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Geoderma 135 (2006) 118 – 132
GEODERMA
www.elsevier.com/locate/geoderma

Laser diffraction, transmission electron microscopy and image analysis to evaluate a bimodal Gaussian model for particle size distribution in soils

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Received 19 April 2005; received in revised form 20 October 2005; accepted 22 November 2005
Available online 23 January 2006

Abstract

The Shiozawa and Campbell Gaussian bimodal model describes the particle size distribution (PSD) in soils as a weighted sum of two fractions: the primary minerals (sand and silt) and the secondary minerals (clay) fraction, each described by a Gaussian function.

This model was developed and tested using traditional sedimentation techniques analysis for PSD such as sieving and hydrometer. Because of the lack of particle size distribution data in the clay range, Shiozawa and Campbell set the mean and the standard deviation in the clay fraction as a constant. Today, the availability of laser diffraction (LD) techniques makes it possible to overcome this limit and test the model by using a soil dataset that includes the clay fraction distribution.

This paper describes the results of the test of the Shiozawa and Campbell Gaussian bimodal model on eight samples, six of them from different locations in Washington State (USA) and two from a hillside area of Northern Italy. PSD analysis was performed with sedimentation techniques, small-angle laser diffraction apparatus and transmission electron microscopy, the latter allowing measurement of very fine particles (sizes down to 0.05 μm).

To test the effect of the PSD technique on the particle-size measurement and therefore on the model reliability, a comparison between sedimentation techniques and LD was performed. Moreover a validation of the LD method in the clay range was performed by comparison of LD to Transmission Electron Microscopy and Image Analysis methodologies.

The results from the bimodal model showed that the model provides a good characterization of PSD for five of the eight samples analyzed only, revealing that more complex distributions are required for a loam, a silt loam and for a clay soil, where multimodal modes were found.

The comparison between sedimentation technique and LD showed that the volume percentage of the clay-size fraction obtained by laser diffraction was lower than the mass percentage of the clay-size fraction measured by pipette. The silt fraction displayed the opposite trend. Transmission Electron Microscopy and Image Analysis of the clay fraction showed that Laser Diffraction provides an overestimation of the mean diameter in the clay fraction, when particles are assumed to be represented as spheres.

Keywords: Particle size distribution; Bimodal Gaussian model; Laser diffraction; Transmission electron microscopy

1. Introduction

Particle Size Distribution (PSD) is a soil property that provides fundamental information about the size and the

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0016-7061/$ - see front matter
doi:10.1016/j.geoderma.2005.11.009

distribution of the soil mass fraction. It is commonly used for soil classification (Gee and Bauder, 1986) as well as for the estimation of other soil properties, such as the water retention curve and the soil thermal conductivity (Campbell and Shiozawa, 1992; Campbell et al., 1994; van Genuchten et al., 1999; Wösten et al., 2001).

A particle size analysis usually involves the measurement of the fractions of clay, silt and sand. Once the values of the three fractions are known, a textural triangle can be used for soil classification. While the textural triangle and the size fractions have been extensively used for soil classification, neither the former nor the latter provide adequate PSD characterization (Shiozawa and Campbell, 1991; Bittelli et al., 1999).

A better characterization of soil texture can be obtained by describing the PSD by means of mathematical models. Many alternative models have been proposed to characterize PSD.

Among them, Shiozawa and Campbell (1991) presented a bimodal lognormal Gaussian distribution to characterize the PSD of various soil samples. Since the traditional sedimentation methods for PSD analysis did not provide detailed data in the clay range, Shiozawa and Campbell (1991) set the mean and the standard deviation as constants in the clay fraction. Buchan et al. (1993) pointed out the lack of measurement of PSD in the clay fraction, noting that the assumption of arbitrary and constant mean and standard deviation is a limitation for the proposed model.

In the last few decades, there have been considerable research efforts to develop alternative techniques that would provide more detailed particle size characterization in the clay range as well (diameter <2 μm). Because of its mineralogical properties and high specific surface, the clay fraction is usually the most important fraction affecting solute adsorption and exchange (Hillel, 1998). It is therefore very important to correctly describe PSD in this size range. Laser diffraction (LD) techniques available today are powerful methods for particle size measurement and can be successfully used for broad-particle size distribution analysis (Martin and Montero, 2002). Consequently the lack of PSD data in the clay range can now be overcome by using these techniques, where PSD can be measured down to 0.05 μm with as many as 25 size classes below 2 μm (Wu et al., 1993).

Because of the availability of this technique, it is now possible to test the Gaussian model in the clay range as well, and test if this model is applicable to soil PSD data.

The purpose of this paper is: (a) to test the Shiozawa and Campbell (1991) model by using a soil dataset encompassing a wide range of textural classes and providing a broad particle size analysis, and (b) to verify the applicability of a bimodal Gaussian model when more detailed information on the clay fractions are available.

1.1. The effect of the measuring technique on PSD analysis

While LD has been progressively more utilized for PSD analysis, there are still debates regarding the validity and applicability of this method, especially when compared to the common sedimentation-based techniques.

The traditional techniques used to measure PSD in soils are based on sedimentation analysis, where the particle size is determined by measuring its settling time into a liquid (Gee and Bauder, 1986). The two most common sedimentation methods are the pipette and the hydrometer, which provide comparable results if similar pre-treatment protocols are followed (Walter et al., 1978). Usually the pipette also requires a measurement of the sand fraction by wet and dry sieving.

The sedimentation methods have several disadvantages: (a) small ranges and limited number of size classes when compared to other techniques such as LD, (b) a lack of reliable data at smaller sizes (<2 μm) due to Brownian motion effects on sedimentation times (Loveland and Whalley, 2001), (c) long analysis time and, (d) assumptions about particle density because of the mass-based nature of the analysis (Clifton et al., 1999).

On the other hand, most of the PSD databases have been implemented using data from sedimentation-based measurements, therefore most of the soil classification and characterization have been based on these techniques. However, because of the experimental limitations, many alternative methods have been developed and tested (Allen, 1997). Among them, LD is a promising method because it overcomes many of the disadvantages of the sedimentation techniques. LD has the following advantages: (a) it provides a wide range of size classes including many data points <2 μm, (b) it is fast (usually, one sample analysis after pre-treatment takes between 5 to 15 min), and (c) it is independent of the particle density because it provides a volume-based distribution.

Comparisons between sedimentation methods and LD have been performed by several authors, however there is still disagreement between results. Konert and Vandenberghe (1997) found that LD 'underestimated' the clay fraction when compared to the sieve and pipette method. These authors found a coefficient of determination $R^2 = 0.91$ for 158 soils, by applying the relationship $y = 0.361x - 0.232$ in the clay fraction, where x is