Characterization of surface topography of sand

Caractéristiques de surface de sables

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ABSTRACT

This study was conducted to investigate surface characteristics of sand particles. Surface topography of sand particles was determined in 3-D using a commercially available optical profiler. Measurements were made on areas that had side dimensions on the order of 0.1 mm at a lateral resolution of 0.3 µm and height resolution of less than 6 nm. The 3-D representation of a surface obtained using the measurement system is analyzed to determine 3-D as well as 2-D surface texture parameters. The parameters included amplitude, spacing, hybrid (amplitude and spacing), and functional (performance related) parameters. Tests were conducted on two silica sands: one rounded and one angular. The tests were conducted in 2 sets, initially single measurements were made on multiple particles and then multiple measurements were made on a single sand particle. Results of the analysis indicated that surface texture parameters were statistically dissimilar for the rounded and angular sands. In addition, single measurements can be used to investigate surface texture characteristics of sands.

RÉSUMÉ

Cette étude a été effectuée pour examiner les caractéristiques de surface de particules de sable. Les caractéristiques de surface des particules de sable ont été déterminées à l'aide d'un système de balayage optique en 3 D commercialement disponible dans le marché. Les mesures ont été faites sur les surfaces qui ont des dimensions latérales de l'ordre de 0,1 mm à une résolution latérale de 0,3 µm et une résolution verticale de moins de 6 nm. La représentation en 3 D d'une surface obtenue utilisant le système de mesure est analysée pour déterminer les paramètres de texture de surface aussi bien en 3 D qu'en 2 D. Les paramètres pris en considération sont l'amplitude, l'espacement, une variable hybride constituée à la fois de l'amplitude et de l'espacement, et un paramètre fonctionnel, soit la performance de l'essai. Les tests ont été effectués selon deux groupes de sables siliceux : un arrondi et un angulaire. Les essais ont été menés sur deux (2) séries ; initialement les mesures optiques sont effectuées d'abord par l'examen individuel des grains sur un ensemble constitue d'une multitude de particules et ensuite les mesures ont été effectuées grain par grain. Les résultats de l'etude ont indiqué que ces paramètres de texture de surface étaient statistiquement dissemblables pour les sables arrondis et angulaires. Enfin, les mesures individuelles peuvent être utilisées pour examiner les caractéristiques de texture de surface de sables.

1 INTRODUCTION

Size, shape, and surface characteristics of soil particles can have significant effects on the engineering properties and behavior of soil masses. The interaction between adjacent particles and in turn, the overall fabric, is affected by texture due to the contacts made at the asperities present on the surface of soils. Surface texture of soil particles can affect both mechanical and transport properties of granular soils. Specific surface of soils depends on surface roughness. The contact area and resulting contact stresses affect shearing resistance and deformation characteristics of coarse-grained soils (Mitchell, 1993). Both peak shear strength and void ratio range for sands were experimentally determined to be functions of surface roughness (Oda et al., 1971 as referenced by Matsushima and Konagai, 2001). Similarly, Matsushima and Konagai (2001) determined that peak shear strength increased with surface roughness using numerical analysis. Koplik et al. (1984) stated "a long-standing problem in the physics of random media is the calculation of transport coefficients in terms of the medium's microscopic geometry." Conduction through soils (hydraulic, chemical, thermal, electrical) is affected by surface characteristics due to texture effects on contact between particles as well as texture effects on void structure and void size distribution. In hydraulic analyses, saturated hydraulic conductivity of granular soils has been described as a function of pore shapes and tortuosity factors in addition to void ratio, which are all affected by surface roughness. Wetting characteristics of soils are also affected by surface texture. Solid matter present in pore liquids can have variably interact with different soil surfaces. This phenomenon has implications for contaminant transport as well as remediation analyses (Sharma and Reddy, 2004).

Even though the effects of surface characteristics of soils on the engineering behavior of soil masses are recognized, surface texture characteristics have generally been represented using simplistic, qualitative analysis or texture characteristics have been lumped into generalized empirical terms that describe the effects of these parameters on soil behavior (Mitchell, 1993). The main reason for this trend has been the difficulty of accurate and representative determination of surface texture characteristics of soil particles. Recent developments in image and microscopy analyses methods allow for detailed quantitative analysis of surface texture of soils. This study was conducted to determine the surface texture characteristics of sands using optical profilometry.

2 SURFACE TEXTURE ANALYSIS

Texture parameters that are commonly used in surface metrology analysis include amplitude, spatial, hybrid, and functional parameters (Whitehouse, 2002; Cohen, 2004). These parameters may be determined on raw (unfiltered) profiles (referred to as preliminary profiles) directly or on filtered profiles at roughness, waviness, or form scales. Roughness scale is used commonly in the surface metrology discipline and is also adopted in this study. Use of notation R_i describes parameter "i" determined at the roughness scale. 2-D parameters are provided in this section for simplicity. Similar concepts are applicable to the determination of these parameters in 3-D.

The common amplitude parameters include average roughness (R_a); RMS roughness (R_q); second and third moments of height distribution: skewness (R_{sk}) and kurtosis (R_{ku}), respectively; maximum peak-to-valley height (R_t); average height of high peaks (R_{pm}); average depth of low valleys (R_{vm}); and average peak-to-valley height (R_z). R_a is determined as:

$$R_a = \frac{1}{L_x}\int_0^{L_x} |Z(x)| dx \tag{1}$$

where, L_x is the length of a profile along a horizontal direction, x, and $Z(x)$ is the function representing the vertical height of the profile with respect to a horizontal best-fit line (with a mean height of zero). R_a quantifies the absolute magnitude of profile heights. R_q is the root mean square amplitude parameter. These parameters are not sensitive to the distribution, magnitude, or directional variations of peaks and valleys in a profile. The polarity of a profile is maintained in the skewness analysis and therefore R_{sk} may be used to assess the similarity of a surface (around a mean line). R_{ku} may be used to determine the deviation of amplitude distribution for a surface from a normal distribution (Gaussian distribution), which may be used to detect anomalies on a surface (Cohen, 2004). A surface with normally distributed textures is expected to have an R_{ku} of 3. R_{ku} may also be used to estimate the sharpness/bluntness of peaks or valleys (Whitehouse, 2002). Softer features result in R_{ku} less than 3 and sharper features result in R_{ku} that are greater than 3.

R_t is the maximum peak-to-valley height (difference between the height of the highest peak and depth of the deepest valley), which needs to be determined on a high number of surfaces to obtain statistically significant results. R_t is a divergent parameter (*i.e.*, it increases as a greater surface area is investigated). An averaged peak-to-valley height (R_z) is used to provide a stable peak-to-valley amplitude parameter for a given surface (Cohen, 2004). This parameter is calculated as the difference in height between the average of 10 highest peaks (R_{pm}) and the average of 10 lowest valleys (R_{vm}) measured on a surface. Overall, the amplitude parameters provide little information about spatial distribution of texture features on a surface.

The spatial texture parameters are related to the spacing of surface features. RS is the average distance between local peaks and RS_m is the mean width of texture features. RS_m represents the average distance between the positive/upward crossings of the profile over the mean line. RS and RS_m are equivalent for simple periodic profiles. RP_c is the number of peaks above the mean line for a given profile. The spatial parameters do not provide information related to the amplitude characteristics of a profile (Whitehouse, 2002).

The hybrid parameters combine amplitude and spatial analysis. These parameters include average slope ($R_{\Delta a}$); RMS slope ($R_{\Delta q}$); and average wavelength ($R_{\lambda q}$). The average slope is calculated as:

$$R_{\Delta a} = \frac{1}{L_x}\int_0^{L}\left|\frac{d(z)}{d(x)}\right| dx \tag{2}$$

The RMS slope ($R_{\Delta q}$) is the standard deviation of the average slope and is calculated as:

$$R_{\Delta q} = \left[\frac{1}{L_x}\int_0^{L}\left(\frac{dZ(x)}{dx} - \left\langle\frac{dZ(x)}{dx}\right\rangle\right)^2 dx\right]^{1/2} \tag{3}$$

where the term in the brackets, < >, represents the average value of all slopes along the profile direction. Analysis of distribution of slopes can be used to differentiate between peaks and valleys along varying directions.

The average wavelength ($R_{\lambda q}$) provides a measure of the dominant spatial wavelength for a profile weighted by the amplitude of the components at varying wavelengths that comprise the profile. $R_{\lambda q}$ can be used to differentiate between dominant long wavelength and short wavelength profile structures (Cohen, 2004). $R_{\lambda q}$ is calculated as:

$$R_{\lambda q} = 2\pi \frac{R_q}{R_{\Delta q}} \tag{4}$$

The functional parameters have generally been developed in relation to an intended use of a material (Whitehouse, 2002). A set of functional parameters that can be used for sand is material ratio (also referred to as bearing ratio) parameters. In 2-D, a material ratio curve is generated by assuming that a horizontal line is moving through a profile from the highest peak to the lowest valley (Fig. 1). The percentage of contact the horizontal line would make with the profile is quantified at each level. The curve provides the material-to-air (or other material) ratio at any given depth. The y-axis is the total height of the profile (from the lowest valley to the highest peak) and the x-axis is the percent material above a corresponding height in a material ratio graph. R_k is the core roughness depth. The cutoff values used to determine R_k are based on the intersection points of the straight line that passes through the lowest slope portion of the material curve and the vertical boundary lines corresponding to 0% and 100% on the x-axis. Mr1 and Mr2 closely approximate the upper and lower boundaries of the core roughness, respectively. R_{pk} and R_{vk} represent the average height of the peaks and the average depth of the valleys, respectively around the core roughness. Material ratio parameters can be used for progressive determination of contact area (and thus contact stresses) with depth. The amount of material removed from the profile under applied load may be estimated as well as interlocking or filling of adjacent materials in the profile may be determined using material ratio analysis.

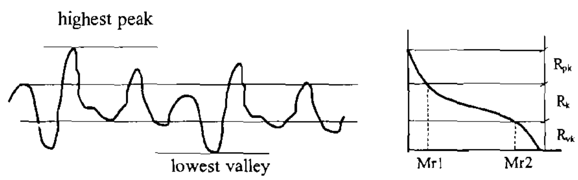

Figure 1. Material ratio parameters

The Surface Area Index (SAI) is determined as the quotient of a measured surface area to the area of a perfectly smooth surface at the same lateral resolution (Brown et al., 1993).

3 TESTING PROGRAM

A commercially available optical profiler (WYKO NT2000 – Cohen et al., 1992) was used in the study. The device includes a microscope, which provides the "image" of a surface, and specially designed interferometers, which provide the height information comprising the surface. The instrument is capable of making measurements over various fields of view from approximately 100 μm X 100 μm with lateral resolution on the order of microns to 7 mm x 5 mm with lateral resolution on the order of 20 μm. The height resolution is approximately 6nm for the Vertical Scanning Interferometric mode and less than 0.3 nm for the Phase Shifting Interferometric mode, which is used for applications when the average roughness of a surface (R_a) is less than 50 nm (Cohen, 2004). A field of view of 120 μm x 91 μm, a lateral resolution of 0.33 μm, and a height resolution < 6 nm were used in this study. Surface data were obtained in 3-D and 2-D profiles were extracted from the measured data to obtain 2-D parameters. Data were analyzed using procedures described in ANSI/ASME 46.1 (2002) and ISO 13565-2 (1998).

Tests were conducted on 2 silica sands: Ottawa sand and Granusil® sand. Ottawa sand originates in the St. Peter deposit of Ottawa, Illinois, can be described as a reworked beach sand, has rounded to subrounded particles, conforms to ASTM C778, and was obtained through U.S. Silica Company. A sorted Ottawa sand (ASTM 20/30) with particle diameters between 0.60 and 0.85 mm was used in the study. Granusil® sand originates in Emmett, Idaho, is a naturally occurring angular to subangular sand, is processed using a rod mill, and was obtained through Unimin Corporation. The Granusil® 4095 sand was sorted to obtain particle diameters between 0.60 and 0.85 mm.

The experimental program consisted of 2 sets of tests. Initially single measurements were made on multiple particles and then multiple measurements were made on a single particle. The initial single measurements on multiple particles were used for both sands, whereas, the second set of tests were used only for Ottawa sand. The sand particles were mounted on a glass plate with 2-part epoxy for the initial set of tests. The sand particles were mounted at approximately 3-mm-intervals along a linear axis on the plate. The plate was advanced along a linear path underneath the profiler and a single measurement was recorded on each sand particle. A specimen holder was designed and constructed for the second set of tests. The device consisted of a 107:1 gearbox, a drill chuck, manual rotary handle, a counter, and a mounting needle for the test specimen. A sand particle was attached to the end of the mounting needle using 2-part epoxy. The arrangement allowed for controlled rotation of a specimen around a fixed axis while maintaining a clear field of view for the specimen, free from shadows or other interferences. Measurements along a single continuous strip around a specimen were taken. A 360-degree rotation was completed in 107 turns of the manual rotary handle. An image was obtained after each 10 turns of the gearbox and therefore 11 measurements were made on each specimen.

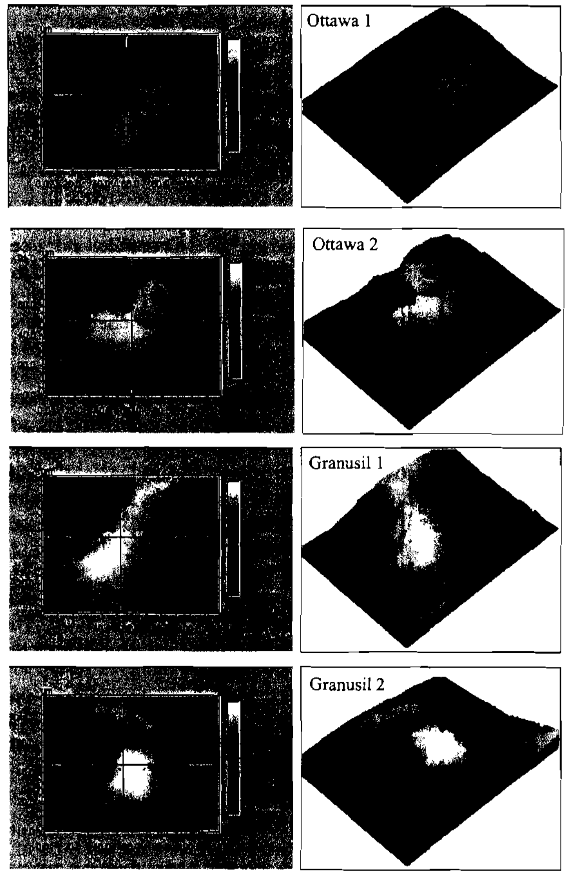

Figure 2. Graphical representation of data obtained for Ottawa and Granusil® sands

4 RESULTS AND DISCUSSION

Typical examples of images obtained for the two sands are presented in Fig. 2 (contour maps and 3-D views). As can be seen in the figure, it is not possible to differentiate between the sands using visual inspection of the images.

Various texture parameters determined for the sands are provided in Table 1. Results of the tests that consisted of a single measurement on multiple sand particles are presented in the table. Average texture parameters are presented for 35 particles of each sand. The variability in the data was high: the average coefficients of variation (COVs) for the parameters presented in Table 1 for the angular Granusil® sand and the rounded Ottawa sand were 56% and 42%, respectively. The negative R_{sk} values and the absolute magnitudes of R_{vm} relative to R_{pm} indicate the dominant presence of valleys on the surfaces of both sands. The R_{ku} values indicate near normal distribution of texture features on the sands. In general, the values obtained for Granusil® sand are higher than the values obtained for the Ottawa sand indicating an overall "rougher" surface texture for the Granusil® soil. While Barrett (1980) identified roundness and surface texture as independent particle shape parameters, in the current study it was determined that surface texture was directly related to roundness. The surface texture parameters provided in Table 1 were determined to be significantly different for the two sands using t-tests at 95% significance level with the exception of Mr1 and Mr2. The similarity of Mr1 and Mr2 indicate that similar percentage of texture features form the core, peak, and valley structures of the surfaces of the sands. However, the amplitudes of the texture features are significantly different between the two sands.

Table 1: 3-D Texture Parameters

Parameter	Ottawa	Granusil®
R_a (μm)	3.286	7.514
R_q (μm)	4.116	9.259
R_{sk}	-0.59	-0.66
R_{ku}	3.49	3.68
R_t (μm)	23.071	47.347
R_{pm} (μm)	7.877	16.084
R_{vm} (μm)	-13.353	-28.212
R_z (μm)	21.230	44.296
R_{pk} (μm)	1.342	2.402
R_{vk} (μm)	4.762	10.279
R_k (μm)	9.574	22.300
Mr1 (%)	6.1	4.8
Mr2 (%)	85.6	85.5
SAI	1.259	1.568

[1] "-" indicates below mean line
[2] individual slope calculations were made along the x- and y-directions

Amplitude parameters (R_a, R_q, R_{sk}, R_{ku}, R_t, R_p – height of the highest peak measured on a surface, R_v – depth of the lowest valley measured on a surface) were reported for a finer Ottawa sand and a sand obtained from Unimin Corporation (Alshibli and Alsaleh, 2004). The amplitude measurements provided by Alshibli and Alsaleh (2004) were 2 to over 10 times lower than the values obtained in the current study with similar values obtained for the two sands (they did not perform statistical analysis for comparison of the test data). The sands that were used in the two studies were obtained from the same sources; however, the gradations of the sands were different, which may have caused the differences in the amplitude values. While similar test devices were used in the two studies, there were differences in test conditions and data analyses. The sands were coated with gold in the study by Alshibli and Alsaleh (2004). In addition, they have shown "R" parameters in their definitions; however, scale of measurement and filtering techniques were not clearly described in the paper. The scale of data analyses and filtering techniques used significantly affect determination of surface texture parameters and need to be provided for reference in texture analysis.

Texture parameters determined on the 2-D profiles extracted from the measured 3-D data for the 35 particles of each sand are provided in Table 2. Determination of texture parameters in x- and y-directions allow for identifying directional characteristics of surface texture of the sands. Ratios of the 2-D parameters in the x- and y-directions are also provided in the table. These ratios are used to estimate the isotropy of the measured surfaces. The texture parameters obtained using the 2-D analysis are lower than the values obtained using the 3-D analysis. The 2-D analysis does not allow for determining the full extent of the surface roughness of the test soils. However, the 2-D values obtained for Granusil® sand are generally higher than the values obtained for the Ottawa sand indicating an overall "rougher" surface texture for the Granusil® soil similar to the trend observed for 3-D data. Anisotropy was observed for the sands based on all the measured parameters to varying degrees. The anisotropy observed for the Granusil® sand was higher than the anisotropy observed for the Ottawa sand.

Table 2: 2-D Texture Parameters

Parameter	Ottawa	Granusil®
X R_a (μm)	1.256	2.683
Y R_a (μm)	1.219	2.257
X R_z (μm)	6.492	12.388
Y R_z (μm)	5.898	9.916
X RP_c (mm^{-1})	9.3	7.4
Y RP_c (mm^{-1})	10.3	7.9
X $R_{\Delta q}$ (rad)	0.393	0.576
Y $R_{\Delta q}$ (rad)	0.380	0.550
X $R_{\lambda q}$ (μm)	25.173	34.644
Y $R_{\lambda q}$ (μm)	25.344	31.859
X R_{pk} (μm)	1.107	1.730
Y R_{pk} (μm)	0.905	1.790
X R_{vk} (μm)	2.606	5.676
Y R_{vk} (μm)	2.416	4.458
X R_k (μm)	2.759	5.694
Y R_k (μm)	2.830	4.800
X R_a / Y R_a	1.10	1.21
X R_z / Y R_z	1.16	1.25
X RP_c / Y RP_c	1.06	1.14
X $R_{\Delta q}$ / Y $R_{\Delta q}$	1.05	1.06
X $R_{\lambda q}$ / Y $R_{\lambda q}$	1.03	1.10

The second set of tests was conducted to assess the effectiveness of single measurements on particles for determining the surface texture characteristics of sand. These tests were conducted only for Ottawa sand. A total of 11 measurements were conducted on each specimen. Comparisons were made between the data obtained in the second set of tests. The surface texture data were statistically similar for all of the specimens tested in the second set of tests. Comparisons were also made between the results obtained in the two sets of tests. It was determined that 79% of the data were similar between the two sets of experiments. Surface texture characteristics of sands can be determined using single measurements on multiple particles.

The predictive significance of the various surface texture parameters and measurement scales can be determined by establishing correlations to performance parameters such as shear behavior and transport characteristics. Studies need to be conducted to provide such analysis, which was outside the scope of this study.

5 CONCLUSIONS

This study was conducted to investigate surface characteristics of sand particles. Surface topography of sand particles was determined in 3-D using a commercially available optical profiler.

The following conclusions were drawn based on the results of this study:

1. Optical profilometry can be used effectively to determine surface texture characteristics of sands.
2. The surface texture characteristics of the rounded and angular sands tested in the study were statistically dissimilar. The angular sand had an overall "rougher" surface texture than the rounded sand.
3. Tests for surface texture analysis of sands can be conducted by making single measurements on multiple particles of the sands. Results from 35 particles were used in this study.

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