The determination of particle size distribution (PSD) of clayey and silty formations using the hydrostatic method

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Abstract
The determination of particle size distribution (PSD) is one of the most important fundamental physical property of soils, which determines both the physico-chemical, mechanical, geotechnical, moreover environmental behavior of the sediments. Although the measurement of PSD is continuously performed in soil labs using different techniques there are two important problems not solved: automation and continuous PSD curve generation. To overcome the mentioned troubles the new, hydrostatic method of continuous particle size distribution measurement was introduced, and also a new evaluation method the method of finite tangents was developed. To prove the developed methods both for soil testing and measurement evaluation the pilot test EQUIPMENT called ASTA was built. The first measurements shows that the introduced hydrostatic method is suitable for the measurement of PSD curves, the accuracy of measurements using ASTA device was adequate to the measurements with the traditional hydrometer method.

1 INTRODUCTION

Soil moisture and contaminant transport, erosion etc. models are widely used all over the world to solve wide range of problems on the fields of geology, soil sciences, environmental geotechnics, contaminant hydrogeology. The mentioned models require a big amount of input data. The measurements to obtain soil hydraulic, transport and other data are not only time-consuming but costly, as well, that is why for many applications, the prediction of these properties by pedotransfer functions (PTFs) can be a competitive alternative. In many cases the need of input parameters lead to the application of soil property databases (such as Envirobrowser of GEOREF, Inc.) which is a wrong alternative, since it is neither based on the behavior of the actual soil (medium) nor on the characteristics of the permeant liquid (water, dilutant, contaminants, etc.).

Particle-size distribution (PSD) is a fundamental physical property of soils, correlated to many other soil properties. As there is continuous 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.

PSD is not only a key parameter of PTFs but it is the basis of petrologic classification of loose sediments (silts, sands, gravels, etc.). Despite a number of recognized international standards, soil texture data are rarely compatible across national frontiers, which make them difficult to use (Fig. 1.).

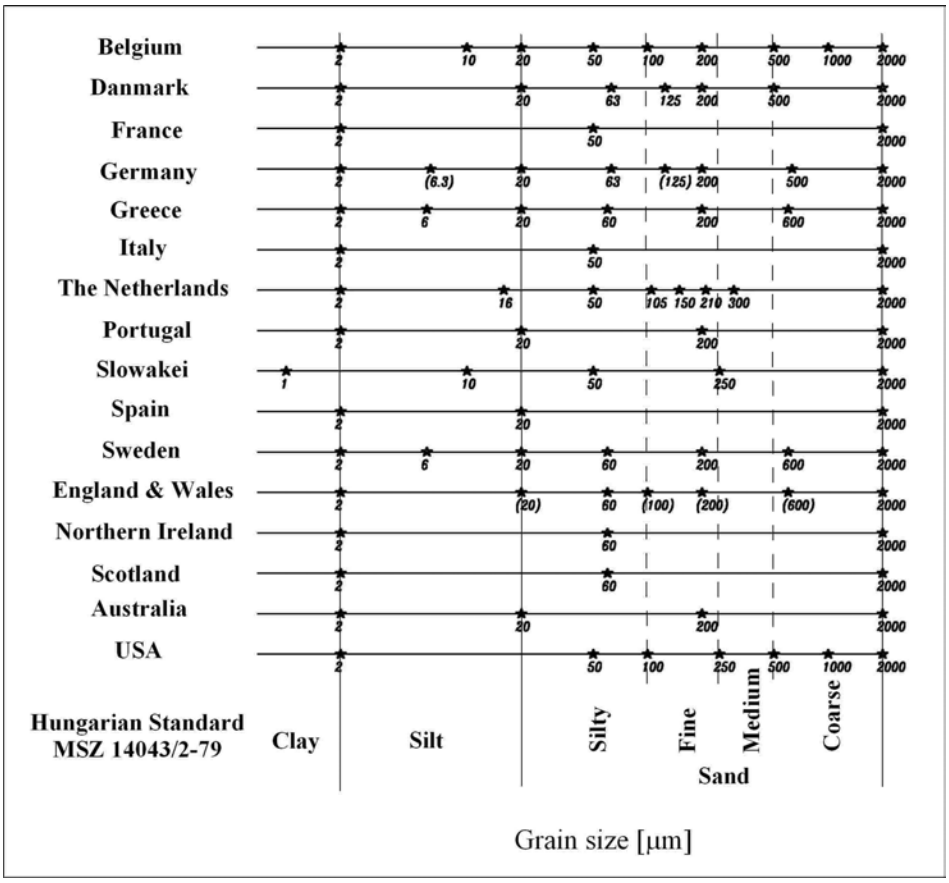

Fig 1.: The different grain size limits for soil classification in the world (Nemes et. al, 2002)

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 can not be generated by most of the standard methods. The only solution for this problem is to determine the quasi- continuous PSD curve from which the classification upon each national and international standard can be performed separately.

2 TRADITIONALLY USED MEASUREMENT METHODS IN PARTICLE SIZE ANALYSIS

There are several principles widely used for particle size analysis in different fields of life. The methods can be classified into two groups: methods based on the settling of particles and all the other methods.

2.1 Methods based on settling of particles

The methods based on settling particles from soil suspension uses the Stokes-law to determine the position of particles of different size in the suspension. The Stokes law describes the settling velocity of the particles in a fluid from which the vertical settling path of the particles can be calculated during a time interval:

$$v = \frac{2g \cdot (\rho_p - \rho_w) \cdot r^2}{9\eta},$$

where v is the settling velocity, $\rho_{p\ and}\ \rho_w$ are the particle- and fluidum densities, r is the radius of the particle and η of the dynamic viscosity η.

The settling path can be achieved considering constant settling velocities from:

$$h = \frac{2g \cdot (\rho_p - \rho_w) \cdot r^2}{9\eta} \cdot t$$

where h is the settling path and t is the time interval of settling.

Considering a settling period (determined by the sampling frequency) the size (radius) of the particles can be calculated which are already settled to the bottom of the cylinder or which are surely at a deeper position as a given depth.

- **The pipette method**. Several times a small amount of soil suspension is taken from the soil suspension settling in a cylinder from a given depth. The solid content of sample is measured by scale after drying. The particle size distribution is calculated from the change of weight of particles in the sample series taken. To simplify the procedure different suspension sampling devices were developed Fig.2. such as the Andreasen-pipette or the Köhn-pipette with suction unit, but also the Atterberg-cylinder is used to divide particles upon their settling velocity. All the mentioned methods are not adequate for quasi-continuous measurements since there is a time demand of sampling so the sampling frequency cannot be increased, moreover the amount of suspension decreases due to the samplings which causes an error proportional to the sampling frequency.

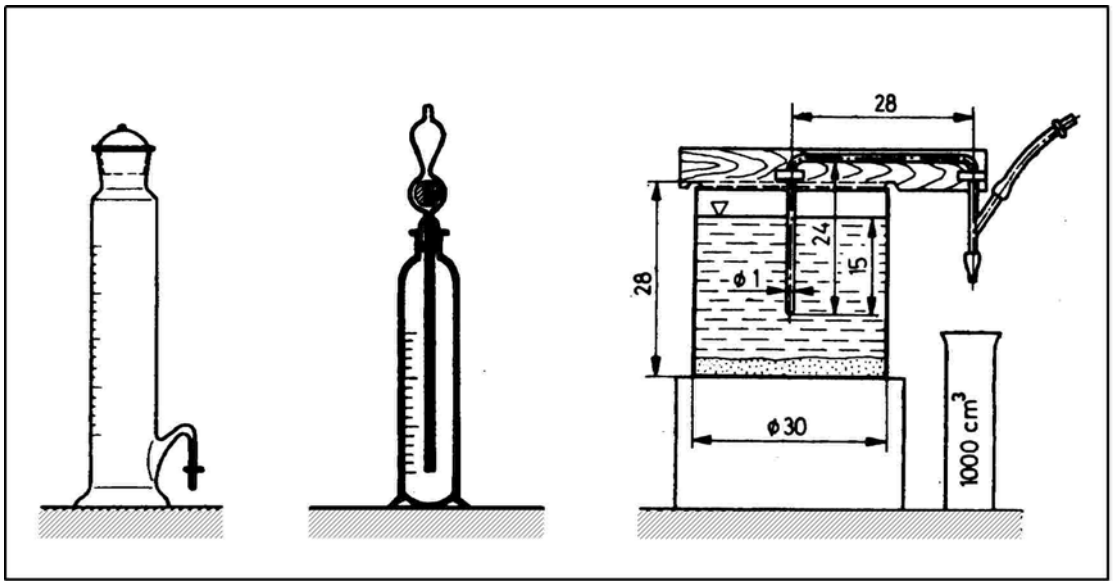

Fig. 2. Different standardized devices (Atterberg-cylinder, Andreasen-pipette, Köhn-pipette with suction unit) standardized in Hungary (MSZ 18288)

- **The hydrometer method**. The hydrometer measures the average density of a given changing volume of the suspension using the areometer(hydrometer)

swimming in - soil suspension settling in a cylinder, in given time athe suspension. The device uses the Archimedes law, where the weight of the swimming device is equal to the weight of liquid displaced from which the density of the liquid can be calculated, or can be read on the hydrometer directly. The particle size is calculated from the depth of the weight center of the hydrometer and the time using Stokes-law, the percentage of the particle is calculated using the actual density of the suspension. (Fig.3.) The hydrometer principle theoretically suitable for quasi-continuous measurements since the increase of hydrometer-reading-frequency lead to more points on the PSD curve. There are already some first developments to make the readings with higher frequency such as to make digital photographs of the hydrometer at high frequency, but the automation of PSD curve production and evaluation is not solved. Since the evaluation efforts are proportional to the points on the curve this development lead to more accurate but time consuming solutions.

Fig. 3. Measurement with the hydrometer method (Pappfalvi-type hydrometer is used)

– **Measurement with sedimentation scale**. The sedimentation scale is a special scale with ducked plate in the suspension, which measures the weight of the particles just settled on the plate. In case of a scale with serial (RS232) interface it is possible to perform quasi-continuous measurement measurements (Fig.4.). Experiences show that this method has several problems: The whole system is very sensitive to draughty places; moreover

the weight measured never stabilizes which disturbs the built-in electronics of the scale.

Fig. 4. A digital sedimentation scale

– **Methods of counter-current**. There are several realizations of counter-current systems (Stefanovits, 1992). Some of them use air, other use different liquids with variable flow velocity against the settling of particles. The separation of particle fractions is performed using different flow velocities, the particles with higher settling velocity than the counter-current are collected and measured. With fine control of flow velocity the quasi-continuous measurement can be realized but the automation of evaluation stays problematic.

2.2 Other particle size analysis methods

There are several methods for determining the PSD curve, which use different principles to measure than settling. The general problem of such measurements, that the used sample has very small weight, where it is rather problematic to assure the representativity of the sample. Another disadvantage of these methods is the difference in measurement principle which makes the comparisons of measurements with dominantly used particle settling based methods almost impossible. Since there is no way of parallel measurements using this expensive equipments the cost-efficiency of these solutions is rather low.

- **The coulter-counter method.** The method is suitable to determine the PSD of very fine grains. The diluted soil suspension flows through a capillary tube between two electrodes. The particles of the suspension modify the electric field nearby the electrodes due to changes of the impedancy of the system. It is proven that the changes of impedance are proportional to the volume of the particles form which the particle size is to be calculated. The measurement range lies in the 0,5-1000 μm interval, but the adaptation for soil suspensions is not easy since the bigger soil particles can choke the capillary tube.

- **Laser beam scattering method**. The method is dominantly used in the 0,02-5000 μm grain size interval. The equipments use two laser beams with different wavelength (for example blue and red): The laser beam projected to the weak solution of the soil suspension and the diffracted waves are collected with lenses. The PSD curve is determined from the analysis of diffracted waves. The measurement results are highly influenced by the anisometry of the grains, the color of the suspension and the assimilated beams due to the different refraction characteristics of different minerals.

3 THE HYDROSTATIC APPROACH TO DETERMINE THE PSD CURVE

The aim of the research work was to develop an automated method for PSD curve determination with quasi-continuous measurement. Since almost all the traditional measurements based on settling of particles in a cylinder, the same principle was chosen to assure the compatibility with existing results. It was evident that the quasi-continuous curve determination requires high frequency of measuring which can be only realized using an electronic measurement and test control system. After evaluation of the existing standard methods the hydrostatic principle was selected where the measurement of density changes are recorded using high precision detection of water levels.

For the density measurement of the soil suspension another liquid of known density is used. To avoid chemical and surface reactions between the suspension and the measuring liquid, the pure dilutant of the suspension is suggested to use as measuring liquid. The measurement based on the equivalency hydrostatic pressure in a given depth caused by the suspension and by the known density liquid (Fig.5.):

$$h_1 \cdot \rho_w = h_2 \cdot \rho \quad \Rightarrow \quad \rho = \frac{h_1}{h_2} \cdot \rho_w .$$

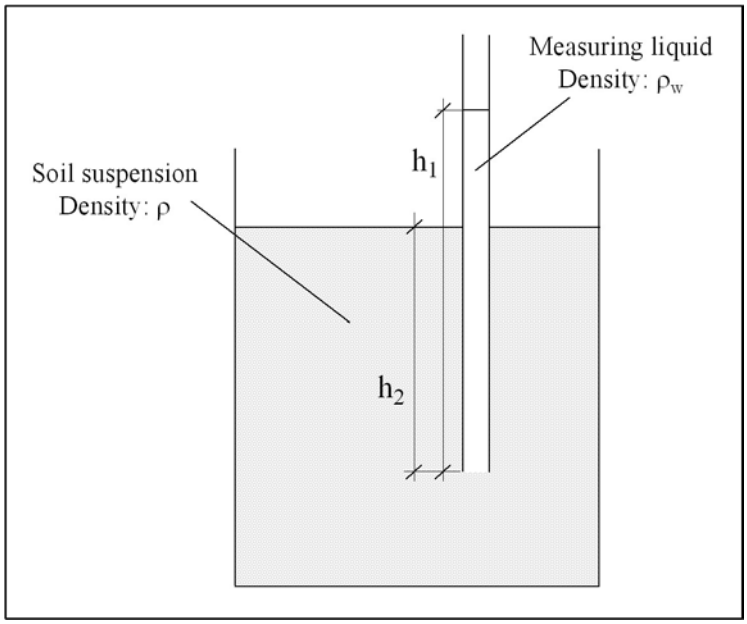

Fig.5. The hydrostatic principle for measuring the density of soil suspension

4 THE REALIZATION – THE ASTA DEVICE

The very first prototype of the device, called Automated Soil Texture Analyser (ASTA) is shown on Fig. 6. The ASTA device contacts the soil suspension by two tubes. The shorter tube transmits the pressure of the measured suspension to the signal oscillator, and the other tube is filled with the pure dispersant solution used to the preparation of soil suspension or with water. The experiments shows, that considering a measuring depth of 30 cm, the difference between the two liquid levels in the tubes at the beginning of the test is 5 to 10 mm (Fig 7.).

Fig. 6. The very first prototype of the ASTA device

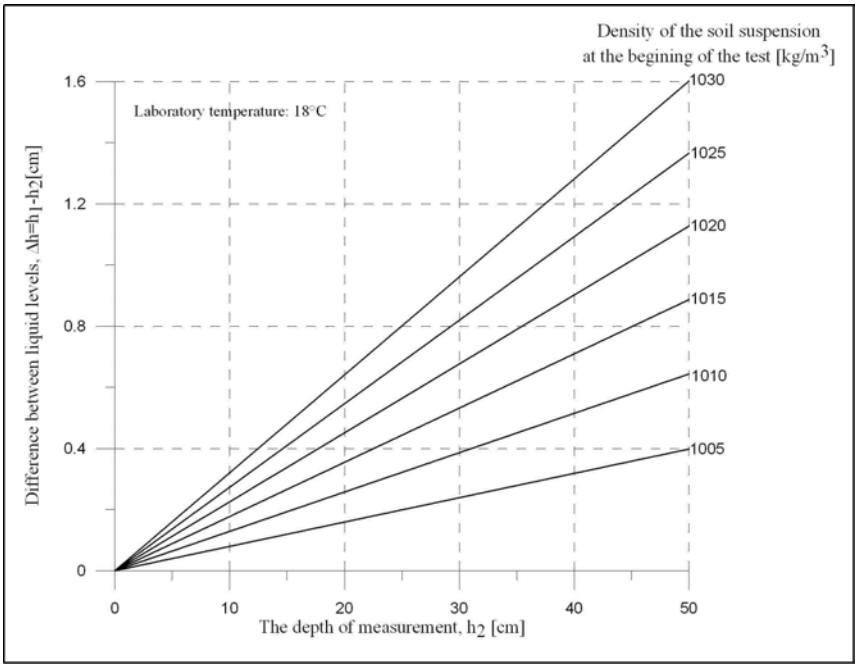

Fig 7. The signal (liquid level difference) to be measured vs. measurement depth at different soil suspensions

The using of ASTA equipment makes possible to apply any additives (soluble glass, solution of sodium carbonate, solution of lithium carbonate, sodium pyrophosphate , etc.) to dispergate the soil particles, which have no influence to the measured results, because the device is detecting the difference between the levels of the clean reference solution and the suspension (Fig. 8.).

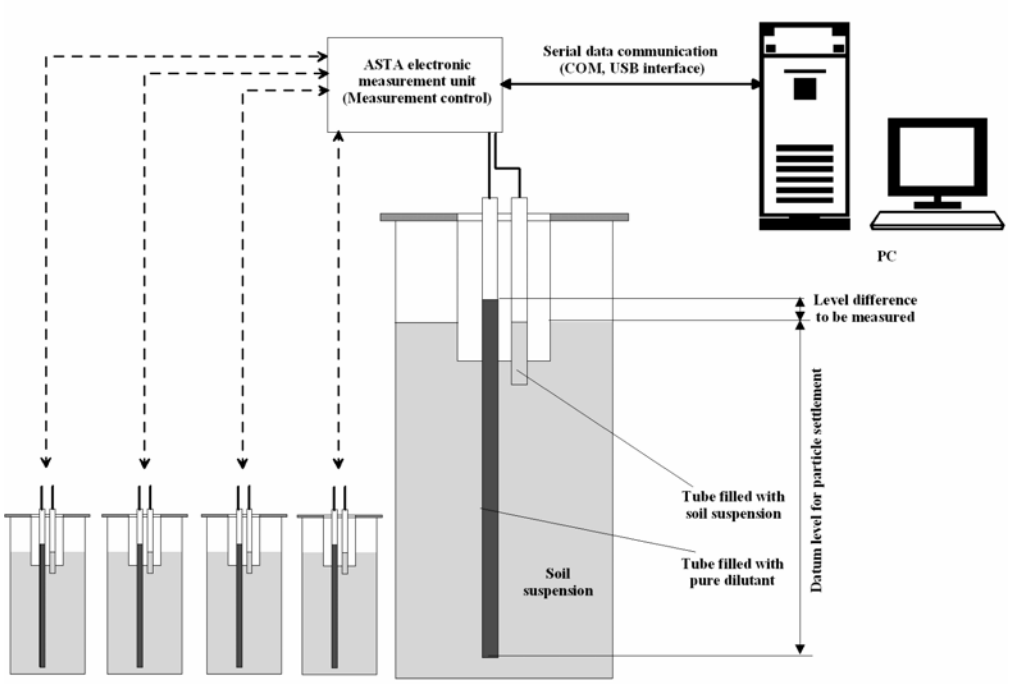

Fig. 8. The scheme of the device (Kovács et. al., 2003)

The objective is to detect and measure this maximum 3-10 mm level difference, by an electronic instrument head with high detectability threshold. The ASTA device is built with capacitive instrument head, which theoretically can detect 1-2 μm liquid level difference, but the practical detectability threshold is 10 μm. Due to the identical configuration and material of both tubes, the meniscus-problem is eliminated.

The detectability threshold and the linearity of the instrument head was tested in laboratory (Fig. 9.). The calibration curve represents well, that the electronic signal of the instrument head is practically linear (Czinkota et. al. 2002).

The instrument head detects the decreasing of the liquid level difference, which represents the decreasing density of the suspension.

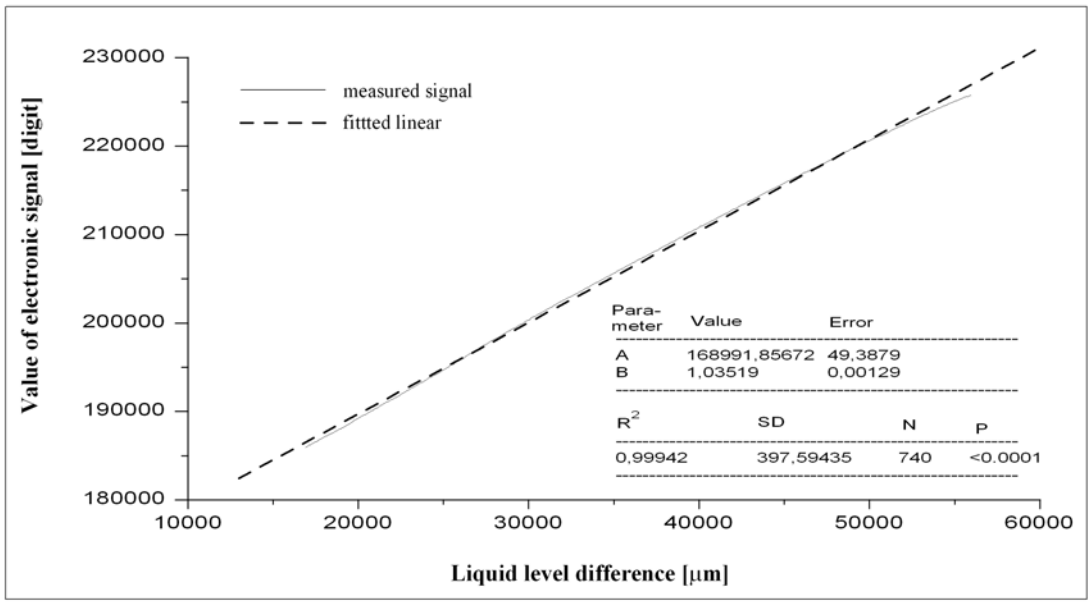

Fig. 9. The linearity of the instrument head's signal (Czinkota et. al., 2002)

Since there is a great demand to do parallel measurements the laboratory scale instrumentation with 64 parallel cylinders was also developed (Fig. 10.). In this case the PC controls 2x32 ASTA cylinders using USB interface.

Fig. 10. Laboratory scale pilot-test of parallel 64 cylinder ASTA devices

5 EVALUATION OF DENSITY CHANGES IN TIME USING THE "FIT" METHOD. THE PSD DETERMINATION USING FINITE TANGENTS

The hydrostatic approach and therefore the ASTA device generates the soil suspension density vs. time curve. The big number of measured data points led to the introduction of a new evaluation method, the Method of FInite Tangents or shortly: the "FIT method".

To better understanding the basic idea of the FIT method let us investigate the density changes in a mono- and a bi-disperse system. In a monodisperse system all the particles has the same density and size, meanwhile the bi-disperse system consists of a larger and a smaller grain agglomeration.

When the speed of deposition is continuous (derived form Stokes-law), then in case of a mono-disperse system the changing of density is linear, until the last particle – which was found in the highest position at the beginning of the measurement – merged under the reference-point. After that the density is constant, and equal with the density of the pure liquid. (Fig. 11., Curve 1.).

When the mono-disperse system was made from smaller particles, then the density-time function is similar, but the settlement of the liquid and the reaching of constant density needs longer/more time (Fig. 11., Curve 2.). In the case of bi-disperse system, both processes happens together, which results an integrated curve of the two density-time functions (Fig. 11., Curve 3.) (Czinkota et. al, 2002).

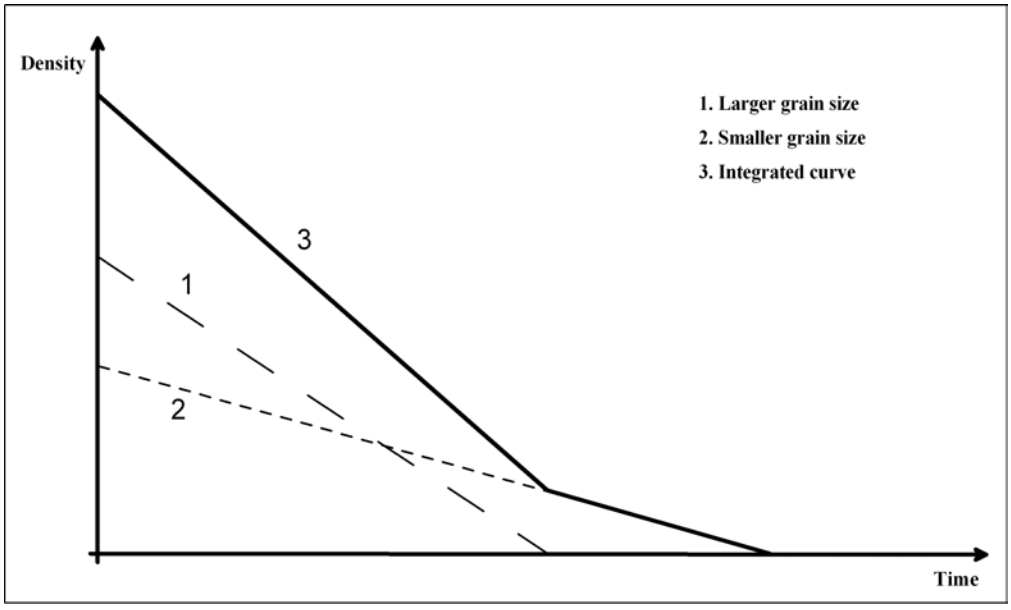

Fig. 11. Density-time characteristics of mono- and bi-disperse systems

Because the soil-suspension is a poly-disperse system, the measured density decreasing can be considered as an integration of finite mono-disperse systems, which means that it can be interpreted as the sum of linear density vs. time functions.

This hypothesis is only true, while the particles does not disturbs each other's movement, namely the suspension is weak enough.

Because the whole system can be managed as the aggregation of many mono-disperse systems, it is possible to divide the measured density-time function into grain-size fractions with tangent lines drawn to finite but optional points (Fig. 12.).

The intersection point of the tangent line and the ordinate is proportional with the quantity of particles in the suspension, and the distance between the breakpoints of the tangent lines along the abscissa gives the maximum time which is needed by the particle of given size to merge under the reference point. Knowing the density and

the viscosity of the liquid the average particle size can be calculated using the Stokes-law:

$$r[\mu m] = 10^6 \cdot \sqrt{\frac{9 \cdot \eta[Pa.s] \cdot h[m]}{2 \cdot g\left[\frac{m}{s^2}\right] \cdot (\rho - \rho_w)\left[\frac{kg}{m^3}\right] \cdot t[s]}}$$

The traditional PSD curve is obtained after norming the amount of substance defined by the ordinate intersections of particle-size fractions (Fig 13.).

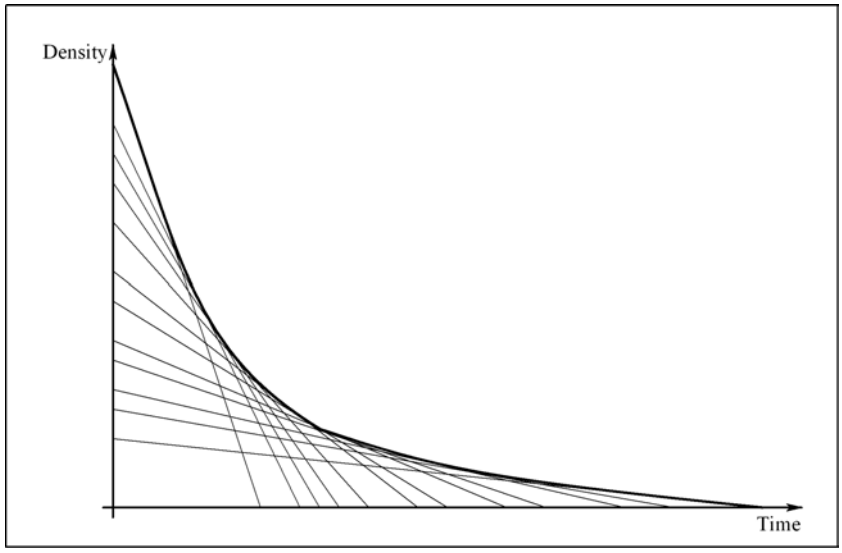

Fig. 12. Evaluation of density vs. time curve using the FIT-method

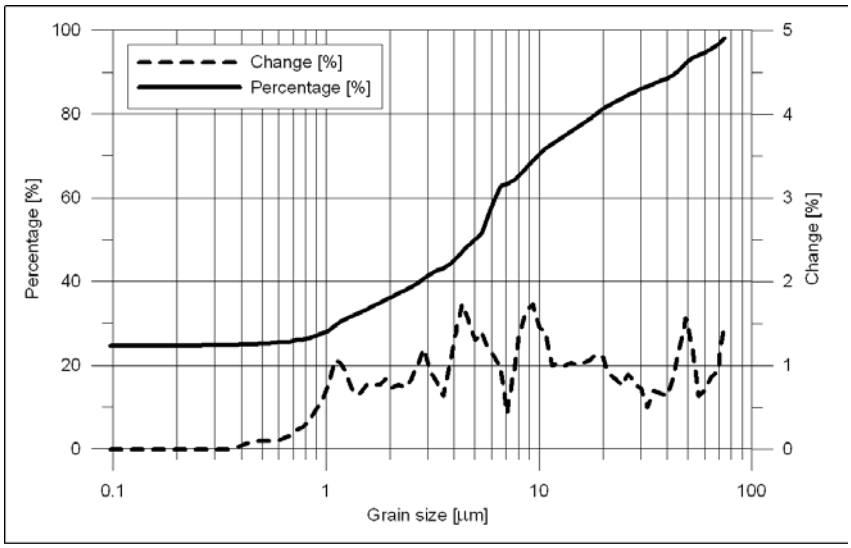

Fig. 13. The cumulative and differentiative PSD curve generated with ASTA

6 CONCLUSIONS

Considering a demand on automation of particle size distribution determination the introduction of new testing equipment was decided. After an overview and evaluation of the standardized methods new principle was chosen to work with. The hydrostatic principle was found adequate to make automated measurements and to create high-resolution PSD curves. To control the theory pilot-test were done in one

cylinder and multi-cylinder scales using the Automated Soil Texture Analyzer (ASTA). The high-resolution measurement results gave opportunity to develop a new evaluation method the method of finite tangents (FIT-method). The mentioned device and method lead to finer measurements of particle size distribution and hopefully will give the opportunity for better understanding the environmental, geotechnical, etc. behavior of loose sediments.

ACKNOWLEDGEMENTS

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