A Low Cost Implementation of the Settling-Tube Measurement Technique for Sand Granulometry

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Abstract- The settling-tube measurement technique is implemented by an experimental setup developed and tested for low-cost automated sand granulometry. The measurement is based on monitoring very small pressure variations created by samples of sand as they settle down in a water-filled cylinder. The pressure variations are monitored by low cost air-pressure differential transducers in an appropriate experimental setup which monitors air pressure variations caused by water pressure variations. It is shown that this low-cost automated approach manages to calculate properly size distribution and other statistical parameters of sand samples efficiently and quickly offering thus an attractive alternative to the traditional sheaving method.

I. Introduction

Determinations of the grain size distribution along with all assorted statistical parameters of unconsolidated sediments are very important to Earth Sciences. Geologists and Physical Geographers use this information to reveal trends in surface processes and the dynamics of transportation and deposition of sediments. Engineers use grain size distribution to study the stability of the soils under load and hydro geologists, as well as petroleum geologists to study the movement of the subsurface fluids and the storage characteristics of the reservoirs [3]. The laboratory techniques and apparatus used for particle-size analysis must be fast and yield results with high reproducibility. The accuracy of these measurements is limited by sampling techniques in the field, storage conditions of the sample, analytical methods, equipment, and, especially, the experience of the operator.

For many years, the size distribution of the sand and gravel fractions were determined solely by sieve analyses, and silt and clay fractions were determined by pipette or hydrometer methods [4]. Later, rapid sediment analyzers [5,6] and Laser Granulometers, automated the analysis and removed much of the tedium from grain-size analyses [1]. However, the cost of this equipment is very high. Expensive equipment limits rapid sediment analysis to a few big laboratories, but as the need for analyzing large number of samples is increasing, the need for inexpensive apparatus for fast analysis is imminent.

Rapid sediment analyzers are based on the pressure difference created by a sample of sand, as it settles down in a water column, as the physical laws that predict the settling velocity of sand grains are well known. The pressure variations generated by small samples of sand are extremely low; therefore these instruments incorporate very sensitive pressure transducers capable of operating underwater. In this paper, an experimental setup based on the principle of rapid sediment analyzers for sand is designed and tested, using differential air pressure transducers instead of liquid, in an appropriate arrangement to transfer the liquid pressure variations to air pressure variations and resolve the accompanying implications.

II. Implementation of the Measurement Setup

The instrument described and tested in the present paper based on the principle described by the well known Stokes Law [2] that describes the phenomenon where different sizes of sand grains, settle down with different, well predicted, velocities in a liquid. If a small sand sample is introduced into a water column, then the pressure in a given depth is increased due to the difference in the special weight of the two materials (sand – water). After a while as the sand grains settle down and pass below the pressure sensors at a given depth, this pressure change is canceled. Consequently the time needed for these sand grains to reach the sensor depth can be measured and the volume of these grains can be estimated. According to Stokes Law the terminal fall velocity is described by the following formula:

$$\upsilon = \frac{2.(d_s - d_f).g.r^3}{9.\mu}$$

where   *r = radious of the sphere (in cm), d_s = density of the sphere (in gm/cm^3), d_f = density of the fluid (in gm/cm^3), g = acceleration due to gravity (in cm/sec^2), μ = viscosity of the fluid (in mPa.sec)*
Since $\upsilon = H / t$, where *H = sedimentation depth (tube height), in meters, t = time needed for sand to settle down, in sec* and $d = 2.r$ where *d, r = diameter and radius of sphere*
Stokes Law is converted to the following formula

$$d = \frac{6}{\sqrt{2}} \sqrt{\frac{n.H}{(d_1 - d_2).g}} \frac{1}{\sqrt{t}}$$

which defines the sphere diameter as a function of time needed to settle down. If units mentioned above are used then d is calculated in mm. The following plot shows a graphical representation of Stokes Law in diameter units and in (φ) units as explained next.
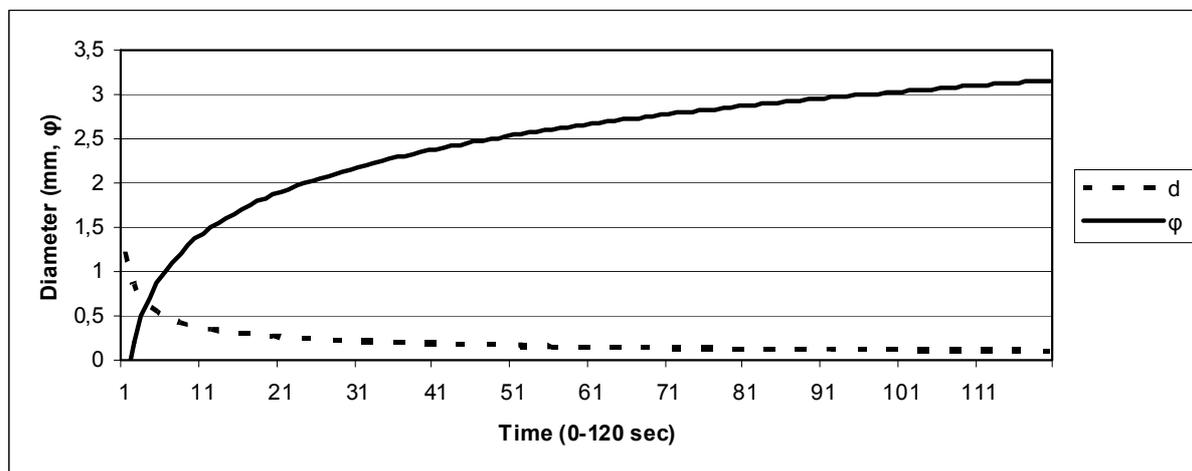

Figure 1. Sand particle diameter versus time needed to settle down in settling tube
(theoretical curve according to Stokes Law)

In most cases of studies in the fields of geological research another unit is used to represent the diameter of sand particles instead of the theoretical diameter of a sphere (d). The most common unit if (φ), which is a number (no units) and may be obtained from the diameter (d) by the following equation: φ = -log2(d), where (d) is the diameter of sphere in mm.

The corresponding curve of the Stokes Law for (φ) units is also shown in Fig. 1. A very

important issue though is applying Stokes Law in such a case is related to the many and strong considerations which are demanded in order for the Stokes Law to be applicable especially in case of larger diameter particles (above 1φ). A good number of alternative formulas have been presented in the literature for such cases, along with semi-empirical approaches based on experimental tables and graphs. In our design, the simple Stokes Law is used as an initial measurement and results are converted according to experimental curves. The advantage of this method is that errors introduced either by Stokes Law or by the experimental set-up may be easily corrected by appropriate software calculations.

In order to measure the low pressure differences, created by the sand grains, with a sensitive air pressure transducer, an apparatus with two vertical tubes 150cm long, connected below a small water tank, was constructed (Fig. 2). The differential air pressure transducer was connected in the highest point of an inverted U shape plastic transparent tube of 0,7cm diameter, Figure 2 point S. The two ends of this plastic tube were connected 130cm below free water surface of each vertical tube, Fig. 2 points M_1, M_2.
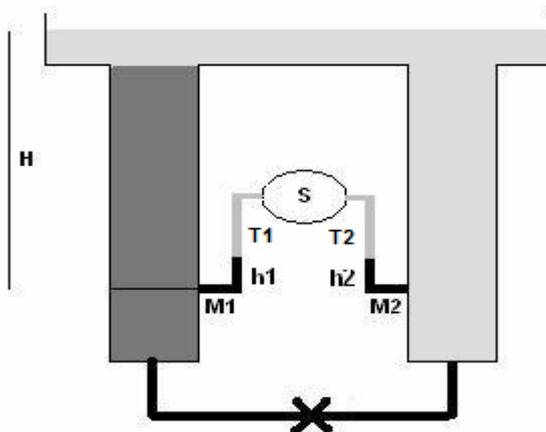

Figure 2. Schematic presentation of the experimental setup of the settling tube

The sample of the sand is introduced in one tube only and the pressure differences are measured between the clean and the sediment-laden water columns as shown in Fig 2.
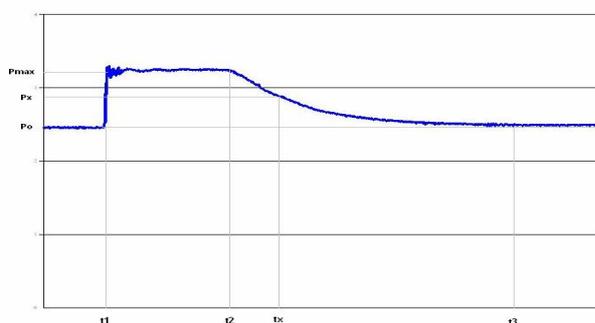

Figure 3. Typical experimental plot of the pressure variations

Pressure differences exist only when grains are above point M_1 and gradually diminish to zero as sand grains settle lower to M_1. A typical graph of pressure change is shown in Fig. 3. When the sample is inserted in tube A, pressure difference changes instantly from P_o to P_{max} as liquid density changes instantly at time moment t_1 (Figure 3). At time moment t_2 the first grain passes lower to point

M_1 (Fig 2) and until t_3 all grains have been settle lower to M_1 allowing pressure to return to its original value P_o. By monitoring accurately the time-pressure variation during this phase, one may calculate the percentage of the grains with a certain diameter range in the sample of the sand immersed in the water. As it is clear the differential pressure sensitivity of the sensors is of extreme importance for the successful implementation of the measurement technique.

A very low range pressure transmitter is needed, so the series 5266 by GEMS Sensors has been chosen, which offers a very low pressure range of 50Pa with a 1% accuracy. As all low cost sensors, it can be used only in air or non conductive gases, so the experimental setup is constructed in a way to work efficiently with such sensors. It includes all necessary analog circuits for signal amplification and temperature compensation and produces an analog output signal in the 0-10V range. This signal is digitized by a TLC2543 A/D converter with 12-bits resolution controlled by a MC68HC908GP32 microcontroller. Pressure data are then transmitted serially (RS232 interface) to a PC which handles all calculating procedures. The measurement technique is implemented by the following procedures which are performed by the software developed for this application: 1)Calibration of the experimental setup, 2)Data acquisition and pressure variations plotting (Fig.3a), 3)Graphical definition of important points on the pressure variations plot (stating and ending point of each phase), 4)Plot re-design on the basis of the previous results (as shown in Fig.3b), 5)Particle size calculation by applying Stoke's Law and filtering procedure for compensating variations, 6)Presentation of the results in different forms useful for geological analysis (grain diameters as percentage of the total volume, grain velocity, grain statistics, total weight curve, etc).
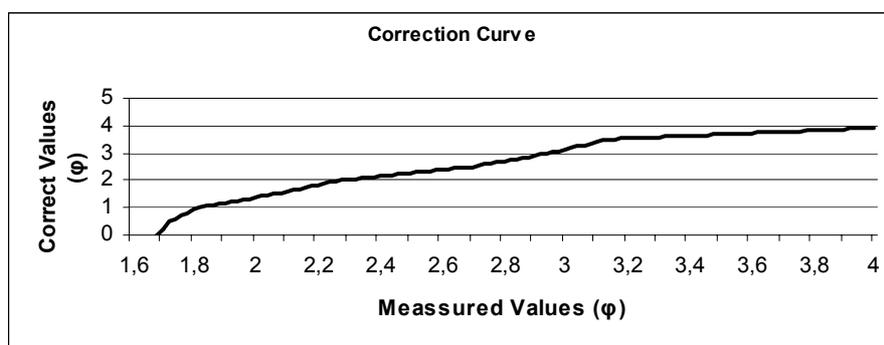

Figure 4. Plot of the experimental correction curve

Calibration of the experimental setup is related to the correction approach that is applied to compensate the errors of the theoretical calculations (which are based on Stokes Law) and require a very accurate knoledge of a wide set of parameters. Engaging the actual value of such parameters (i.e. viscisity, etc) would require a very precise and time-consuming measuring environment which prevents the main advantage of the proposed approach: fast, and easy results, with rather high levels of measurement errors, up to i.e. 10%). Towards this direction the calibration procedure invoves repoetitive mmeasurements of samples (particles) of known sizes and storing the corresponding plots of the experimental curves. The result of this procedure is to obtain an experimental "correction curve" for the specific installation, which is used to convert each measured value to its corresponding real size range (in φ units) by interpolation. This experimental correction curve for the specific experimental system developed is shown in Fig. 4.

Considering the other parameters that may also affect the measurements, we note the following. Although temperature affects measurement by changing fluid viscosity, such a change is negligible in

our measurements, since all experiments were accomplished in room temperature (about 25°C). Therefore, viscosity value has been considered constant at 1mPa.sec. Another important factor is related to the weight of the samples of sand thrown in the tube for each measurement. The weight of the samples was found to affect strongly the accuracy of the measurements and the general set-up operation. Experimentally, by observing plot shapes, 10gr of sample weight is considered as the optimal value. Regarding the type of water used, although it is well known that distilled water has to be used to avoid interference with smaller particles, normal water has been finally used to simplify the implementation of the measurements method. It, definitely, affects accuracy for smaller sizes but this size range is of less importance for the type of applications of interest. For the same reason the turbidity effect was not considered at all. The results of turbidity are almost the same as the hysteresis phenomenon that have been observed (final differential pressure does not settle down to its initial value). Since hysteresis is corrected by software, turbidity effect is corrected also. However, subsequent measurements with very low diameters gradually deteriorate instrument's functionality and require frequent cleaning the tubes and all parts of the system.

III. Experimental Results and Conclusions

The calibration procedure is introduced before each set of measurements in order to compensate the hysteresis effect which appears at the starting and ending phase of each measurement as may be seen in the experimental plots of Figure 5. The final value of the recorded pressure value is slightly higher at the end of the curve of Figure 5a than the one at the beginning of the curve before starting the measurements. Calibration and mean value filtering of the decay part of the curve have increased the measurement accuracy of the procedure by more than 30% resulting in a measurement error of less than 10%. This is a typical figure for the error expected in such measurements and may be reduced further by compensating further the hysteresis effect caused by the PVC tubes and pipes.
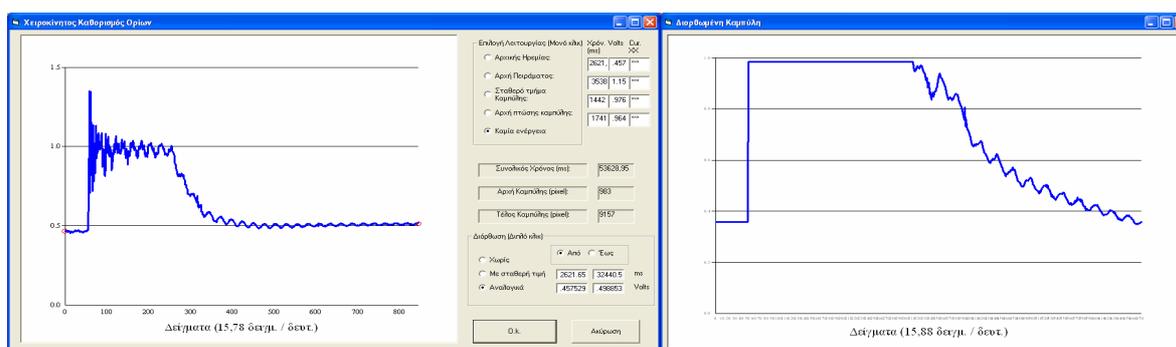

Figure 5. a) Original plot of experimental variations of pressure,
b) Graphical definition of useful measurement points for the calculations

The measurement setup has been tested with different sizes of sand grains and the results are compared with the standard sieve method. The results obtained were compared with those obtained by the traditional sheaving method (which is certainly quite time-consuming) and have been found to be in remarkably good agreement regarding the grain size distribution. Four samples of sand with different grain size distribution were used to perform analysis of the gain size distribution with both methods: The standard sieve method [2] and the setting tube granulometer. Each of the four samples were approximately 200gr, from witch two subsamples were prepared with the standard sample

reduction method. One subsample 100gr for sieve analysis and one 10gr for the settling tube granulometer. The sieve apertures were at 0.5 (φ) phi intervals. The same size intervals were used in the processing software of the settling tube granulometer, in order to achieve comparable results. The results are presented in a Microsoft Excel spreadsheet in figure 6 containing the tables and the diagrams. The subsample names were coded as DG1, DG2, DG3 & DG4 for the granulometer and as DS1, DS2, DS3 & DS4 the sub-samples for the sieve method.

As a first evaluation of the measurement technique, we can see an encouraging agreement between the two methods, taking into account the experimental stage of the granulometer and the possible discrepancies introduced by the small differentiations of the subsamples in respect to the original sample. More vigorous test are needed repeating several times analysis of the same sample in order to demonstrate the adequate repeatability of the method.

Φ - size	DG1	DS1
1	0	0.052243
1.5	0.1028	0.102797
2	0.1892	0.147094
2.5	0.268	0.186573
3	0.533	0.589501
3.5	0.9924	

Φ - size	DG2	DS2
1	0.2377	0.275714
1.5	0.5717	0.52705
2	0.843	0.714633
2.5	0.8804	0.734357
3	0.9794	0.945482
3.5	0.9904	0.99

Φ - size	DG3	DS3
1	0.674	0.802387
1.5	0.974	0.940785
2	0.974	0.963737
2.5	0.974	0.968097
3	0.974	0.992655
3.5	0.974	

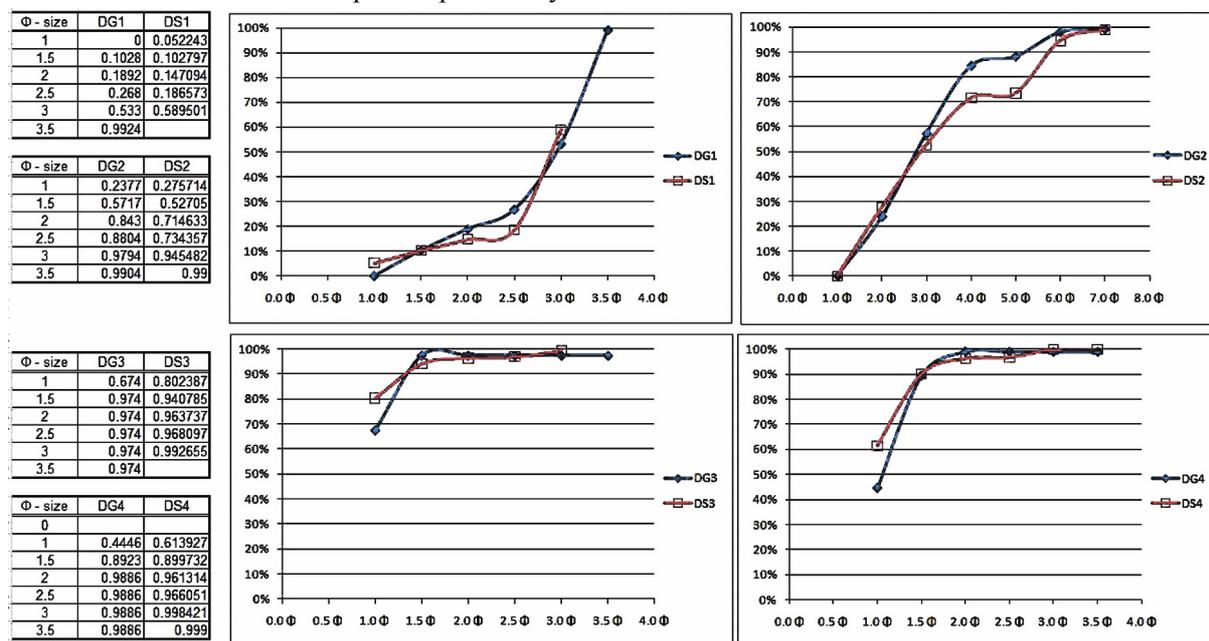| Φ - size	DG4	DS4
0		
1	0.4446	0.613927
1.5	0.8923	0.899732
2	0.9886	0.961314
2.5	0.9886	0.966051
3	0.9886	0.998421
3.5	0.9886	0.999

Figure 6. Sieve and settling tube granulometer results of four sand samples, coded as DG1, DG2, DG3 & DG4 for the granulometer and as DS1, DS2, DS3 & DS4 for the sieve method.

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