confirmed this. This marks a significant advance for the VisCPT as the image analysis has now become somewhat less empirical.

DISCUSSION

Both the Haralick textural indices, with the exception of *Energy*, as well as the HWT-based image analysis were shown as promising methods for determining soil particle sizes from the silt range to medium sand. Additional research is needed to generate formal correlations between the Haralick textural indices and *PPD*. Future work will also determine how the textural indices and the HWT-based methods can be effectively combined for use with the new VisCPT.

It is important to emphasize that the soil images used in this preliminary investigation utilized only one sand (2NS). Furthermore, the specimens were dry. Additional tests are therefore needed on other sands to refine the required constants for Eq. (3). The authors believe that the constants will vary with soil color and its uniformity, particle translucency, and light reflectivity. Future research will involve repeating the investigation for other soil types, as well as for saturated conditions. Doing so will determine if these image analysis methods can also be used to distinguish between different soils.

CONCLUSIONS

A new version of the Vision Cone Penetrometer (VisCPT) – which utilizes a high resolution, 13 Megapixel, UVC USB camera – has been developed. The new hardware design merited an investigation of the existing image analysis method used with previous VisCPTs and with laboratory image-based soil characterization tests. The results showed that four of Haralick's textural indices were able to distinguish soil particle sizes ranging from silt to medium sand. Another image analysis method based on the Haar Wavelet Transform (HWT), also characterized the different particle sizes. Future research will involve testing a wider range of soil types and moisture conditions.

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REFERENCES

Abbaszadeh Shahri, A., Malehmir, A., and Juhlin, C., (2015). "Soil Classification Analysis Based on Piezocone Penetration Test Data – A Case Study From a Quick-Clay Landslide Site in Southwestern Sweden." *Engrg. Geology.* 189: 32-47.

ASTM (2014). "Standard test method for sieve analysis of fine and coarse aggregates." ASTM C136/C136M-14, West Conshohocken, PA.

Ghalib, A.M., Hryciw, R.D., and Susila, E. (2000). "Soil Stratigraphy Delineation by VisCPT." *Proc. ASCE Geo-Institute Innovations and Applications in Geotechnical Site Characterization*, 65-79.

Haralick, R.M., Shanmugam, K., and Dinstein, I. (1973). "Textural Features for Image Classification." *IEEE Transactions on System, Man, and Cybernetics*, 3(6): 610-621.

Hryciw, R. D., Jung, Y., Susila, E., and Ibrahim, A. (2009). "Thin soil layer detection by VisCPT and FEM simulations." *Proc., 17th Int. Conf. on Soil Mechanics and Geotechnical Engineering (ICSMGE)*, IOS, Amsterdam, Netherlands, 1052–1055.

Hryciw, R.D., Ohm H-S, and Zhou J. (2015). "Theoretical basis for optical granulometry by wavelet transformation." *J. Comput. Civil Eng.* 29(3): 1-10.

Jung, Y., Hryciw, R.D. and Elsworth, D. (2008). "Vision Cone Penetrometer Calibration for Soil Grain Size." *Proc. Of the 3rd Int. Conf. on Site Characterization*, Taipei, Taiwan: 1303-1308.

Kulhawy, F.H. and Mayne, P.W. (1990). *Manual on Estimating Soil Properties for Foundation Design.* Report EL-6800, Electric Power Research Institute, Palo Alto, p. 306.

Michigan Department of Transportation (MDOT). (2010). "Materials Source Guide." *902,* Lansing, MI.

Ohm, H.-S. and Hryciw, R.D. (2014). "Size Distribution of Coarse-Grained Soil by Sedimaging." *J. Geotech. Geoenviron. Engrg.,* 140(4) 04013053.

Raschke, S.A. and Hryciw, R.D. (1997). "Vision Cone Penetrometer (VisCPT) for Direct Subsurface Soil Observation." *J. Geotech. Geoenviron. Engrg*., 123 (11): 1074-1076.

Robertson, P.K., Campanella, R.G., Gillespie, D., and Grieg, J. (1986). "Use of Piezometer Cone Data," *Use of In Situ Tests in Geothn. Engrg.,* GSP 6, ASCE, Reston, VA: 1263-1280.

Schneider, J.A., Randolph, M.F., Mayne, P.W., and Ramsey, N.R. (2008). "Analysis of Factors Influencing Soil Classification Using Normalized Piezocone Tip Resistance and Pore Pressure Parameters." *J. Geotech. Geoenviron. Engrg*. 134(11): 1569-1586.

Shin, S. (2005). *High Resolution Subsurface Soil Characterization by Image Analysis and Vision CPT*, Ph.D. Thesis, University of Michigan.

Ventola, A., and Hryciw, R. D. (2019). "On-Site Particle Size Distribution by FieldSed," In Meehan, C. L., Kumar, S., Pando, M. A., and Coe, J. T. *Geo-Congress 2019: Engineering Geology, Site Characterization, and Geophysics*. Paper presented at *ASCE Geo-Congress 2019: The Eighth International Conference on Case Histories in Geotechnical Engineering*, Philadelphia, PA, 24 – 27 March (143-151).