A microcomputer-based sensing system for measuring the erosive disposition of clay and silt sized soil particles

Ghulam Sarwar Buller

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Timothy N. Burcham, Major Professor

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Date 10/22/92
A MICROCOMPUTER-BASED SENSING SYSTEM FOR MEASURING
THE EROSGE DISPOSITION OF CLAY AND
SILT SIZED SOIL PARTICLES

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Ghulam Sarwar Buller
December 1992
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I would like to thank my major professor, Dr. Timothy N. Burcham, for his guidance and continuous support during this program of study. He was not only my mentor, and the chairman of my committee, he was a constant friend and source of inspiration and encouragement. He will always have my deepest appreciation. I would also like to thank the other committee members, Dr. Bobby Bledsoe, Dr. John Wilkerson, and Dr. Bruce Tschawnz for their comments and assistance over the past two and half years.

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Accurate knowledge of particle size distribution plays an important role in controlling soil erosion from farm lands, construction sites, tropical areas, channel beds, and forest lands. The concept of the vortical particle size distribution system (VPSDS) was developed by Burcham (1989) for determining particle size and concentration in soil-water mixtures on a real-time or near real-time basis. The VPSDS has three main components: (1) the VPSDS vortex chamber and sensing zone, (2) a laser light detection system, and (3) the data acquisition and control system.

Experiments were developed to determine relationships between the output of the VPSDS (voltage) and actual particle concentration in the 4 to 63 micron range using eight soils from four unified soil classifications (CL, CH, ML, MH). A modified pipette method was developed to collect soil-water mixture samples from the VPSDS sensing zone. The light blocked by soil particles in the sensing zone is detected by a logarithmic light extinction circuit, which produces voltage relative to the mass of particles blocking the laser light. The experiment compared recorded voltage with measured particle concentration at various computed particle sizes from 4 to 63 microns.

A computer control and data acquisition system was developed to operate the VPSDS and record data. The control
program stores the instrument's voltage response, impeller speed, and elapsed time for each experiment.

Results related the VPSDS voltage response to actual particle size and sample concentration for the 4 to 63 micron particle size range. Regression analyses of the data indicated a good correlation between the VPSDS voltage response and sample concentration. The mass-voltage relationship for the eight soils tested in this study was described with one equation having $r^2$ values ranging 0.98 to 0.99. Voltage as an independent variable to predict mass was statistically significant ($\alpha = 0.01$).
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CHAPTER I

INTRODUCTION

Accelerated soil erosion is recognized as the major contributor to the deterioration of productive lands in the United States (Knox County-SCD, 1981; Gordon and Schierow, 1985). Sediment concentrations in U.S. rivers range from 200 to 50,000 ppm (Wischmeier, 1976). Wischmeier further reported that the amount of sediment moved by runoff water annually is at least 4 billion tons, with about one billion tons reaching major streams. Myers et al. (1985) reported that sediment erosion from construction sites and from silvicultural activities is less prevalent than from agricultural farms. However, the localized effects on water quality are severe due to the high unit loads of eroded material involved. They further reported that the magnitude of soil erosion from construction sites can be 10 to 20 times higher than from agricultural lands.

Cooper et al. (1984) indicated that new techniques capable of rapidly analyzing a large number of soil samples are needed. USDA-SCS (1975), Rhoton and Meyer (1987) indicated that the size distribution of the eroded material is important in predicting sediment transport and deposition. None of the above methods determine particle-size distribution in-situ on a real-time or near real-time basis (Burcham and Hayes, 1989).

Many conventional methods (pipette, hydrometer, and
sieve techniques) and automated methods (electrostatic resistance microscopy, X-ray-diffraction, and light scattering) have been developed for sizing eroded sediment in laboratories (Meyer and Scott, 1983). Conventional methods are laborious and time consuming (Sullivan and Jacobsen, 1958; Perry and Chilton, 1973; Cooper et al. 1984). On the other hand, automated methods are expensive and require trained personnel to process samples (Loveland, 1958; Olivier et al. 1970-71; Schiebe et al. 1981).

Burcham (1989) developed the Vortical Particle Size Distribution System (VPSDS). His initial tests indicate that the VPSDS may prove suitable as an alternative method for determining particle size and concentration in soil-water mixtures on a real-time or near real-time basis.

1. OPERATION OF THE VPSDS

The basic operating principle of the VPSDS is differential particle transport via secondary boundary layer fluid flow. Figure 1 shows the path of soil particles transported from the vortex chamber into the sensing zone. The particles move up the inclined surface of the inverted cone due to a secondary boundary layer flow which is created by the axial flow about the gravitational axis ($g_r$) of the soil-water mixture in the frustum section of the chamber. The axial fluid flow (a free vortex) is created by an impeller located in the bottom of the chamber. As impeller speed increases,
Figure 1. Path of soil particles from the vortex chamber into the sensing zone via secondary boundary layer flow. (Source: Burcham, 1989)
additional energy is added to the boundary layer flow, and subsequently, additional particles (with higher potential energies) are transported into the sensing zone. Therefore, as impeller speed increases, the particle concentration in the sensing zone increases proportionally to the additional amount of particles transported. The particle concentration in the sensing zone is monitored by passing a helium-neon laser beam through suspension onto a photodiode. Matched photodiodes are connected to a logarithmic amplifier circuit which produces an output voltage proportional to the mass of particles in the sensing zone. The output voltage is recorded automatically by a computer at each successive impeller speed.

2. BACKGROUND OF THE VPSDS

Burcham (1989) tested the VPSDS on twenty-three soils\textsuperscript{1} from seven unified soil classes for particle size and concentration determination. He developed two different methods, (1) the Set Point Method, and (2) the Calibration Curve Method, to estimate percent finer information from the VPSDS voltage response curve. The Set Point Method (SPM) was used by selecting values from the voltage response curve.

\textsuperscript{1} These soils samples were received from the Soil Mechanics Laboratory, South National Technical Service, Fort Worth, Texas. These soils were originally taken from Arkansas, Georgia, Kentucky, Mississippi, North Carolina, and Tennessee.
based only on impeller rpm, while the Calibration Curve Method (CCM) incorporated other factors such as: variable light extinction due to clay, particle density, and particle shape. Results using the Set Point Method were promising on particles larger than 50 microns; but were less accurate on smaller particles (2 to 20 micron). Burcham attributed this to variations in particle shape, density, and variable light extinction. Results from the CCM indicated that the system responded favorably to the calibration process. With this method voltage responses from each unified soil classification were averaged to develop a "standard response". The computer then used this "calibration" to predict percent finer information. He also reported that further refinement of mechanical components and circuitry would enhance the VPSDS ability to determine particle size and concentration of soil-water mixtures. Burcham (1989) recommended that further research should be conducted: (1) to quantify the transport capabilities of the VPSDS Vortex chamber with respect to the actual particle size and shape factor, (2) to quantify the output variation due to light extinction coefficients of various soil particles, and (3) to develop a second generation VPSDS suitable for in-field measurements.

3. PROJECT DEVELOPMENT

To help the reader better understand the basis for this study, the data collection methods utilized by Burcham (1989)
are reviewed. Burcham's basic design goal for the VPSDS was to develop an instrument whose output (voltage) could be related to the particle size distribution of soil samples and/or sediment-laden runoff.

The data presented by Burcham was acquired by measuring the extinction circuit voltage at 28 distinct impeller speeds ranging from 0 to 1920 rpm. The impeller speed was stepped by 64 rpm for each interval. This produced a data file containing 28 voltage values along with their corresponding impeller speeds. Burcham refers to this output as the "voltage response curve." Figure 2 shows typical "voltage response curves" from five unified soil classifications (CL, CH, ML, MH, and SP) as presented by Burcham (1989). This presentation format is referred to as the "up-curve" voltage response, since the voltage values (instrument response) increase with increasing impeller speed.

Burcham noted that sandy soils, such as SC-615 (shown in Figure 2), produced no voltage response until impeller speeds (energy input) became relatively high (900 rpm). This was as expected, since he hypothesized that large soil particles would require more energy (higher impeller speeds) to be lifted into the sensing zone of the VPSDS. Likewise, he demonstrated that soils with high clay content (unified class MH and CH), produced a relatively large voltage response even at low impeller speeds (600 rpm) as is illustrated by the response for soil NC-2A in Figure 2.
Figure 2. VPSDS up-curve voltage response (volts) curves for soil samples AR-1L, GA-1083, MS-6A, NC-2A, and SC-615 from unified soil groups CL, CH, ML, MH, and SP respectively (Source: Burcham, 1989).
Again, this followed the basic hypothesis, i.e., small particles would be transported into the sensing zone with relatively low energy inputs (low impeller speeds).

Note that this output format is based on voltage versus impeller speed only, and no relationship is given or implied as to actual particle mass at each impeller speed. Figure 2 graphically illustrates that each of the unified soil classifications yields an independent response from the VPSDS.

While these tests did show that the VPSDS was responding to particles of various sizes as hypothesized, Burcham did not physically relate voltage response to actual particle size. He presented two methods to predict percent finer information from the recorded voltage response, but neither of these methods definitively measured the mass of soil particles in the sensing zone at a given impeller speed (energy input). In his conclusions, Burcham stated that the successful use of the VPSDS as an alternative particle sizing device would require quantification of the voltage response curves, i.e., developing relationships between output voltage and actual soil mass in the sensing zone.

Since accepted particle size measurement devices such as SediGraph (Micromeritics Instrument Corporation, 1 Micromeritics Drive, Norcross, Georgia 30093-1877) and Coulter (Coulter Electronics Inc., Hialeah, Florida) were not available for this research project, an alternative method
relating voltage output to actual particle mass had to be developed.

4. OBJECTIVES

This research project concentrates on quantifying the response of the VPSDS to actual particle concentration. This quantification was accomplished by pipetting soil-water mixtures directly from the sensing zone of the VPSDS as the particles settle due to gravity. This quantification will allow the development of more accurate VPSDS prediction algorithms which include variations caused by particle size, shape, and light extinction.

The objectives for this project were to:
1. Develop a method for relating VPSDS voltage response to actual particle size in the 4 to 63 micron size range.
2. Compare the pipetted mass to VPSDS output voltage.
3. Compare VPSDS voltage response and pipetted mass to computed Stokes' diameter in the 4 to 63 micron size range.

5. DEVELOPMENT OF TESTING PROCEDURE

The mass of particles in the sensing zone of the VPSDS is greatest at maximum impeller speed (1923 rpm). If the impeller is instantaneously stopped, the soil particles in the sensing zone immediately begin to fall due to gravitational forces. As particles fall, they pass through the laser
beam and subsequently, block light. The extinction of light is monitored by a logarithmic circuit which outputs a voltage proportional to the mass of particles in the light path. This is the same circuit used to output a voltage at various impeller speeds during the "up-curve" portion of the sampling process. Since the particles are falling due to gravitational forces, Stokes' Law can be applied to determine the size of particles passing a given point in the suspension (the laser beam) at a given time. By pipetting samples from the sensing zone at calculated times and depths, the mass of particles of a specific size range can be determined and consequently a particle size distribution of the sample can be established.

Since the particle concentration in the sensing zone continually decreases, once the impeller is stopped, the voltage output by the light extinction circuit likewise decreases. If the particles are allowed to settle over a long period of time, the output voltage will diminish from a maximum and approach zero (over a long time period, e.g., hours). Once the impeller has stopped, the light extinction circuit output voltage and time can be recorded at predetermined time intervals. This output format is referred to as the "down-curve" voltage response, since the output voltage continually decreases with time.

Theoretically the maximum voltage value of the up-curve and down-curve, for a given group of soil particles, is
equal. Figure 3 shows this theoretical relationship. Notice that the point where the up-curve ends (impeller speed = 1923 rpm) coincides with the beginning of the down-curve (time = 0).

Since the light extinction circuit measures only the mass of particles intercepting the beam, it may be concluded that the mass of particles producing a given voltage on the up-curve side of the theoretical curve also relates to the same mass of particles on the down-curve side of the bell curve shown in Figure 3. The voltage value at point A of Figure 3 can be related to particle mass using pipette analysis. Moving horizontally from point A until the up-curve is intercepted at point B allows the voltage-mass relationship at point A to be related to the voltage-impeller speed relationship at point B. Equations can be determined from both the up-curve and down-curve segments of Figure 3, thus allowing a simultaneous solution resulting in particle mass as a function of impeller speed.

Figure 4 shows the down-curve voltage responses for the five sample soils used to generate the up-curve response of Figure 2. Notice that the soils with high clay contents (unified classes MH and CH) settle slowly over time. In fact, they are still producing a significant voltage response even after 1800 seconds of settling. Contrast this to the sandy soil (unified class SP), which settles quickly and produces no voltage response after only a few seconds.
Figure 3. Theoretical relationship of up-curve voltage and down-curve voltage of soil from any unified soil group.
Figure 4. VPSDS down-curve voltage response (volts) curves for soil samples AR-1L, GA-1083, MS-6A, NC-2A, and SC-615 of unified soil groups CL, CH, ML, MH, and SP respectively.
Figure 4 also illustrates that each soil produced a unique voltage response during the down-curve measurement segment.
CHAPTER II

LITERATURE REVIEW

Syvitski (1991) reported that thick deposits of sedimentary particles, gravel, sand, silt, and clay cover most of the world's surface. He further described the nature of these deposits and determined that their formation was dependent on the distribution of particles of various sizes. Other properties of sediment such as porosity and permeability also depend on particle size (Syvitski, 1991). Sediment size information has been used in evaluating sediment yield, determining chemical transport capabilities of the sediment, sediment transport, sediment delivery, and sediment deposition both on land areas and in bodies of water.

The main objective in size analysis is to group particles into different size ranges. (Jelinek, 1970; Head, 1980; Gee, 1986) and to determine the relative proportion by dry weight of each size range.

Particle size distribution is one of the most stable soil characteristics, only slightly modified by cultivation practices (Day, 1965). Particle-size analysis is used as the basis of soil textural classification. Particle-size analysis is useful in problems dealing with weathering, segregation of soil particles by leaching, soil structure, settling, erosion, and sediment transport by water and wind.

There is a wealth of literature available in scientific
and technical journals on the various methods for determining particle size. This literature review will discuss the leading detection techniques for determining particle size. Particle-size distribution methods discussed in this review include:

1. Microscopy
2. Ultramicroscopy
3. Electron Microscopy
4. Light Scattering methods
5. Sieve Analysis
6. Sedimentation
   6.1. Pipette Method
   6.2. Hydrometer Method
7. Centrifugation
8. SediGraph
9. Adsorption Methods
10. Electrostatic Particle Counter

1. MICROSCOPY

Microscopy is the most illustrative and direct method for measuring sediment particles (Irani and Callis, 1963; Jelinek, 1970). In this method of size analysis, direct measurements are made on enlarged images of the particles. Perry and Chilton (1973) described the simplest technique where linear measurements of particles are made using a scale placed on top of the particle image.
The measurement of particle size and shape, using a microscope, is carried out in three distinct steps. (1) slide preparation, (2) particle observation, and (3) actual counting and sizing of particles (Irani and Callis, 1963). Allen (1968); Stockham and Fochtman (1977) reported that microscopy can be used to acquire information on size, shape, color, refractive index, melting point, and other physical and chemical characteristics.

The advantage of using microscopy is that it provides a direct measurement of sediment particle size, while the major drawback of microscopy is that it requires an experienced operator to get accurate results (Rose, 1954). Perry and Chilton (1973) reported three important problems in microscope methods of analysis: (1) collection of sufficient data to ensure adequate precision in the derived parameters; (2) elimination of variables in the data due to operator performance; (3) impractical for large range of soils; and (4) operator fatigue.

2. ULTRAMICROSCOPY

Ultramicroscopy is an old method for sizing particles. This method has lost much of its importance since the introduction of electron microscopy (Jelinek, 1970). The ultramicroscope method determines the average size by count methods, but it does not measure size distribution. Irani and Callis (1963) described how the total number of particles in
a known volume of fluid, containing a known weight of fully dispersed (Cadle, 1955) material can be observed and counted by an ultramicroscope. The average weight of particle is determined by dividing the weight of material per unit volume by the number of particles per unit volume.

Particle size, as sphere diameters, can be determined using the equation given below (Jelinek, 1970).

\[ d'_k = \sqrt[3]{6 \frac{G}{\pi n \rho}} = 1.24 \sqrt[3]{\frac{G}{n \rho}} \]

where,

- \( d'_k \) = particle size in \( \mu m \),
- \( n \) = number of particles in a unit volume,
- \( G \) = weight of particles in this volume in grams,
- \( \rho \) = density of particles in g/cm\(^3\).

There are two primary disadvantages of ultramicroscope method using a quartz cell (Loveland, 1958): (1) Brownian motion of fine particles that occur during counting, and (2) cleaning of the quartz cell, particularly when many samples are to be counted.

3. ELECTRON MICROSCOPY

The Electron Microscope method is used for the direct measurement of particles in the range of 0.001 microns to 5 microns. A photographic plate (Allen, 1968) or a fluorescent screen is used to display the image of sediment particles on
the electron beam by using an electron microscope. Allen (1968) reported that particles are opaque to the electron beam, when the particles are only a few hundred Angstroms thick.

A thin membrane (100 Å to 200 Å), which rests on a grid that is made of copper, is used to examine the sediment particles. The sample is usually placed on or in this membrane for determining particles size distribution. Walton (1952) and Payne (1964) have published an excellent discussion on electron microscopy.

The advent of the electron microscope has greatly reduced the time factor for data collection and fatigue of the operator. The advantage (Cadle, 1955) of an electron microscope is that images of greatly enhanced intensity can be formed on the screen of a cathode ray tube. The disadvantage is the limited capability to analyze particles greater than 5 microns diameter.

4. LIGHT SCATTERING METHODS

Methods based on the modulation of light by particles have been employed for obtaining particle size information (Syvitski, 1991). O'Konski et al. (1958) reported that the relative angular intensity of light is dependent on particle size, refractive index, and wavelength of light. Two main techniques are used for sizing of particles in a liquid medium: light scattering and light extinction. In the light
scattering technique, light scattered at angles other than zero degrees may be measured with a photometer (Frock, 1987). The principles of light scattering such as Mie scattering, Fraunhofer diffraction, and Side (90°) scattering are used to determine the particle sizes over the range of 0.1 to 1000 microns. Olivier et al. (1970-71) reported a problem with light scattering methods. They indicated that the light-scattering devices are influenced by the size, shape, and color of the particles, as well as by concentration. They further described that this influence becomes particularly complex when particle dimension approaches the wavelength of the light.

5. SIEVE METHOD

The sieve method is simple, consequently it is the most frequently used method of soil particle size analysis (Allen, 1968). In sieving, the sediment is separated through sieves which contain relatively uniform openings resulting from a plain square mesh of uniform wires (Irani and Callis, 1963). The sieve size is normally specified as a mesh number, which refers to the number of openings per linear inch (2.54 cm). Each mesh corresponds to a specific aperture since the wire size corresponding to each sieve mesh is also set by specific standards.

Cadle (1955) reported that the lower limit for sieve analysis was set at 43 microns (325 mesh). According to
Syvitski (1991), this lower size limitation has been removed by the introduction of electroformed sieves. This development has extended the range down to 5 microns. The deviations of the actual aperture size are on the order of 2 microns from the nominal size.

Perry and Chilton (1973) indicated that sieve analysis presents three major problems: (1) the apertures of commercial sieves are not identical despite the highest quality sieves, (2) sieving surfaces are easily damaged while being used, and (3) inefficiency in presenting the particles to the aperture.

6. SEDIMENTATION METHODS

Hydrodynamic (sedimentation) methods are widely used for determining the size distribution of particles in soil-water mixtures containing particles in the subsieve range (Allen, 1968). Sedimentation methods of particle size distribution are based on Stokes’ Law for the settling velocity of a particle in a fluid (Cadle, 1955). Head (1980) described the rate of fall of particles in suspension as being dependent upon their size, density, shape, and mass density and upon dynamic viscosity of liquid medium. Perry and Chilton (1973) mentioned that the settling of sediment particles in the liquid medium is subjected to gravity or centrifugal forces, drag or frictional, and buoyant forces.

Stokes’ Law states that for small particles (i.e.,
particles <64 \mu m), settling velocity is proportional to the square of the diameter of the particles (Cadle, 1955; Jelinek, 1970; Head, 1980). This relationship is described by Troeh and Palmer (1966), as:

\[ V = D^2 \]

or \[ V = kD^2 \]

where,

- \( V \) = settling velocity of particle in cm min\(^{-1}\),
- \( D \) = diameter of falling particles in mm, and
- \( k \) = constant of proportionality which depends upon the units of \( V \) and \( D \), the shape and density of the particles, and the temperature of fluid medium.

Assumptions and limitations involved in the use of Stokes' Law are summarized as below:

1. The particles should be large (>2 \( \mu m \)) in comparison to molecules of water so that the Brownian movement does not affect the particles' free fall due to gravity.
2. The condition of viscous flow in a still liquid is maintained.
3. The particles should be approximately spherical, smooth, and rigid.
4. Slippage between the particles and the medium should be negligible.
5. The temperature of the liquid should remain constant.
6. Terminal velocity of particles should be small.
7. All particles have the same density.

6.1 PIPETTE METHOD

The pipette method is a standard technique used to characterize soils. This technique was first introduced in the early 1920s by Jennings and Robinson (Day, 1965). This method is based on Stokes' Law and the physical principle of the method is to determine the concentration of soil particles at a given depth as a function of time (Allen, 1968). The settling velocity of spherical particles (Cadle, 1955) is related to the diameter of the particle by Stokes' Law as follows:

$$d = \frac{\sqrt{18\mu v}}{(\rho - \rho')g}$$

where,

- $d$ = diameter of particle in mm,
- $v$ = settling velocity of particle in cm sec$^{-1}$,
- $g$ = acceleration of gravity in cm sec$^{-2}$,
- $\rho$ = density of the sphere particle in g cm$^{-3}$,
- $\rho'$ = density of the fluid in g cm$^{-3}$,
- $\mu$ = viscosity of the fluid in g cm$^{-1}$ sec$^{-1}$.

The concentration changes within the suspension are monitored by taking samples at specified depths from the body of the suspension using a pipette. The particle-size distri-
bution is calculated from the measured concentration changes (Day, 1965).

6.2 HYDROMETER METHOD

This method was developed by G. J. Bouyoucos in 1927 (Day, 1965) and is useful for sizing particles having diameters less than 74 microns. This method measures the decrease in density in soil-water suspension caused by the settling of soil particles at a particular depth (Bauer, 1958). This method is also based on Stokes' Law, which is written for the hydrometer in the following form (Day, 1965).

\[ d = \theta t^{-1/2} \]

where,

\[ d = \text{particle diameter in mm,} \]
\[ \theta = \text{sedimentation parameter which is a function of the hydrometer settling depth, solution viscosity, and particle and solution density,} \]
\[ t = \text{settling time of particles at particular depth in seconds.} \]

Sullivan and Jacobsen (1958) reported two problems about measurement of difference in density: (1) disturbance due to the insertion and removal of the hydrometer in the suspension, and (2) density convection currents due to sinking of hydrometer in the suspension column while
sedimentation was in progress.

7. CENTRIFUGAL METHOD

The centrifugal method was developed for analyzing very fine soil particles (Slater and Cohen, 1962). This method is typically used to determine particle size in the range of 0.1 to 5 microns (Stockham and Fochtman, 1977). This method is also based on the rate of settlement of particles in a fluid medium as in gravitational sedimentation (Allen, 1981). However in this method, particles, particularly finer fractions, are forced to settle rapidly by applying forces many times that of gravity (Cadle, 1955). Svedberg (1938) presented the modified Stokes' equation for particle size analysis using centrifugal technique as follows:

\[ d = \frac{6}{\omega} \sqrt{\frac{\eta \ln \frac{s_2}{s_1}}{2(\rho - \rho') t}} \]

where,

- \( d \) = diameter of particle in mm,
- \( \omega \) = angular velocity in radians per sec,
- \( t \) = time in sec,
- \( s_2 \) = distance from the axis of rotation to the bottom of centrifuge tube in mm,
- \( s_1 \) = distance from the axis of rotation to the
meniscus of the suspension in \( \text{mm} \),

\[ \rho = \text{particle density in g cm}^{-3}, \]

\[ \rho' = \text{fluid density in g cm}^{-3}. \]

Assumptions and limitations of the centrifugal methods (Barth, 1984) are described as follows:

1. sediment particle is spherical, smooth, and rigid,
2. particle terminal velocity is reached instantly,
3. particle to particle interference is negligible,
4. volume concentration well below 1% is preferred,
5. inertial effect is negligible, and
6. the fluid continuum only exhibits Newtonian flow characteristics.

8. SEDIGRAPH METHOD

The Sedigraph is a widely used automated method for determining particle size distribution in the range of 0.1 m to 100 microns (Syvitski, 1991). Berezin and Voronin (1981) indicated that this method is based on the sedimentation principle of Stoke's Law and on the assumption that the particles are fully dispersed in a fluid and settle in accordance with the Stokes' Law. This method monitors the particle settling velocity and accurately measures the cumulative size distribution of sediment in suspension. The instrument uses a finely collimated beam (Syvitski, 1991) of X-rays to determine the concentration of particles remaining
at decreasing sedimentation depths as a function of time. Two advantages (Norman et al., 1979) of Sedigraph are: (1) capability to eliminate much of the operator error and (2) isolating the sample from temperature fluctuations, contamination, and physical disturbances. These advantages increase its analytical accuracy.

Duncan and Rukavina (1982) reported that a complete analysis of the 0.1 to 100 micron range requires more than one scan. Berezin and Voronin (1981) indicated that a material with a density of 2.65 g/cm$^3$ requires 10 min to analyze from 50 to 2 microns, 20 min for 50 to 1 microns, and 100 min to analyze from 50 to 0.2 microns.

Advantages of the Sedigraph method are listed below:
1. sample analysis requires short time period,
2. can provide accurate results, but requires a very skilled operator to run the samples,
3. allows automated or unattended operation,
4. requires a small sample size as compared to pipette or hydrometer methods, and
5. environmental fluctuations have no effect on SediGraph operation.

9. ADSORPTION METHODS

The fundamental principle of this method is to determine the specific surface of solids using physical adsorption of gases on solids (Irani and Callis, 1963). If the quantity of
gas required to cover a powder with a complete monolayer of gas molecules is measured, then the surface area can be calculated using the cross-sectional area of gas molecules (Allen, 1968). Allen (1968) noted that the surface area measured by gas-adsorption techniques is directly related to the surface area available in chemical reactions.

Cadle (1955) used the following expression to determine particle size distribution.

\[
d_{vs} = \frac{6}{S_w \cdot P}
\]

where,
\(d_{vs}\) = derived surface mean diameter in mm,  
\(S_w\) = specific surface,  
\(P\) = density of the spheres in g cm\(^{-3}\).

Many theories on gaseous adsorption have been presented, but measurements on powders are usually interpreted using the Brunauer, Emmett, and Teller theory (Stockham and Fochtman, 1977).

### 10. ELECTROSTATIC PARTICLE COUNTER

This technique was introduced in 1950’s for sizing sediment particles in the submicron range (Barth, 1984). In this method, the particles to be measured are examined individually (Syvitski, 1991) in a stream of fluid. When
particles, in a very dilute liquid suspension, pass through an orifice submerged in an electrolytic solution with two electrodes on either side, the resistance between the two electrodes is increased for a short period of time. This change in resistance caused by the individual particle passing through the orifice is a measure of the electrolyte displaced by the particle, and hence the size of particle is determined from this displaced volume of electrolyte.

Stockham and Fochtman (1977) reported that electrostatic counters require a conductive liquid in which the particle is essentially insoluble. These methods are applicable to the measurement of particles in the 1 to 500 micron range. The most widely used electrostatic counter is the Coulter counter (Coulter Electronics Inc., Hialeah, Florida).
SEDIMENTATION PROCEDURES BACKGROUND

Sedimentation methods have been utilized for particle size determination (Barth, 1984). These methods are based on Stokes’ Law for the settling velocity of particles in a suspension medium (Miller, 1987). The pipette method is widely used for determining particle size in soil-water suspensions (Stockham and Fochtman, 1977). Before taking samples using any sedimentation technique, the soil-water mixture should be stirred. A recommended method is to continually invert the container for one minute (Allen, 1968). This is important to ensure that the suspension is completely homogeneous prior to beginning the pipetting process. Particles start settling when agitation ceases and samples (usually 25 ml) are pipetted from the suspension at specified times and depths according to Stokes’ Law. Once the mass of the pipetted sample is determined, a particle size distribution can be established.

1. DEVELOPMENT OF MODIFIED PIPETTE METHOD

The Modified Pipette Method (MPM) was developed to relate the VPSDS voltage response to actual sample mass in the 4 to 63 micron range. The working principle for the VPSDS is to transport (move) soil particles from the bottom of the vortex chamber into the VPSDS sensing zone via the secondary
flow of the vortex chamber as shown previously in Figure 1. The maximum concentration of soil particles in the sensing zone is achieved when the impeller is at maximum speed (1923 rpm).

The initial soil-water concentration in the VPSDS vortex chamber (prior to the impeller rotating) is 1.33 mg/ml. Table 1 shows the soil-water concentrations that were measured in the sensing zone at maximum impeller speed.

Table 1. Maximum concentration for each soil type at maximum impeller speed of 1923 rpm and an initial soil concentration of 1.33 mg/ml.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Maximum concentration in the sensing zone at maximum impeller speed. (mg/ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR-1L</td>
<td>5.14</td>
</tr>
<tr>
<td>KY-1F</td>
<td>4.89</td>
</tr>
<tr>
<td>GA-1083</td>
<td>8.12</td>
</tr>
<tr>
<td>TX-4D</td>
<td>4.87</td>
</tr>
<tr>
<td>MS-6A</td>
<td>6.18</td>
</tr>
<tr>
<td>TN-6B</td>
<td>6.18</td>
</tr>
<tr>
<td>NC-2A</td>
<td>6.16</td>
</tr>
<tr>
<td>TX-2F</td>
<td>7.45</td>
</tr>
</tbody>
</table>

As can be seen in Table 1, the soil-water concentration in the sensing zone is increased over four fold from the initial concentration. (Note: this provides additional proof that the secondary boundary layer flow is transporting soil particles from the vortex chamber and concentrating them in the sensing zone.)

The sensing zone of the VPSDS is therefore analogous to a 1000 ml graduated cylinder used in the standard pipette
analysis, but the sensing zone (cylinder) is only 60 mm in height and 9 mm in diameter. At time $t = 0$, the impeller (i.e., the energy source suspending the particles in the sensing zone) is stopped, therefore allowing the soil particles in the sensing zone to fall due to gravity. This is analogous to setting the graduated cylinder in the measurement position immediately after the shaking process is completed. Since the soil particles attain a definite elevation in the sensing zone, the top of the soil-water mixture is defined as the datum ($h=0$) for subsequent depth measurements for predicting particle size using Stokes' Law. The fall depths ($h$) are measured from the top of the soil-water mixture (cloudy water) to the point where the laser passes through the sensing zone as shown in the Figure 5.

Particles were assumed to fall according to Stokes' Law and all assumptions of that law are valid (e.g. particles are small spheres, condition of viscous fluid in still water, no turbulence, constant liquid temperature, small terminal velocity, and all particles are of same density).

While assumptions from Stokes' Law are applicable, other disturbances not found in the standard pipette analysis must be noted for the MPM.

At the instant the impeller stops, the soil particles in the sensing zone are moving radially due to influence from the axial flow in the vortex chamber. This radial motion was observed to diminish after 3 seconds. Since the first sample
Figure 5. Fall elevation of settling particles for the soil-water mixture in the VPSDS sensing zone.
is taken at 10 seconds, the radial disturbance was assumed to cause minor errors. It was also observed that some air bubbles appeared in the sensing zone when the impeller stopped. These bubbles were clear of the point where the laser passed through the sensing zone at the first sampling event (i.e., 10 seconds).

Because of these variations from the standard pipette analysis, this procedure was termed the "Modified Pipette Method."
CHAPTER IV

EXPERIMENTAL PROCEDURE

A personal computer, a 5 ml pipette, aluminum pans, an electronic balance, a drying oven, a desiccator, a mortar pestle, a 105 (μm) soil sieve, and a stop watch are required to process samples using the modified pipette method and the VPSDS.

Two soil samples from each of four unified soil groups (CL, CH, ML, and MH) were selected for the experiment, resulting in a total of eight samples. Sample weights of 0.3 grams were used for the duration of the experiment. Three grams of each of the eight soil types were sieved using a 105 (μm) sieve to complete replication. Individual samples of 0.3 grams were weighed using an electronic balance. Aluminum pan weights were recorded before initiating each test. Codes were placed on each pan for quick sample identification.

Settling times for the soil samples were determined using Stokes' Law, which relates the settling time to particle diameter (Troeh and Palmer, 1966). Particles were assumed to be spherical and to have a constant density of 2.65 g/cm³. The values of K (using in Equation 2-2) for various water temperatures (Troeh and Palmer, 1966) are given in Table 2.

The samples were taken at room temperature which averaged 24°C (Troeh and Palmer, 1966). Settling rates and
settling velocities for individual particles of all eight soils were calculated using Stokes' Law. A value of 6000 was used for K.

Table 2. K values for given water temperature.

<table>
<thead>
<tr>
<th>Water Temperature (°C)</th>
<th>K Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0</td>
<td>4150</td>
</tr>
<tr>
<td>20.0</td>
<td>5500</td>
</tr>
<tr>
<td>30.0</td>
<td>6800</td>
</tr>
<tr>
<td>38.8</td>
<td>8000</td>
</tr>
</tbody>
</table>

Fall depths for each of the eight samples were established at maximum impeller speed. The particles are assumed to reach the terminal velocity computed by Equation 2-2. Since fall depth (h) and terminal velocity (V) are known, the pipetting time can be computed using the following equation:

\[ Pt = \frac{h}{V} \]  

(4-1)

where,

Pt = the pipetting time (sampling time) in minutes,

h = the depth of fall in centimeters, and

V = the terminal velocity given by Equation 2-2 in cm/min.

The fall depths and pipetting times for specific particle sizes of each soil tested are listed in Table 3.
Table 3. Values of fall depth, fall velocity, and settling time for all eight soil samples.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Soil Class</th>
<th>Particle Size</th>
<th>Fall Depth (cm)</th>
<th>Fall Velocity (cm/min)</th>
<th>Settling Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR-1L</td>
<td>CL</td>
<td>63 4.50</td>
<td>23.814</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>31</td>
<td>5.766</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>16</td>
<td>1.536</td>
<td>175</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>0.384</td>
<td>703</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>0.096</td>
<td>2812</td>
<td></td>
</tr>
<tr>
<td>KY-1F</td>
<td>CL</td>
<td>63 4.10</td>
<td>23.814</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>31</td>
<td>5.766</td>
<td>42</td>
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</tr>
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<td></td>
<td></td>
<td>16</td>
<td>1.536</td>
<td>160</td>
<td></td>
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<td></td>
<td></td>
<td>8</td>
<td>0.384</td>
<td>640</td>
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</tr>
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<td></td>
<td></td>
<td>4</td>
<td>0.096</td>
<td>2562</td>
<td></td>
</tr>
<tr>
<td>GA-1083</td>
<td>CH</td>
<td>63 4.40</td>
<td>23.814</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>31</td>
<td>5.766</td>
<td>46</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>16</td>
<td>1.536</td>
<td>172</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>0.384</td>
<td>687</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>0.096</td>
<td>2750</td>
<td></td>
</tr>
<tr>
<td>TX-4D</td>
<td>CH</td>
<td>63 5.20</td>
<td>23.814</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>31</td>
<td>5.766</td>
<td>52</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>16</td>
<td>1.536</td>
<td>195</td>
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<td></td>
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<td>0.384</td>
<td>781</td>
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</tr>
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<td></td>
<td></td>
<td>4</td>
<td>0.096</td>
<td>3125</td>
<td></td>
</tr>
<tr>
<td>MS-6A</td>
<td>ML</td>
<td>63 4.30</td>
<td>23.814</td>
<td>11</td>
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<tr>
<td>TN-6B</td>
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<td>23.814</td>
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<tr>
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</tr>
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</table>
1. SAMPLING PROCEDURE

The following procedure was used to collect data.

The soil sample was placed next to the impeller of the VPSDS. The conical section (vortex chamber) was then attached and secured. The chamber was then filled with 225 ml of clean tap water. The upper base (monitoring section) was then put in place. This completed the setup procedure and sampling was then initiated.

Control of the sampling procedure and recording of data was initiated by running a custom data acquisition and control program written in Borland C++, Version 2.0 (Borland International, Inc., 1800 Green Hills Road, P.O. Box 660001, Scotts Valley, CA 95067-0001). Interactive input screens were developed using the HI-SCREEN XL Professional Series program (Softway, Inc., PC/Soft Product Line, 500 Suter St., Suite 222, San Francisco, CA 94102). The VPSDS control program consisted of a main body and three functions. The C++ data acquisition and control program is listed in Appendix A.

A typical test procedure for a particular soil is described as follows:

Upon program initiation, the computer prompts the user to input sampling time (a sampling time of two seconds was used for all samples). The VPSDS control program takes samples continuously during this two second interval, then determines an average voltage value occurring over the sampling interval. The control program stores the average
voltage value and impeller speed. The impeller speed is then increased by 64 rpm. This portion of the data collection cycle stores the "up-curve" voltage response.

Once the up-curve portion of the sampling process is completed, the impeller stops and the suspended soil particles in the sensing zone begin to settle due to gravity. This marks the beginning of the "down-curve" portion of the sampling process. It is during this portion of the VPSDS sampling procedure that the modified pipette sampling procedure is utilized.

A specific pipetting time, related to the particle size (from Table 3) is entered when the VPSDS data acquisition and control program is initiated. Pipetting times ranged from 10 to 3125 seconds, depending on the computed Stokes' particle size (63, 31, 16, 8, and 4 microns) and fall depth for a particular soil type. When this predetermined pipetting time occurs, the computer prompts (beeps) the user to immediately pipette a 5 ml sample from the sensing zone of VPSDS. A rubber stopper (mounted on the pipette) positions the pipette directly above the laser beam. Pre-insertion of the pipette minimizes disturbance during the sampling process.

The pipetted soil-water mixture was then transferred to aluminum pans and transferred to a drying oven. The samples remained in the oven twenty-four hours at 105 °C. Samples were then transferred to a desiccator where they remained for two hours. Each sample was weighed using an electronic
balance. Empty pan weights were then subtracted from gross pan weight to determine the mass of soil taken at each of the predetermined pipetting times. Pipetted mass and corresponding VPSDS voltage values were then available to be plotted against computed Stokes' diameter.
CHAPTER V

RESULTS AND DISCUSSION

Using the procedure outlined in Chapter 4, two soils from four unified soil classifications were analyzed using the VPSDS. Soils with the following identifiers and unified classifications were selected for testing: AR-1L, KY-1F (unified soil class CL), GA-1083, TX-4D (unified soil class CH), MS-6A, TN-6B (unified soil class ML), and NC-2A, TX-2F (unified soil class MH).

The letter L in these soil classes represents the low clay content in the samples and letter H represents high clay content in the samples. Table 4 shows the mechanical properties of the soils as tested by the Soil Mechanics Laboratory. Since fall depths were not sufficient for sampling particles greater than 64 microns (using the Modified Pipette Method), the experiment concentrated on particles ranging from 4 to 64 microns. Particles less than 2 microns were not tested due to the extremely long settling times required. Three replications were completed on each of the eight soil types for a total of 24 individual tests. Each replication took approximately three hours.

Voltage data for each sample was stored via computer. The modified pipette method (MPM) described in Chapter 3 was used to determine the particle size range of particles extracted from the VPSDS sensing zone. The pipetted mass
Table 4. Liquid-plastic limits and unified classification for 9 test soils.

<table>
<thead>
<tr>
<th>Soil Identifier</th>
<th>Liquid Limit</th>
<th>Plastic Limit</th>
<th>Unified Classification</th>
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</thead>
<tbody>
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<td>15</td>
<td>CL</td>
</tr>
<tr>
<td>GA-1083</td>
<td>96</td>
<td>64</td>
<td>CH</td>
</tr>
<tr>
<td>KY-1F</td>
<td>36</td>
<td>15</td>
<td>CL</td>
</tr>
<tr>
<td>MS-6A</td>
<td>-</td>
<td>-</td>
<td>ML</td>
</tr>
<tr>
<td>NC-2A</td>
<td>66</td>
<td>22</td>
<td>MH</td>
</tr>
<tr>
<td>SC-615</td>
<td>-</td>
<td>-</td>
<td>SP</td>
</tr>
<tr>
<td>TN-6B</td>
<td>-</td>
<td>-</td>
<td>ML</td>
</tr>
<tr>
<td>TX-2F</td>
<td>82</td>
<td>41</td>
<td>MH</td>
</tr>
<tr>
<td>TX-4D</td>
<td>74</td>
<td>49</td>
<td>CH</td>
</tr>
</tbody>
</table>

a. The first two letters identify the state. The alphanumeric value following the dash is the soil identification value.

b. Atterburg liquid and plastic limits.

data were recorded in a computer-based spreadsheet for subsequent retrieval and manipulation.

1. PIPETTED SOIL MASS VERSUS VPSDS VOLTAGE OUTPUT

The output voltage of the VPSDS was recorded just before pipetting a sample from the sensing zone. This allowed the instrument’s response (light extinction circuit voltage output) to be compared with actual particle concentration (mass). The mass-voltage replicated data was fitted mathematically using a commercial curve fitting computer program (TableCurve, Curve Fitting Software, Jandel Scientific, 2591 Kerner Boulevard, San Rafael, CA 94901). The mass-voltage relationship was described with the following relationship:

\[
\text{mass} = a + b \times e^{-x/c}
\]

where \(a\), \(b\), and \(c\) are regression coefficients (see Table 5) and \(x\) is the VPSDS voltage response. The \(r^2\) values ranged from 0.985 to 0.996, indicating excellent fit. Table 5 gives a summary of the \(r^2\) values, coefficients, and F-Statistics. Figures 6 thru 13 show fitted mass-voltage relationships for the eight soils tested.

With the exception of sample GA-1083, all of the mass-voltage curves have a pronounced exponential form. While the mass-voltage relationship of sample GA-1083 has a near
Table 5. Model equation and coefficients for sample mass concentration as a function of VPSDS voltage for eight soils.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Soil Class</th>
<th>Best Model Equation</th>
<th>DF Adj $r^2$</th>
<th>F-Stat</th>
<th>Param a</th>
<th>Param b</th>
<th>Param c</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR-1L</td>
<td>CL</td>
<td>$y = a + b \exp(-x/c)$</td>
<td>0.995</td>
<td>1764.002</td>
<td>-0.00260</td>
<td>0.00297</td>
<td>-0.5881</td>
</tr>
<tr>
<td>KY-1F</td>
<td>CL</td>
<td>$y = a + b \exp(-x/c)$</td>
<td>0.992</td>
<td>1046.455</td>
<td>-0.00043</td>
<td>0.00095</td>
<td>-0.3913</td>
</tr>
<tr>
<td>GA-1083</td>
<td>CH</td>
<td>$y = a + b \exp(-x/c)$</td>
<td>0.996</td>
<td>1996.655</td>
<td>-0.02672</td>
<td>0.02712</td>
<td>-2.5774</td>
</tr>
<tr>
<td>TX-4D</td>
<td>CH</td>
<td>$y = a + b \exp(-x/c)$</td>
<td>0.985</td>
<td>528.839</td>
<td>-0.00338</td>
<td>0.00384</td>
<td>-0.9621</td>
</tr>
<tr>
<td>MS-6A</td>
<td>ML</td>
<td>$y = a + b \exp(-x/c)$</td>
<td>0.992</td>
<td>977.446</td>
<td>-0.00395</td>
<td>0.00465</td>
<td>-0.6266</td>
</tr>
<tr>
<td>TN-6B</td>
<td>ML</td>
<td>$y = a + b \exp(-x/c)$</td>
<td>0.995</td>
<td>1664.206</td>
<td>-0.00222</td>
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<td>-0.5009</td>
</tr>
<tr>
<td>NC-2A</td>
<td>MH</td>
<td>$y = a + b \exp(-x/c)$</td>
<td>0.995</td>
<td>1572.065</td>
<td>-0.00335</td>
<td>0.00415</td>
<td>-0.9599</td>
</tr>
<tr>
<td>TX-2F</td>
<td>MH</td>
<td>$y = a + b \exp(-x/c)$</td>
<td>0.985</td>
<td>513.266</td>
<td>-0.00234</td>
<td>0.00309</td>
<td>-0.8331</td>
</tr>
</tbody>
</table>
Figure 6. Sample mass (grams) versus VPSDS response (volts) for soil AR-1L (CL soil group) fitted to the equation $y = a + b \cdot \exp(-x/c)$. (Outer bands are 95% prediction interval)
Figure 7. Sample mass (grams) versus VPSDS response (volts) for soil KY-1F (CL soil group) fitted to the equation $y = a + b \exp(-x/c)$. (outer bands are 95% prediction interval)
Figure 8. Sample mass (grams) versus VPSDS response (volts) for soil GA-1083 (CH soil group) fitted to the equation $y = a + b \times \exp\left(-\frac{x}{c}\right)$. (outer bands are 95% prediction interval)
Figure 9. Sample mass (grams) versus VPSDS response (volts) for soil TX-4D (CH soil group) fitted to the equation $y = a + b \exp\left(\frac{-x}{c}\right)$. (Outer bands are 95% prediction interval)
Figure 10. Sample mass (grams) versus VPSDS response (volts) for soil MS-6A (ML soil group) fitted to the equation $y = a + b \exp(-x/c)$. (outer bands are 95% prediction interval)
Figure 11. Sample mass (grams) versus VPSDS response (volts) for soil TN-6B (ML soil group) fitted to the equation \( y = a + b \times \exp\left(-\frac{z}{c}\right) \). (outer bands are 95% prediction interval)
Figure 12. Sample mass (grams) versus VPSDS response (volts) for soil NC-2A (MH soil group) fitted to the equation $y = a + b \cdot \exp(-x/c)$. (Outer bands are 95% prediction interval)
Figure 13. Sample mass (grams) versus VPSDS response (volts) for soil TX-2F (MH soil group) fitted to the equation $y = a + b \times \exp(-x/c)$. (outer bands are 95% prediction interval)
linear relationship, its $r^2$ value using Equation 5-1 is 0.996 indicating excellent fit.

The statistical analysis of mass as a function of voltage given in Table 5 indicates that voltage is statistically significant ($\alpha = 0.01$). Replication and interaction are not significant ($\alpha = 0.01$).

2. VOLTAGE RESPONSE VERSUS PREDICTED STOKES' DIAMETER

Graphs of the replicated VPSDS voltage response (volts) versus Stokes' particle size (microns) for the four unified soil groups are shown in Appendix B Figures 1B thru 4B. VPSDS voltage values versus Stokes' diameter are listed in Table 6. These plots indicate that VPSDS voltage response for the three replications are consistent for each of the eight soils tested.

Equations best describing VPSDS voltage response versus Stokes' diameter were determined using the curve fitting computer software described previously. Mathematically fitted data for VPSDS voltage response versus computed Stokes' diameter are shown in Figures 14 thru 17. The $r^2$ values, coefficients, and F-Statistics are listed in table 7. The $r^2$ values ranged from 0.990 to 0.996 indicating that the model equations described the data set well. Particle size is statistically significant ($\alpha = 0.01$). Replication and interaction are not statistically significant ($\alpha = 0.01$).
Table 6. VPSDS voltage response (volts) for eight soils at stokes’ particle sizes in the sensing zone.

<table>
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<tr>
<th>Sample</th>
<th>Class</th>
<th>Size</th>
<th>rep. 1</th>
<th>rep. 2</th>
<th>rep. 3</th>
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</table>
Figure 14. VPSDS response (volts) versus computed particle size (Stokes' dia.) in microns for CL group soils, (a) soil AR-1L fitted to the equation \( y = a + b \times x \times \ln x \) and (b) soil KY-1F fitted to the equation \( y = a + b \times x^2 \times \ln x \). (outer bands are 95% prediction interval)
Figure 15. VPSDS response (volts) versus computed particle size (Stokes' dia.) in microns for CH group soils. (a) soil GA-1083 fitted to the equation $y=a+b*x^2$ and (b) soil TX-4D fitted to the equation $y=a+b*\ln x$. (outer bands are 95% prediction interval)
Figure 16. VPSDS response (volts) versus computed particle size (Stokes' dia.) in microns for ML group soils, (a) soil MS-6A and (b) soil TN-6B. Both (a) and (b) are fitted to the equation $y = a + b \times x \times \ln x$. (outer bands are 95% prediction interval)
Figure 17. VPSDS response (volt) versus computed particle size (Stokes' dia.) in microns for MH group soils, (a) soil NC-2A and (b) soil TX-2F. Both (a) and (b) are fitted to the equation $y=a+b\times\ln x$. (outer bands are 95% prediction interval)
Table 7. Model equations and coefficients for VPSDS voltage response (volts) versus Stokes’ particle size for eight soils.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Soil Class</th>
<th>Best Model Equation</th>
<th>DF</th>
<th>Adj r²</th>
<th>F-Stat</th>
<th>Param a</th>
<th>Param b</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR-1L</td>
<td>CL</td>
<td>y=a+bxlnx</td>
<td>0</td>
<td>0.9928</td>
<td>2099.560</td>
<td>0.11980</td>
<td>0.00375</td>
</tr>
<tr>
<td>KY-1F</td>
<td>CL</td>
<td>y=a+bSQRTxlnx</td>
<td>0</td>
<td>0.9903</td>
<td>1565.435</td>
<td>0.05281</td>
<td>0.03378</td>
</tr>
<tr>
<td>GA-1083</td>
<td>CH</td>
<td>y=a+bSQRTx</td>
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<td>0.9965</td>
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<td>-0.29435</td>
<td>0.18474</td>
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<tr>
<td>TX-4D</td>
<td>CH</td>
<td>y=a+blnx</td>
<td>0</td>
<td>0.9949</td>
<td>2971.652</td>
<td>-0.62758</td>
<td>0.59518</td>
</tr>
<tr>
<td>MS-6A</td>
<td>ML</td>
<td>y=a+bxlnx</td>
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<td>0.9924</td>
<td>1996.699</td>
<td>-0.00478</td>
<td>0.00344</td>
</tr>
<tr>
<td>TN-6B</td>
<td>ML</td>
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<td>0.9948</td>
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<tr>
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<td>-0.59524</td>
<td>0.56612</td>
</tr>
</tbody>
</table>
3. CONCENTRATION DATA VERSUS STOKES’ DIAMETER

Plots of sample concentration (grams) versus computed Stokes’ diameter (microns) for samples pipetted from the VPSDS sensing zone at pipetting times (as listed in Table 3), for four unified soil groups are shown in Appendix C Figures 1C thru 4C. Notice that the pattern of these plots is similar to the pattern of voltage versus particle diameter which confirms the relationship between VPSDS voltage response and pipetted mass. Sample concentration data for eight soils tested is listed in Table 8.

4. COMPARISONS OF VPSDS VOLTAGE RESPONSE AND MEASURED CONCENTRATION VERSUS COMPUTED STOKES’ DIAMETER

Equations from Table 7 were used to model the relationship between concentration (pipetted mass) and computed Stokes’ diameter. This was done to determine the graphical similarity, if any, between plots of concentration versus Stokes’ diameter and plots of VPSDS voltage versus Stokes’ diameter for a given soil sample. Table 9 shows the statistical information computed by modeling the concentration data using Table 7 equations for each individual soil, respectfully. Analysis of Table 9 equations indicates that particle diameter is statistically significant ($\alpha = 0.01$). Replication and interaction are not statistically significant ($\alpha = 0.01$). Figures 18 thru 21 show the concentration
Table 8. Sample concentrations (mass) of eight soils in the VPSDS sensing zone for stokes’ particle sizes.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Class</th>
<th>Size</th>
<th>Sample Concentration (grams)</th>
<th>Sample Concentration (grams)</th>
<th>Sample Concentration (grams)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR-1L</td>
<td>CL</td>
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<td>0.0158</td>
<td>0.0163</td>
<td>0.0153</td>
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<tr>
<td></td>
<td></td>
<td>31</td>
<td>0.0052</td>
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<td>0.0048</td>
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<tr>
<td></td>
<td></td>
<td>16</td>
<td>0.0025</td>
<td>0.0023</td>
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<tr>
<td>KY-1F</td>
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<tr>
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<tr>
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<td>0.0011</td>
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<td>0.0017</td>
<td>0.0015</td>
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<td>0.0012</td>
<td>0.0010</td>
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<td>NC-2A</td>
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<td>0.0016</td>
<td>0.0019</td>
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<td>4</td>
<td>0.0018</td>
<td>0.0015</td>
<td>0.0014</td>
</tr>
</tbody>
</table>
Table 9. Model equations and coefficients for sample concentration (mass) as a function of particle size for eight soils.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Best Model Equation</th>
<th>DF</th>
<th>Adj $r^2$</th>
<th>F-Stat</th>
<th>Param a</th>
<th>Param b</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR-1L</td>
<td>$y=a+bx\ln x$</td>
<td>0.97747</td>
<td>660.216</td>
<td>0.00001</td>
<td>0.00006</td>
<td></td>
</tr>
<tr>
<td>KY-IF</td>
<td>$y=a+b\sqrt{x}\ln x$</td>
<td>0.88650</td>
<td>120.630</td>
<td>-0.00248</td>
<td>0.00056</td>
<td></td>
</tr>
<tr>
<td>GA-1083</td>
<td>$y=a+b\sqrt{x}$</td>
<td>0.98921</td>
<td>1392.826</td>
<td>-0.00420</td>
<td>0.00250</td>
<td></td>
</tr>
<tr>
<td>TX-4D</td>
<td>$y=a+bx\ln x$</td>
<td>0.94702</td>
<td>273.300</td>
<td>-0.01074</td>
<td>0.00741</td>
<td></td>
</tr>
<tr>
<td>MS-6A</td>
<td>$y=a+bx\ln x$</td>
<td>0.96564</td>
<td>428.301</td>
<td>-0.00027</td>
<td>0.00005</td>
<td></td>
</tr>
<tr>
<td>TN-6B</td>
<td>$y=a+bx\ln x$</td>
<td>0.96271</td>
<td>393.952</td>
<td>-0.00013</td>
<td>0.00006</td>
<td></td>
</tr>
<tr>
<td>NC-2A</td>
<td>$y=a+bx\ln x$</td>
<td>0.91661</td>
<td>142.935</td>
<td>-0.01003</td>
<td>0.00685</td>
<td></td>
</tr>
<tr>
<td>TX-2F</td>
<td>$y=a+bx\ln x$</td>
<td>0.93195</td>
<td>209.891</td>
<td>-0.01091</td>
<td>0.00751</td>
<td></td>
</tr>
</tbody>
</table>
(pipetted mass) data fitted to the models from Table 7. Appendix D, Figures 1D through 8D, show VPSDS voltage and concentration plots versus computed Stokes’ diameter for each of the eight soils tested.

The $r^2$ values from Table 9 and graphical similarity of the VPSDS voltage versus computed Stokes’ diameter plots and concentration versus computed Stokes’ diameter plots (Appendix D) validate the modified pipette method. The $r^2$ values ranged from 0.886 to 0.989 for the concentration (pipetted mass) versus computed Stokes’ diameter. With the exception of soil KY-1F, the model equations from the Table 7 fit the concentration data well.

Of the eight soils tested, only the plot of concentration versus computed Stokes’ diameter for sample KY-1F differed appreciably (in basic shape) from the plot of VPSDS voltage versus Stokes’ diameter. This graphical observation is further validated by the corresponding $r^2$ of 0.898 (the lowest in the group). Concentration data for the remaining seven soils indicates that the modified pipette method (with the stated assumptions) is valid for determining the particle size distribution in the sensing zone of the VPSDS.

The probable culprit for the poor relationship on the KY-1F soil is the assumption of a completely homogeneous suspension in the sensing zone, as it was observed that the density of soil particles in the sensing zone decreased near the top of the soil-water mixture.
Figure 18. Sample mass (grams) versus computed particle size (Stokes’ dia.) in microns for CL group soils, (a) soil AR-1L fitted to the equation \( y = a + b \cdot x \cdot \ln x \) and (b) soil KY-1F fitted to the equation \( y = a + b \cdot x^2 \). (Outer bands are 95% prediction interval)
Figure 19. Sample mass (grams) versus computed particle size (Stokes' dia.) in microns for CH group soils. (a) soil GA-1083 fitted to the equation $y = a + b \times x^2$ and (b) soil TX-4D fitted to the equation $y = a + b \times \ln x$. (outer bands are 95% prediction interval)
Figure 20. Sample mass (grams) versus computed particle size (Stokes' dia.) in microns for ML group soils, (a) soil MS-6A and (b) soil TN-6B. Both (a) and (b) are fitted to the equation $y = a + b \times x \times \ln x$. (outer bands are 95% prediction interval)
Figure 21. Sample mass (grams) versus computed particle size (Stokes' dia.) in microns for MH group soils, (a) soil NC-2A and (b) soil TX-2F. Both (a) and (b) are fitted to the equation $y = a + b \times \ln(x)$. (Outer bands are 95% prediction interval)
5. SAMPLE CALCULATION FOR PIPETTED MASS AS A FUNCTION OF IMPELLER SPEED

The following sample calculation is presented to show how sample concentration (mass) can be related to impeller speed (rpm). For this example soil AR-1L was selected to compute the sample concentration at a given impeller speed. An impeller speed of 1000 rpm is used for this example. From Figure 22 the VPSDS response corresponding to 1000 rpm is approximately 0.70 volts. Figure 23 shows the mass versus voltage relationship determined for soil AR-1L. Mathematical expressions for data shown in Figures 22 and 23 were determined to develop an equation relating sample concentration (mass) to impeller speed.

From Figure 22, the relationship between voltage and impeller speed was mathematically fitted and can be expressed as:

\[
\text{Voltage} = a + b \times \ln(x)
\]  
\((5-2)\)

where \(a = -3.542\), \(b = 0.614\) are regression coefficients, and \(x\) is the impeller speed. By inserting the values for \(a\), \(b\), and impeller speed in equation 5-2, we get

\[
\text{voltage} = -3.5421 + 0.6138 \times \ln(\text{speed})
\]  
\((5-3)\)

Similarly, the mass/voltage data shown in Figure 23 can be mathematically described by:
Figure 22. VPSDS up-curve voltage response in volts versus impeller speed (rpm) for soil AR-1L (CL soil group) fitted to the equation $y = a + b \times \ln x$. (outer bands are 95% prediction interval)
Figure 23. Sample mass in grams versus VPSDS response in volts for soil AR-1L (CL soil group) fitted to the equation $y = a + b \times x^2$. (outer bands are 95% prediction interval)
mass = a + b * x²

(5-4)

where \( a = 0.00101 \), \( b = 0.01284 \) and \( x \) is the voltage.

Solving equations 5-3 and 5-4 simultaneously gives the following relationship:

\[
\text{Mass} = 0.1621 + 0.0048 \ln(\text{speed})[\ln(\text{speed}) - 11.5351]
\]

(5-5)

From Figure 23, we find that 0.7 volts corresponds to approximately 0.0075 grams of soil. Now inserting 1000 rpm into Equation 5-5, we get 0.00740 grams. This compares favorably to the 0.0075 grams determined graphically.
CHAPTER VI

SUMMARY AND CONCLUSIONS

1. SUMMARY

The objectives of this study were to; (1) develop a method for relating the VPSDS voltage response to actual particle size in the 4 to 63 micron size range, (2) compare the pipetted mass to VPSDS output voltage, and (3) compare the VPSDS voltage response and pipetted mass to computed Stokes' diameter in the 4 to 63 micron size range.

A computer program was written to control the VPSDS data collection process and save the VPSDS voltage response to a disk file for further manipulation.

Eight soils from four unified soil groups, two soils from each soil group, were selected for analysis in this project. Weights of 0.3 grams of sieved soil were used for the duration of testing.

The modified pipette method was developed for extracting soil-water samples from the VPSDS sensing zone at specific depths and times corresponding to a computed Stokes' diameter range. The corresponding VPSDS voltage response was recorded by the computer.

The VPSDS voltage response versus sample concentration could be described by a single equation (with different coefficients for each soil). Voltage, as an independent
variable to predict mass, was statistically significant ($\alpha = 0.01$). The $r^2$ values range from 0.98 to 0.99 for this portion of the experiment. Mathematical models were used to fit the VPSDS voltage and sample concentration responses as a function of computed Stokes' diameter. Particle diameter, as an independent variable to predict both mass and voltage, was statistically significant ($\alpha = 0.01$), thus validating the modified pipette method.

2. CONCLUSIONS

The modified pipette method used with the Vortical Particle Size Distribution System gave promising results. These results indicated the following:

1. The VPSDS has potential as an alternative instrument for determining sample particle size distribution in the range of 4 to 63 microns.

2. The VPSDS voltage response was consistent and smooth when 0.3 gram soil samples were used.

3. There was little variation in both the VPSDS voltage response and sample concentrations for replicated experiments, indicating excellent instrument repeatability.

4. Fitted up-curve and down-curve data can be used to determine particle concentration (mass) as a function of impeller speed.
BIBLIOGRAPHY
BIBLIOGRAPHY


APPENDICES
APPENDIX A

VPSDS CONTROL AND DATA ACQUISITION COMPUTER PROGRAM
Vortical Particle Size Distribution System Program.

Vortical Particle Size Distribution System program runs the machine and gets the results of channel #3. The results are saved on disk file created by the user.

```c
#include <stdio.h>
#include <conio.h>
#include <string.h>
#include <dos.h>
#include <math.h>
#include <time.h>

#define BASE1 1808
#define LOOPTIME 46

float getdata(int);
void chgspeed(float);
int ften(void);
char *begh, *endh;

main()
{
    FILE *sarwar;
    char ch, ansl, ans2, file[20], *data = ".dat";
    char ans3, *drivea = "a:", *driveb = "b:";
    int sampletime, sampleno, nettime;
    int samplecnt, samplcont, count, i;
    long loopfinish, loopdur, endtime;
    long datatime, begintime, ltime;
    float voltage1, voltage2, indvoltg, rpm, avgvoltgt;
    float samplevltg[30], avgvoltage, totalsample, diff;
    float frpm[30], fvoltag[30], fvoltgt[50], decspd;

    /* **************************************************** */
    begh = "\023\377\001";
    endh = "\001";
    clrscr();
    chgspeed(-2048.0);
    printf("%sUSE, c:\hsps\press.aid%s", begh, endh);
    while((ch = getch()) != 'r');
```
printf("%sUSE,c:\hsps\intro.aid%s", begh, endh);
while((ch = getch()) != '\r');

clrscr();
printf("%sUSE,c:\hsps\intro1.aid%s", begh, endh);
while((ch = getch()) != '\r');

printf("%sUSE,c:\hsps\func1b.aid%s", begh, endh);
while((ch = getch()) != '\r');

printf("%sUSE,c:\hsps\func1n4.aid%s", begh, endh);
printf("%sINPUT,sampletime%s", begh, endh);
scanf("%d", &sampletime);

/*****************************/
sampleno = 0;
for(decspd = -1500.0; decspd<=1200.0; decspd += 900.0)
{  
  chgspeed(decspd);
  delay(500);
  sampleno += 1;
  rpm = decspd * 0.6456 + 1148.042;
  do
  {  
    voltage1 = 0.0;
    for(count =1; count <= 10; count++)
      voltage1 += getdata(3);
    delay(200);
    voltage2 = 0.0;
    for(count = 1; count <= 10; count++)
    {  
      voltage2 += getdata(3);
      diff = fabs(voltage1 - voltage2);
    }
    while(diff >= 0.1);
  }/* *****************************/

/* Take samples for time period defined by user. Our
 * standard time period is 2 seconds. Therefore, let the
 * A/D converter take sample for this predetermined time
 * interval. Take the average of the samples taken and
 * store that average value in the data array. Increment
 * impeller speed and repeat the process. */
*/
/* *****************************/
loopfinish = time(&lttime) + sampletime;
totalsample = 0.0; samplecnt = 0;

do
{
    samplecnt += 1;
totalsample += getdata(3);
}
while(time(&lttime) < loopfinish);
samplevltg[sampleno] = totalsample / samplecnt;
avgvltg = samplevltg[sampleno] * -1;

fvoltag[sampleno] = avgvltg;
frpm[sampleno] = rpm;
printf("%sDISPLAY, diff, = %2.5f\n", begh, diff, endh);
printf("%sDISPLAY, sampleno, = %3d\n", begh, sampleno, endh);
printf("%sDISPLAY, samplecnt, = %4d\n", begh, samplecnt, endh);
printf("%sDISPLAY, rpm, = %4.0f\n", begh, rpm, endh);
printf("%sDISPLAY, avgvltg, = %3.5f\n", begh, avgvltg, endh);

if(kbhit())
{
    if(ften())
        goto filesave;
}

c1rsrc();
printf("%sUSE, c:\hsps\funcntn9b.aid\n", begh, endh);

loopdur = time(&lttime) + LOOPTIME;
chgspeed(-2048.0);
begintime = time(&lttime);
do
{
}
while(time(&lttime) < loopdur);
indvltg = 0.0;
samplcont = 0;
datatime = time(&lttime) + 1;
do
{
    samplcont += 1;
    indvltg += getdata(3);
}
while(time(&lttime) < datatime);

endtime = time(&lttime);
nettime = endtime - begintime;

avgvltggt = indvltg / samplcont;
avgvltggt = avgvltggt * -1;
if(kbhit())
{
    if(ftenO)
        goto filesave;
}

/***********************************************************/
filesave:
    chgspeed (-2048.0);
    clrscr();
    printf( "\nDo you want to save a file? (y or n): ");
    scanf("%ls", &ansl);
    if(ansl == 'y' || ansl == 'Y')
    {
        printf("\nWhich drive you want to save a file? ");
        printf("(a or b or c): ");
        scanf("%ls", &ans2);
        switch(ans2)
        {   
            case 'a':
                case 'A':
                    printf("\nEnter name of datafile: ");
                    scanf("%s", file);
                    strcat(file, data);
                    strcat(drivea, file);
                    sarwar = fopen(drivea, "w");
                    for(i = 1; i <= sampleno; i++)
                    {
                        fprintf(sarwar, "%4.0f\t", frpm[i]);
                        fprintf(sarwar, "%3.5f\n", fvoltag[i]);
                    }
                    fprintf(sarwar, "\n\n");
                    fprintf(sarwar, "%4d\t", nettime);
                    fprintf(sarwar, "%3.5f\n", avgvoltgt);
                    fclose(sarwar);
                    break;
            case 'b':
                case 'B':
                    printf("\nEnter the name of file: ");
                    scanf("%s", file);
strcat(file, data);
strcat(driveb, file);
sarwar = fopen(driveb, "w");
for(i = 1; i <= sampleno; i++)
{
    fprintf(sarwar, "%4.0f\t", frpm[i]);
    fprintf(sarwar, "%3.5f\n", fvoltag[i]);
}
fprintf(sarwar, "\n\n");
fprintf(sarwar, "%4d\t", nettime);
fprintf(sarwar, "%3.5f\n", avgvoltgt);
fclose(sarwar);
break;
case 'c'
case 'C':
    printf("Enter the name of file: ");
    scanf("%s", file);
    strcat(file, data);
    sarwar = fopen(file, "w");
    for(i = 1; i <= sampleno; i++)
    {
        fprintf(sarwar, "%4.0f\t", frpm[i]);
        fprintf(sarwar, "%3.5f\n", fvoltag[i]);
    }
    fprintf(sarwar, "\n\n");
    fprintf(sarwar, "%4d\t", nettime);
    fprintf(sarwar, "%3.5f\n", avgvoltgt);
    fclose(sarwar);
    break;
default:
    printf("Error: invalid choice.\n");
    printf("Do you want to try again?(y or n): ");
    scanf("%ls", &ans3);
    if(ans3 == 'y' || ans3 == 'Y')
        goto filesave;
    break;
}

/* ********** Getdata Function *************** */

/* This function calculates the voltage of the sample run and returns value to the main program. */
float getdata(int channel)
{
    int low, high, x;
    float voltage;

    outportb(BASE1 + 4, 128);
    outportb(BASE1 + 5, channel);
    outportb(BASE1 + 6, 0);
    while(inportb(BASE1 + 4) < 128)
    {
        low = inportb(BASE1 + 5) & (255);
        high = inportb(BASE1 + 6) & (15);
        x = (256 * high) + low;
        if (high > 7)
            x = x - 4096;
        voltage = x/204.8;
        return voltage;
    }
}

void chgspeed(float decspd)
{
    int low;
    float high;

    high = (decspd / 256);
    high = floor(high);
    low = decspd - (256 * high);
    if (high < 0.0)
        high = 16 + high;
    outportb(BASE1 + 1, high);
    outportb(BASE1, low);
}

int ften(void)
{
    int key1, retvalue, key2;

    key1 = getch();
    if(key1 == 0)
    {
        key2 = getch();
        if(key2 == 68)
            retvalue = 1;
        else
            retvalue = 0;
    }
else
    retval = 0;
return retval;
}
APPENDIX B

VPSDS VOLTAGE RESPONSE VS. COMPUTED PARTICLE SIZE
Figure B1. VPSDS response (volts) versus computed particle size (Stokes' dia.) in microns for soils of CL soil group, (a) soil AR-1L and (b) soil KY-1F.
Figure B2. VPSDS response versus computed particle size (Stokes' dia.) in microns for soils of CH soil group, (a) soil GA-1083 and (b) soil TX-4D.
Figure B3. VPSDS response (volts) versus computed particle size (Stokes' dia.) in microns for soils of ML soil group, (a) soil MS6A and (b) soil TN-6B.
Figure B4. VPSDS response (volts) versus computed particle size (Stokes' dia.) in microns for soils of MH soil group, (a) soil NC2A and (b) soil TX-2F.
APPENDIX C

SAMPLE MASS VS. COMPUTED PARTICLE SIZE
Figure C1. Sample mass (grams) versus computed particle size (Stokes' dia.) in microns for soils of CL soil group, (a) soil AR-1L and (b) soil KY-1F.
Figure C2. Sample mass (grams) versus computed particle size (Stokes' dia.) in microns for soils of CH soil group, (a) soil GA-1083 and (b) soil TX-4D.
Figure C3. Sample mass (grams) versus computed particle size (Stokes' dia.) in microns for soils of ML soil group, (a) Soil MS-6A and (b) soil TN-6B.
Figure C4. Sample mass (grams) versus computed particle size (Stokes' dia.) in microns for soils of MH soil group, (a) soil NC-2A and (b) soil TX-2F.
APPENDIX D

VPSDS VOLTAGE RESPONSE AND PIPE TTED MASS VERSUS

COMPUTED PARTICLE SIZE
Figure D1. Soil AR-1L (CL soil group) (a) VPSDS response (volts) versus computed particle size (Stokes’ dia.) in microns and (b) sample mass (grams) versus computed particle size. Both (a) and (b) are fitted to the equation $y = a + b \times x \times \ln(x)$. (outer bands are 95% prediction interval)
Figure D2. Soil KY-1F (CL soil group), (a) VPSDS response (volts) versus computed particle size (Stokes’ dia.) in microns and (b) sample mass (grams) versus computed particle size. Both (a) and (b) are fitted to the equation $y=a+b*x^2*lnx$. (outer bands are 95% prediction interval)
Figure D3. Soil GA-1083 (CH soil group), (a) VPSDS response (volts) versus computed particle size (Stokes' dia.) in microns and (b) sample mass (grams) versus computed particle size. Both (a) and (b) are fitted to the equation $y=a+b*x^2$. (outer bands are 95% prediction interval)
Figure D4. Soil TX-4D (CH soil group), (a) VPSDS response (volts) versus computed particle size (Stokes' dia.) in microns and (b) sample mass (grams) versus computed particle size. Both (a) and (b) are fitted to the equation $y=a+b\times\ln x$. (outer bands are 95% prediction interval)
Figure D5. Soil MS-6A (ML soil group), (a) VPSDS response (volts) versus computed particle size (Stokes' dia.) in microns and (b) sample mass (grams) versus computed particle size. Both (a) and (b) are fitted to the equation $y = a + b \times x \times \ln x$. (outer bands are 95% prediction interval)
Figure D6. Soil TN-6B (ML soil group), (a) VPSDS response (volts) versus computed particle size (Stokes' dia.) in microns and (b) sample mass (grams) versus computed particle size. Both (a) and (b) are fitted to the equation $y=a+b*x*\ln(x)$. (outer bands are 95% prediction interval)
Figure D7. Soil NC-2A (MH soil group), (a) VSPDS response (volts) versus computed particle size (Stokes' dia.) in microns and (b) sample mass (grams) versus computed particle size. Both (a) and (b) are fitted to the equation $y=a+b\ln x$. (outer bands are 95% prediction interval)
Figure D8. Soil TX-2F (MH soil group), (a) VSPDS response (volts) versus computed particle size (Stokes' dia.) in microns and (b) sample mass (grams) versus computed particle size. Both (a) and (b) are fitted to the equation $y=a+b*\ln x$. (outer bands are 95% prediction interval)
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