An Automated System for the Quasi-Continuous Measurement of the Particle-Size Distribution.

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Abstract

Soil texture is an important input parameter for many soil hydraulic pedotransfer functions (PTFs) of the day. Common soil particle-size classes are required to be able to uniformly determine the texture of the soils. However, it is not always possible – due to different national classification systems – and much valuable information is disregarded while either deriving or applying PTFs.

One way to get common particle-size class information is to interpolate the particle-size distribution (PSD) curve. Advanced interpolation solutions are becoming available, but there is always uncertainty associated with these techniques. Another possibility is to measure all PSD curves in such a way that it is compatible to the commonly used classification systems.

A new automated measurement technique is introduced, that can easily provide PSD data compatible to any (and all) of the existing national and international classification systems at the same time, without the burden of extra labor. A computerized measurement system has been developed to record density changes in a settling-tube system in any discretional (small) time steps, which in turn allows the derivation of a quasi-continuous PSD curve. The measurement is based on areometry (Stokes-law), thus the system is compatible to the most commonly applied settling-tube measurements. The new evaluation method of measured values takes into consideration the density changes along the areometer–body so it avoids the problem of reference point determination. The theory and setup of the system are explained and measurement examples are given. The presented comparative measurements show good correspondence with conventional settling-tube results, and the reproducibility of the measurement shows to be very high.

Using this technique does not require more sample preparation than past methods. The automated reading requires less manpower to perform the measurement - which also reduces human error sources - but provides very detailed PSD data that has advantages like revealing multi-modality in the particle-size distribution or providing data that complies with any classification systems.

Keywords: soil texture, particle-size distribution, pedotransfer functions, automated, areometry

Introduction

Environmental problems do not respect manmade national boundaries and therefore require international co-operation to find solutions. Often, these solutions require the ability to use soil data as input in simulation models. Soil water and solute transport models typically require data on soil water retention and hydraulic conductivity characteristics. These measurements are time-consuming and costly, especially when data are needed for large areas. For many applications, the prediction of these properties by pedotransfer functions (PTFs) can be an attractive and competitive alternative to the troublesome and expensive measurements.

Particle-size distribution (PSD) is a fundamental physical property of the soils that is correlated to many other soil properties. As there is continued interest in predicting more complex soil physical and chemical properties from easily measured soil characteristics it also became a key input parameter to the PTFs. Different methods exist and are applied to determine soil PSD. Gee and Bauder (1986) describes the principles of the most basic and most widely used methods. Alternative methods have been developed and proposed by e.g. Stuyt (1992); Oliveira et al. (1997) and Starr et al. (2000). However, despite a number of recognised international standards, soil texture data are rarely compatible across national frontiers, which makes it difficult to make use of such data. Most existing PTFs adhere to the FAO/USDA system. FAO (1990) and USDA (1951) define clay as the particle-size fraction < 2µm, silt as the fraction between 2µm and 50µm and sand as the fraction between 50µm and 2000µm. However, Nemes et al. (1999) gives an example for countries where soils are classified differently. In most of those cases, the silt/sand boundary is defined differently – at 20µm – as adopted by the International Society of Soil Science (ISSS) (International Society of Soil Science, 1929). Other systems also exist, e.g. that applied in the STATSGO database in the United States (Soil Survey Staff, 1991) – which has a lower cutoff limit for sand at 74µm - or that of Katchinski (1956) that is widely applied in the Central and Eastern region of Europe. Latter system defines clay as the mass fraction of particles smaller than 1µm and defines the upper cutoff limit for sand at 3000µm.

Currently, standardisation of particle-size description offers the only solution to achieve compatibility of soil data among different systems. Lack of reliable methods for particle-size standardisation has already resulted in the formation and use of some international soil databases that could not make use of data which did not comply with a certain classification system (Batjes, 1996). An additional reason to comply with a standard system is the attractiveness of using continuous pedotransfer functions as estimators of soil hydraulic properties.

Several studies suggest that the particle-size distributions (PSD) in soils show an approximately lognormal distribution (Campbell, 1985; Shirazi and Boersma 1984). However, soils with bimodal particle-size distributions also do occur (Walker and Chittleborough, 1986). Buchan (1989) described the applicability of lognormal models for particle-size distributions and found that these are only applicable for about half of the USDA soil texture classes (Soil Survey Staff, 1975). He also discussed the effects of the number of particle-size fractions that are measured on the shape of the cumulative PSD curve. The more complex the cumulative distribution is, the greater the number of required model parameters is. Rousseva (1987) applied two different techniques (graph and polynomial fit) to transform particle-size distributions from Katchinski's texture scheme (Katchinski, 1956) to the scheme used by the United States Department of Agriculture (USDA) (Soil Survey Staff, 1975). She concluded that polynomial fits do not convert soil texture data adequately and that use of graphs is better, even though it is time-consuming, laborious and subjective. Rousseva (1997) defined closed-form models of exponential and power law. She investigated the suitability of these models to fit cumulative particle-size distributions of different shapes and with varying numbers of measured points. Suitability of the models appeared to be influenced by texture type (coarse or fine textured soils) rather than by measured size ranges. Shirazi et al. (1988) established connections between texture classifications adopted by the USDA (Soil Survey Staff, 1975), the International Society of Soil Science (ISSS) (International Society of Soil Science, 1929) and the American Society of Civil Engineers (Vanoni, 1980). This work was based on a description of the clay, silt and sand fractions by the geometric mean and the geometric standard deviation of their size ranges. Buchan et al. (1993) compared five different lognormal models for soil PSD. All five models accounted for more than 90% of the variance in the PSD of most of the examined soils. However, the algorithm did not converge for about 10% of the soils in their study. Nemes et al. (1999) compared four methods to interpolate particle-size distributions. They concluded that – depending on the number and the position of the measured points – either fitting a non-parametric spline, or applying the so called 'similarity procedure' may offer the best solution. This procedure does not rely on mathematical interpolation but involves finding similar PSD curves in a sufficiently large external data set. Minasny et al. (1999) developed an empirical model to convert the 2-20-2000μm fraction scheme to the 2-50-2000μm scheme to enable the testing of existing PTFs on Australian soil data. Skaggs et al. (2001) suggest and test a generalized logistic model to estimate particle-size distribution from only clay, silt and fine plus very fine sand contents of the soil. The success of the method highly varies by texture classes, which correspond with the findings of others (e.g. Rousseva, 1997). Shirazi et al. (2001) conclude that unifying the particle-size description into geometric mean and the geometric standard deviation of the particle-size offers a common language of soil texture research, that is independent of classification systems. In practise, the loglinear interpolation has often been used to estimate missing particle-size classes for the FAO/USDA texture classification but that method was shown to be unreliable by others (Nemes et al., 1999).

All of the above suggestions have their own drawbacks. Some are less reliable for certain soil types than for others. Other studies found that prediction accuracy and model applicability rather rely on the number of measured points. Other suggestions require the collection of a large reference database. Considering the number of applied national and international classification systems, the number of unique combinations of points-to-be-predicted vs. available-measured-points on the PSD curve is very high, which may question the general applicability of many standardisation methods.

To overcome the need for such methods, a new measurement equipment is proposed. It is based on the hydrometer theory, so it is compatible to the most commonly applied methods. It is computerised and enables multiple samples or replicates to be measured at the same time. Its need for manpower for operating it is limited to the conventional sample preparation of the hydrometer/pipette methods, which makes its use cost-effective and more importantly it may reduce human errors. In exchange, a quasi-continuous soil PSD curve is provided, which may be subject to any further analysis according to any classification systems.

Materials and Methods

This method is based on the realization, that changing of the average density of a suspension can be measured during the deposition of particles, where the density of particles is larger than the density of the liquid; and that deposition speed is dependent on the particle-size. The density of a suspension can be described with the measurement of the change of force derived from change of the hydrostatic pressure that acts on a cylinder that sinks into the suspension.

Density of the suspension can be turned directly into digital signals with the use of an electric device that measures force, which practically can be an analytical scale. These signals are transmitted through a communication line into a computer. The computer can accept signals from multiple measurement cells in parallel. Data are evaluated quasi-continuously during the measurement as well as after the end of a measurement. Change of density as a function of time can be followed on screen from the beginning of the measurement, as well as the particle-size distribution calculated by a evaluation software. The evaluation software has been developed in Delphi development environment, so the look and feel of the resulting software is similar to other Windows based software. A theoretical outline of the equipment can be seen in Figure 1.

By calculating the speed of deposition of different particle-sizes, relation between time and density of the suspension containing different particle-sizes can be calculated. The evaluating program needs to calculate this in a reverse direction. In the following the deduction of this relation will be briefly shown.

Reduction of lifting power that acts on the floating cylinder as a result of deposing particles needs to be taken into consideration during the calculations. Figure 2 shows the outline of the measurement cell. According to the law of Stokes, deposition speed of particles can be *unambiguously* calculated from particle size and other constants of the system. Therefore it is satisfactory to calculate only the speed-concentration function of the system. This requires the following steps of calculation.
In a homogenous, monodispersed suspension, *G* lifting power acts on a measurement cylinder with a given volume, as:

$$G = A \cdot l \cdot g \cdot \rho$$

where:
A = cross-section of floating cylinder, m^2
l = height of floating cylinder, m
g = gravity acceleration, 9.81 $m \cdot s^{-2}$
ρ = density of suspension, $kg \cdot m^{-3}$.

Density of the suspension is determined by the density of the liquid, the density of suspended particles and the concentration of the suspended particles:

$$\rho = \rho_w + c \cdot (\rho_p - \rho_w)$$

where:

ρ_w = density of liquid, kg·m^{-3}

ρ_p = density of suspended particles, kg·m^{-3}

c = concentration of suspended particles, kg particles/kg suspension.

When the particles in the suspension are settling with speed *v*, they move $v{\cdot}\Delta t$ distance downward during *t* time. Concentration of the suspended particles changes Δc around the measurement cylinder during this time:

$$\Delta c = c \cdot \frac{l - v \cdot \Delta t}{l}$$

This relationship can be interpreted only while the value of $v{\cdot}\Delta t$ does not exceed the height of the floating cylinder. Particles that arrive lower than the bottom of the floating cylinder, no longer influence the lifting power that acts on the floating cylinder. The above function would give zero instead of negative values, therefore the following correction is needed:

$$\Delta c = c \cdot \frac{abs(l - v \cdot \Delta t) + (l - v \cdot \Delta t)}{2 \cdot l}$$

Lifting power changes during *t* time which is related to the density change ($\Delta\rho$) of the suspension in the following way:

$$\Delta G = A \cdot l \cdot g \cdot \Delta\rho$$

where:

$$\Delta\rho = (\rho_p - \rho_w) \cdot c \cdot \frac{abs(l - v \cdot \Delta t) + (l - v \cdot \Delta t)}{2 \cdot l}$$

In a heterodispersed suspension the ith fraction from *n* particle fractions of different size (sinking with different speed) causes ΔG_i change in lifting power during *t* time.

$$\Delta G_i = \frac{1}{2} \cdot A \cdot g \cdot (\rho_p - \rho_w) \cdot c_i \cdot \left[abs(l - v_i \cdot \Delta t) + (l - v_i \cdot \Delta t)\right]$$

The total change of lifting power in a heterogeneous suspension is the sum of changes for all fractions.

$$\Delta G = \frac{1}{2} \cdot A \cdot g \cdot (\rho_p - \rho_w) \cdot \sum_{i=1}^{n} \left\{c_i \cdot \left[abs(l - v_i \cdot \Delta t) + (l - v_i \cdot \Delta t)\right]\right\}$$

During a measurement, *G* is measured as a function of deposition time. Due to the large number of measurement points – provided by the possibility of using of very small time steps - it is possible to determine the concentration of each fraction separately, described with v_i deposition speed, using regression calculations. It is possible to define the proportion of more than hundred fractions of a sample which provides a quasi-continuous curve of particle-size distribution.

Results and Discussion

To develop the algorithm, we carried out model experiments with simulation software. Relation between particle-size distributions and curves measured by the equipment is demonstrated in Figures 3 and 4. In Figure 3 particle-size distributions of three extremely different physical soil types (1. clay, 2. silt, 3. sand) and the sum of the three types can be seen, normalized for the integral value of the total particle size area. In Figure 4, measurement curves calculated for the same samples can be seen. It can be seen that samples of different particle-size distributions result in significantly different curves, which makes a unambiguous identification possible. Curves differ mainly in their slope. Relations of slope are given by the *derivative* function, related to the examined soil sample, as it can be seen in Figure 3.

At present, only limited results are available. Curves from the examination of a soil sample can be seen in Figure 5, as measured by the equipment. The upper curve shows how the density of the suspension decreased around the floating cylinder as a result of deposition. The lower wavier curve is derived from the upper line using the theory outlined above.

Figure 6 outlines a comparison of measurements using the pipette method and the new equipment. Limitations are faced at the coarse end of the distribution curve while using any of the two methods. Particles of large sizes settle very quickly. The quasi-immediate settlement of particles larger than about 0.5mm disables the performance of measurements (new technique) and/or proper sampling (pipette method). At the fine end of the PSD curve (clay) limitations are only measurement time and the need for detailed data. For practical purposes, in Figure 6, the measurement was stopped while particles of size ~0.2μm settled. The presented preliminary data shows good correspondence with data measured at 2, 20 and 500 μm using the pipette method.

Conclusion

Based entirely on fundamental physical constants and equations a method was derived and modeled for the calculation of particle-size distribution using the density-time function of settling soil suspension. The lifting power that acts on the floating cylinder is measured which in turn allowed to design an equipment for the quasi-continuous particle-size analysis. The physical theory of the new system is similar to that of conventionally used systems, therefore data derived using this new system are comparable and compatible to data measured by the pipette or hydrometer methods. The only difference among the above-mentioned methods is that particle size distribution data measured by the new method are more precise and more detailed, therefore no interpolation is needed, no matter what classification system is to be matched. Using solutions that are denser than the conventional water-based solutions may provide the possibility to successfully measure the distribution of coarse materials as well.

Unification of different national particle-size classification systems is possible precisely with an equipment of continuous particle-size analysis. The quasi-continuous particle-size distribution curves, measured with this automated equipment, are suitable to fit with any national particle-size distribution categories, where otherwise possibilities of comparison are limited. With these results, errors of interpolated conversion are eliminated, making it possible to create international databases and maps, and to deduce more reliable conclusions than currently possible. More extended comparisons for the justification of this technique are necessary and are planned.

Acknowledgements

The financial support of Hungarian Scientific Research Fundation under grant No. T 32506 is gratefully acknowledged.

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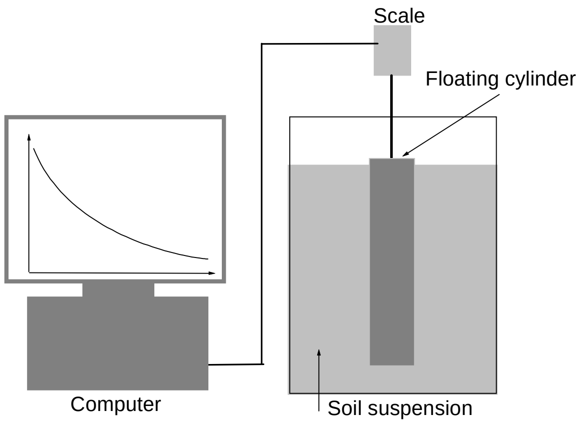

Figure 1. Scheme of the equipment

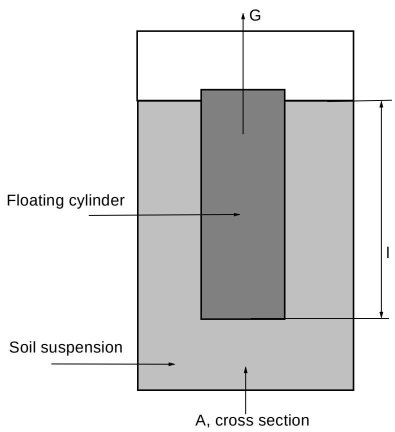

Figure 2. Theoretical outline of the measurement cell

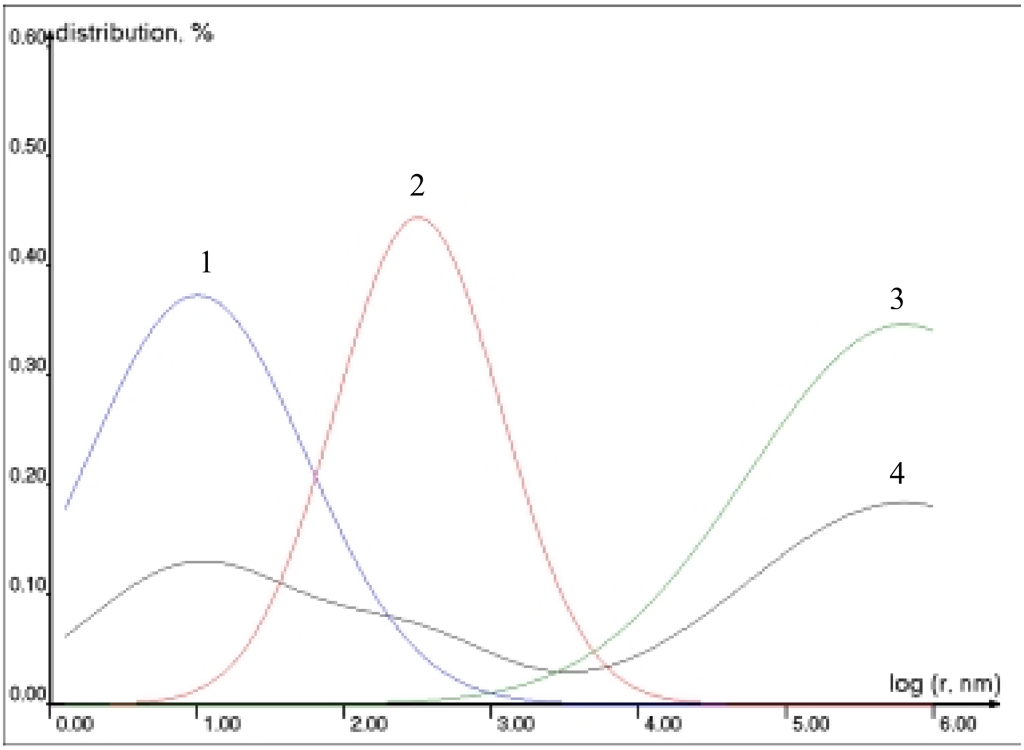

Figure 3. Three extremely different physical soil types (1. clay, 2. silt, 3. sand); and the sum (4.) of the three types normalized for the integral value of the total particle size area

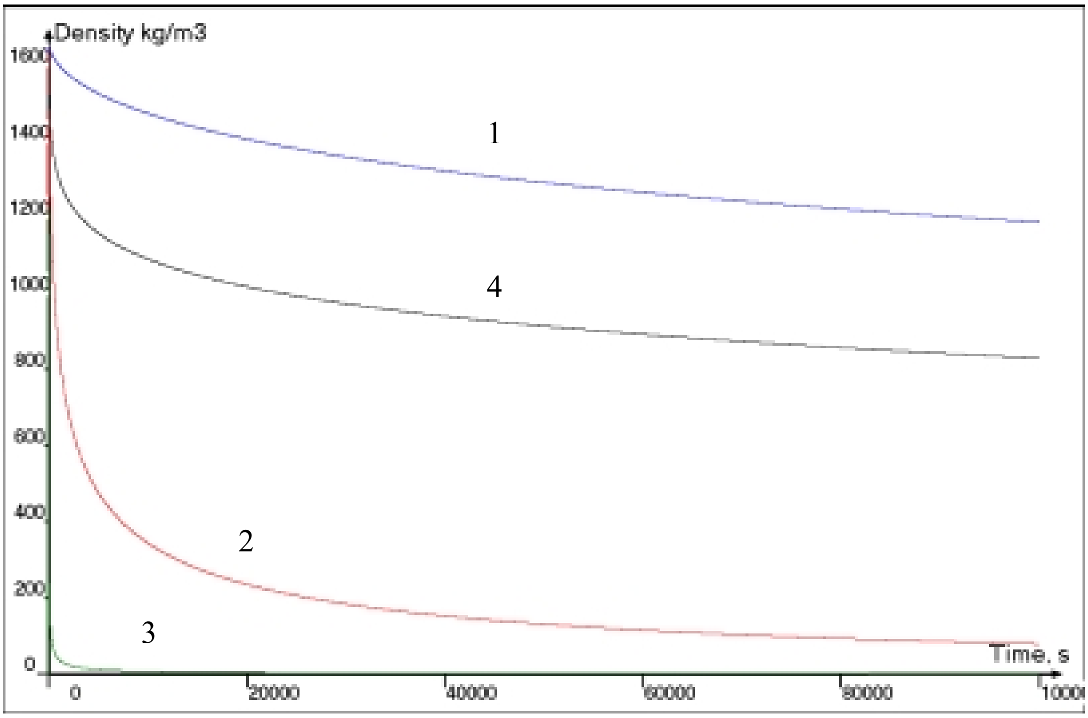

Figure 4. Measurement curves for the same particle-size distributions as seen in Figure 3. (1. clay, 2. silt, 3. sand, 4. sum of the three types)

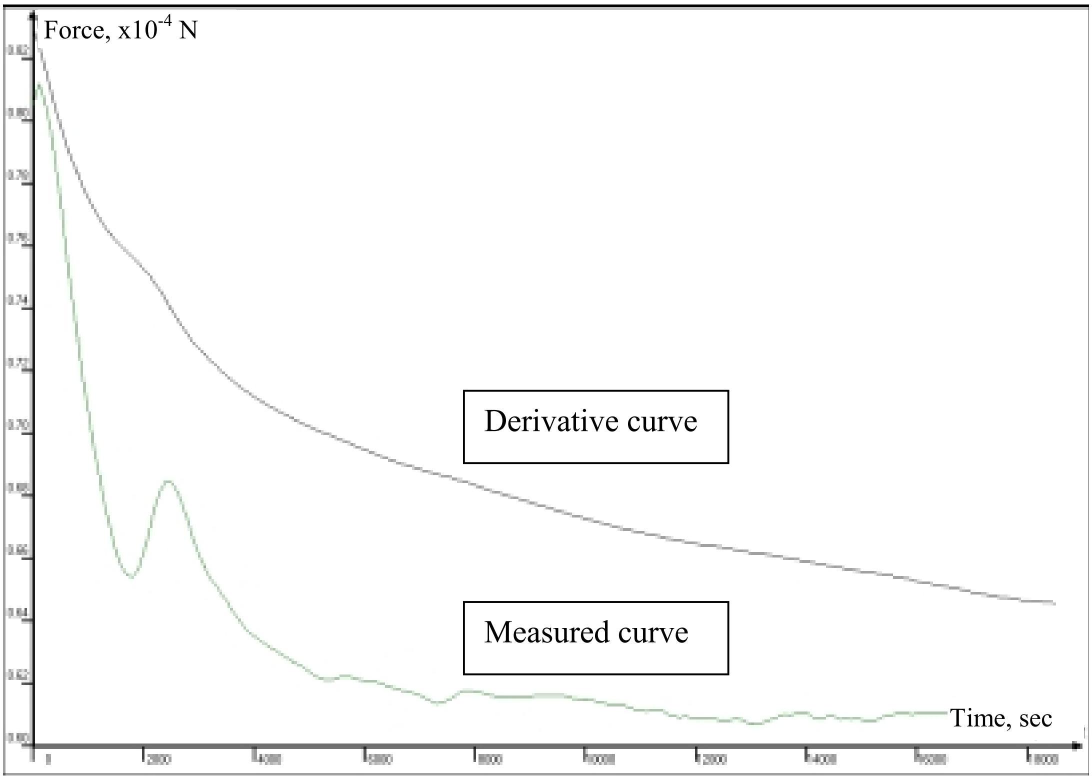

Figure 5. Measured and derived curves from the examination of soil sample GA/1.

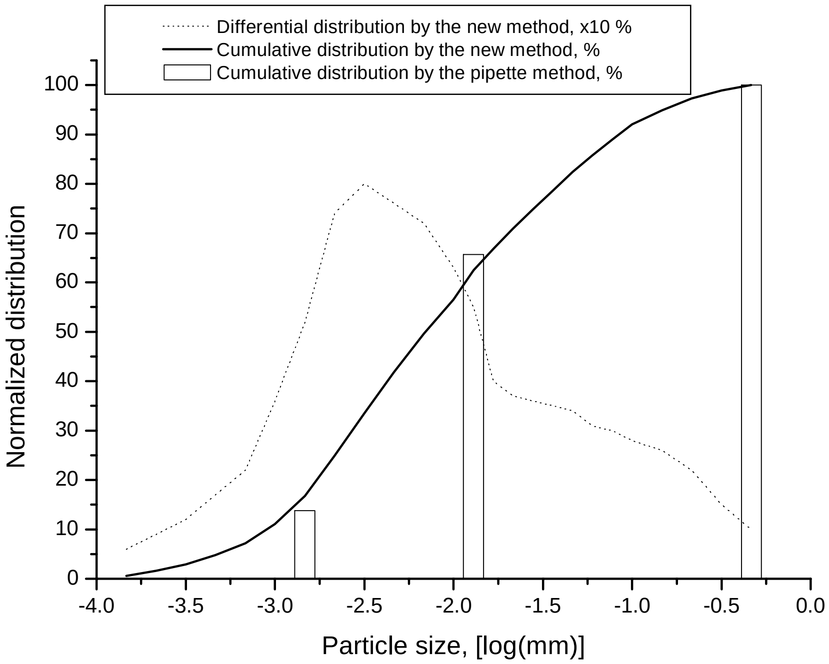

Figure 6. Comparison of measurements using the pipette method and the new automated technique.