The measurement of particle size distribution using the Single Particle Optical Sizing (SPOS) method

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ABSTRACT

A new technique for measuring the Particle Size Distribution (PSD) of a soil, known as Single Particle Optical Sizing (SPOS), has been evaluated. A series of tests were conducted to compare the results obtained from sieve analysis and the SPOS method. It was found that for typical laboratory sands, the SPOS method oversizes particles compared to sieving by 20-30%, as predicted by theoretical analysis. Measurements of particle size gathered from sieving and SPOS methods are not equivalent. However, since neither of the definitions of particle size implicit in each method can be considered as 'correct', this exercise does not represent a 'validation' or otherwise of the SPOS method.

The repeatability of the SPOS method was demonstrated by sizing multiple samples obtained by riffling from the same batch of sand. The accuracy of the SPOS method was demonstrated by the high correlation between the calculated and measured PSD of mixed samples. Finally, a series of tests showed that the system can easily resolve a small (<1%) introduction of fine material into a coarser sample. Since the technique requires only a small sample volume, it is particularly suited to the assessment of changes in PSD during geotechnical model or element testing.

1 INTRODUCTION

1.1 Measurement of particle size distribution (PSD)

The most fundamental method of soil characterization is the measurement of particle size distribution (PSD). The PSD of a coarse-grained soil is usually found by sieving. For particles finer than around 50 μm, a technique based on sedimentation is usually used. If a particular soil contains both coarse and fine particles, a composite procedure is required, in which the results of a sieving and a sedimentation analysis are combined (BS1377, 1990).

This report evaluates a new technique for measuring the PSD of a soil. This technique is known as Single Particle Optical Sizing (SPOS). The SPOS method determines the size of individual particles within a sample as they are drawn past an optical sensor. The sizes of the individual observed particles are collated and combined into a PSD curve.

The key differences between the SPOS method and conventional techniques of sieving and sedimentation are as follows:

1. A reduced sample volume is required
2. The resolution of particle size is increased
3. The particle size range encompasses that covered by both sieving and sedimentation
4. A different definition of particle size is used: sieve diameter ≠ SPOS diameter

This report presents an evaluation of the SPOS method when applied to dry soils. The SPOS machine used during this investigation was an Accusizer 780, manufactured by PSS Nicomp (Santa Barbara, CA, USA) and supplied to Cambridge University Engineering Department (CUED) by Christison Scientific (Gateshead, UK) (PSS Nicomp, 2001). The optical sensor used in this investigation had a quoted size range of 5 to 5000μm.

1.2 Changes in PSD during geotechnical processes

The reduced sample size requirement of the SPOS method is particularly useful in geotechnical research where the breakage of particles is under consideration. A large body of recent research has studied the interaction between particle breakage at the microscopic level and the macroscopic response of the soil (eg. Fukumoto, 1992; McDowell & Bolton, 1998; Nakata *et al.*, 1999). A theme of this research is to link the macroscopic deformation of the soil to the breakage of soil particles and the creation of a 'tail' at the left hand end of the PSD curve.

Whilst measurements of the macroscopic response are easily made, the changes in PSD caused by particle breakage are more difficult to detect. This difficulty arises because changes in particle size during geotechnical modeling processes or element tests affect only a small volume of soil, which is often insufficiently large to analyze through sieving.

Figure 1 shows the change in PSD of a silica sand during triaxial tests on a large (150 mm high) sample at a very high stress level (Vesic & Clough, 1968). Significant particle breakage is evident, which is easily captured by sieving in the range of particle sizes greater than 80 μm. However, the left hand 'tail' of the PSD curve is undefined. The size range of sieving is insufficient to deduce the particle sizes of 40% of the most broken sample.

Figure 2 shows the PSD of a silica soil before and after ring shear testing at a stress level more typical of a geotechnical process (Luzzani & Coop, 2002). At this stress level the changes in the PSD curve are limited to the lower 10% passing by mass. Precise measurement of the left hand 'tail' is hampered by the size resolution of the sieve stack. This report examines the feasibility of better quantifying such changes in PSD during geotechnical element and model testing by using the SPOS method.

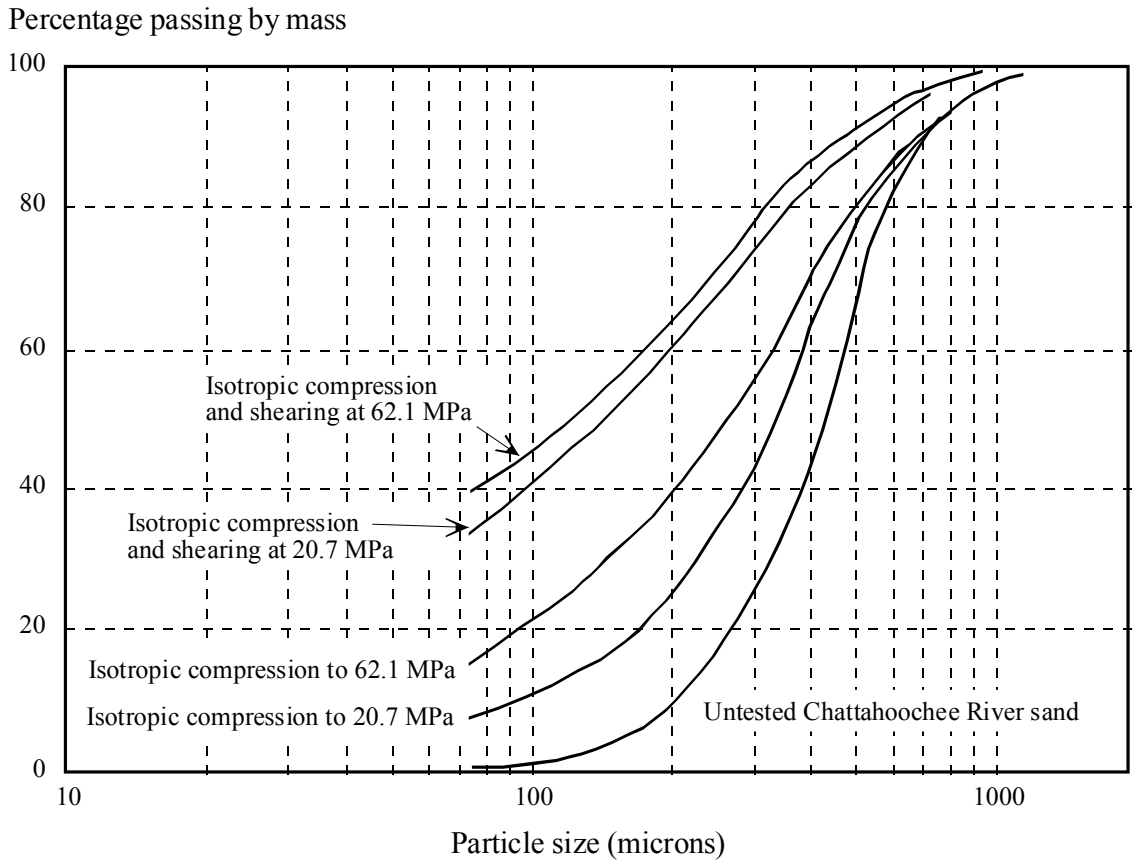


Figure 1. Particle breakage during triaxial testing (Vesic & Clough, 1968)

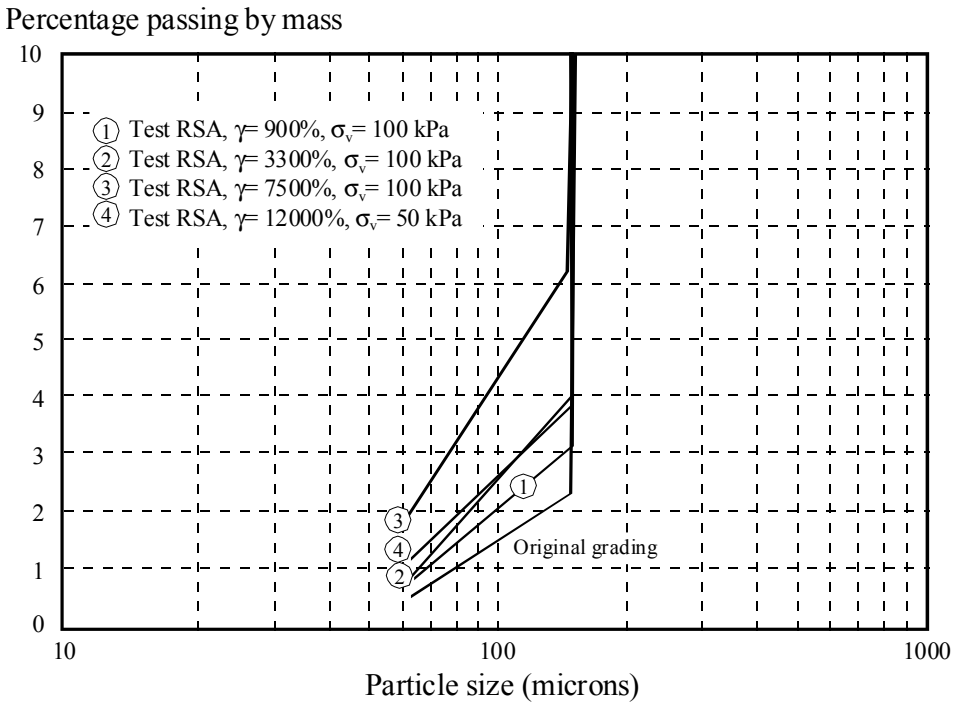


Figure 2. Particle breakage during ring shear testing (Luzzani & Coop 2002)

2 MODERN METHODS OF PARTICLE SIZE MEASUREMENT

2.1 Single Particle Optical Sizing (SPOS)

The SPOS method measures the size of individual particles as they are drawn past an optical sensor. A laser beam is emitted across the flow path of the particles onto a detector (Figure 3). The output voltage from this sensor is sampled at high frequency. In the absence of passing particles a steady baseline voltage, v_b, (also known as the extinction voltage) is received from the detector. A vacuum is used to draw air and particles past the sensor. Passing particles cast a shadow over the detector, changing the output voltage (Figure 4). The magnitude of this change in voltage depends on the size of the particle. This analysis process is known as 'extinction mode'; the degree of light extinction is related to the particle size.

The spike in sensor voltage created by an individual particle is converted to particle size by comparing the pulse height, v_p, with a calibration curve created by passing standard particles of known size through the sensor. The SPOS method measures particle size rather than mass. Therefore, in soils of mixed particulate density, the measured PSD distribution, expressed in terms of percentage passing by volume, is not exactly equal to the PSD expressed as percentage passing by mass, as obtained by sieving.

To prevent multiple particles flowing past the sensor simultaneously and being recorded as a single large particle, feedback control exists between the detector and the feed system. If the frequency of passing particles increases beyond a threshold known as the coincidence limit, the feed system is slowed to reduce the particle flow rate.

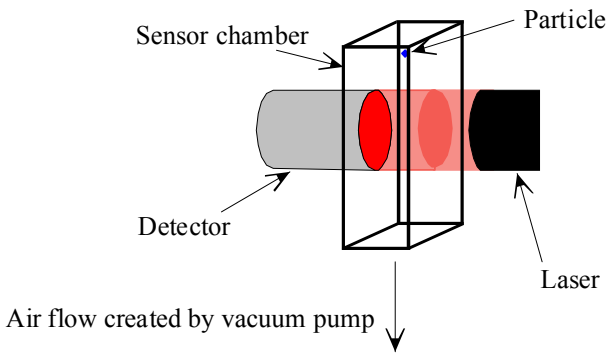


Figure 3. Laser diode sensor chamber

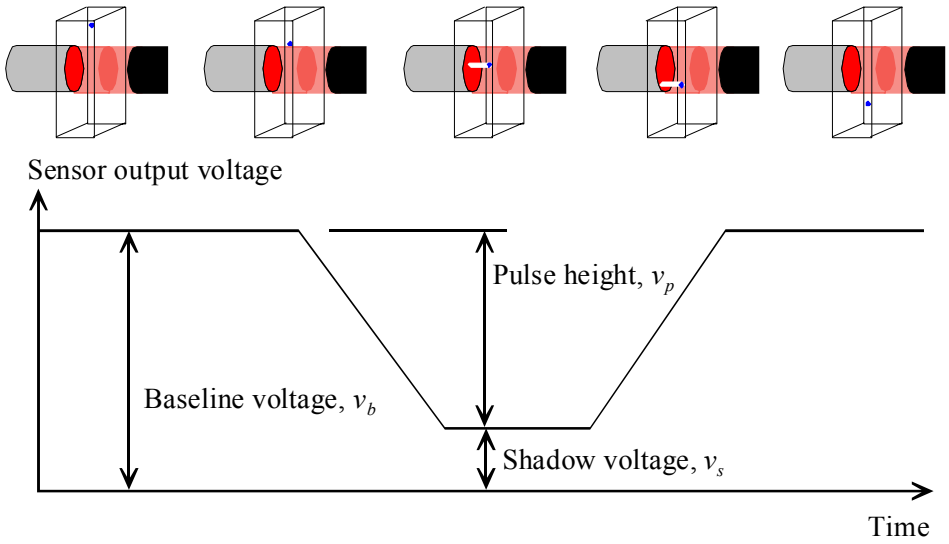


Figure 4. Principle of sensor operation

An additional sensor is fitted in the Accusizer 780 to measure the off-axis scattered laser light. This provides additional resolution at the lower end of the particle size range, and is known as 'summation mode'. However, this mode of analysis has not been used in this investigation.

2.2 Laser diffraction methods

Another laser-based technique for the measurement of particle size is based on the diffraction, rather than the occlusion, of laser light. Laser diffraction systems operate in a high flow density mode, in which multiple particles are passed simultaneously in suspension through a laser beam. The resulting diffraction pattern is the combination of the diffraction patterns created by each single particle. The diffraction pattern created by a single sphere is nearly equivalent to that created by an equally-sized aperture.

Laser diffraction systems use a multi-element optical sensor to measure the variation in intensity of diffracted light with scattering angle. Fraunhofer diffraction theory links the size of an individual particle with the distribution of forward scattered light, but breaks down for particle sizes close to the wavelength of light. Mie theory is used to extend the size range into this region.

An inversion routine is required to convert the measured distribution of scattered laser light into the sum of the scattering produced by each of the contributing particles. Agrawal *et al.* (1991) discuss the difficulties in establishing a unique and stable inversion process. McCave *et al.* (1986) observed differing results from a single instrument using different lenses, implying an inversion algorithm that is not robust. A different instrument, based on the same principle, offered a further different distribution.

Laser diffraction methods are compared to techniques based on sieving and sedimentation by Singer *et al.* (1988), McCave *et al.* (1986), Vitton & Sadler (1997), Lu *et al*. (2000) and Muri *et al*. (2001). After reviewing the first two of these comparison exercises, Agrawal *et al.* (1991) concluded that new particle sizing techniques should not be 'validated' against conventional sedimentation or sieving techniques, since conventional techniques are imprecise and highly dependent on operator technique. Furthermore, the various analysis techniques are based on differing definitions of particle size.

3 THE DEFINITION OF PARTICLE SIZE

Particle size, as a single value, is ill-defined except for perfect spheres. The underlying definitions of particles size assumed by various measurement techniques are described below.

3.1 Sedimentation

Sedimentation methods for evaluating PSD take advantage of the fact that large particles in a liquid suspension settle more quickly than small particles. Stokes' Law (Stokes, 1851) relates the terminal velocity of a spherical particle to its diameter. A collection of particles that are non-spherical have a lower mean terminal velocity than a collection of spherical particles of equivalent volume. Therefore, sedimentation methods of particle size measurement based on Stokes' Law will undersize non-spherical particles. Lu *et al.* (2000) present analytical solutions for the settlement of ellipsoidal particles which demonstrate the influence of non-sphericity on apparent particle size found using Stokes' Law.

3.2 Sieving

The size of a sieve mesh, D_{sieve}, is defined as the side length of the square apertures that form the mesh. The principal dimensions of a soil particle can be defined as shown in Figure 5. L_I is the longest particle dimension and L_{III} is the shortest dimension of the projected view parallel to L_I. L_{II} is the dimension perpendicular to L_I and L_{III}. A sieve will pass all particles for which L_{II} is less than D_{sieve}. However, in the case of disc-shaped particles for which L_{III} is small (Figure 6), particles as large as $L_{II} = \sqrt{2}\, D_{sieve}$ may pass through the sieve by aligning L_{II} with the diagonal of the aperture. Therefore sieve diameter, D_{sieve}, can be described by Equation 1, and is independent of L_I.

$$\frac{L_{II}}{\sqrt{2}}\left(L_{III} \to 0\right) < D_{sieve} < L_{II} \qquad [1]$$

3.3 Single particle optical sizing

When analyzing the SPOS method, it is assumed that the high-speed laminar flow through the sensing unit causes the longest particle dimension, L_I, to be aligned with the direction of flow. Therefore, the observed particle size is related to a projected area containing the long axis (McCave & Syvitski, 1991). In the case of an ellipsoid, this projected area can vary between $\pi L_I L_{III}/4$ and $\pi L_I L_{II}/4$ (Figure 6). SPOS systems are calibrated using standards that are nominally spherical, so the obscuration area measured as a voltage drop at the laser diode is recorded as an equivalent spherical diameter, D_{SPOS}. Equating the obscuration area of a sphere with the range of possible projected areas of an ellipsoid leads to equation 2, showing that D_{SPOS} is strongly dependent on L_I.

$$\sqrt{L_I L_{III}} < D_{SPOS} < \sqrt{L_I L_{II}} \qquad [2]$$

3.4 Laser diffraction

Laser diffraction methods assume that the measured diffraction pattern has been created by ideal spherical particles. The influence of particle shape on this pattern is not well understood. Since the interpretation of laser diffraction measurements is strongly

dependent on the inversion technique, into which research is continuing, any weak dependence on particle shape has received little attention (Agrawal *et al.,* 1991)

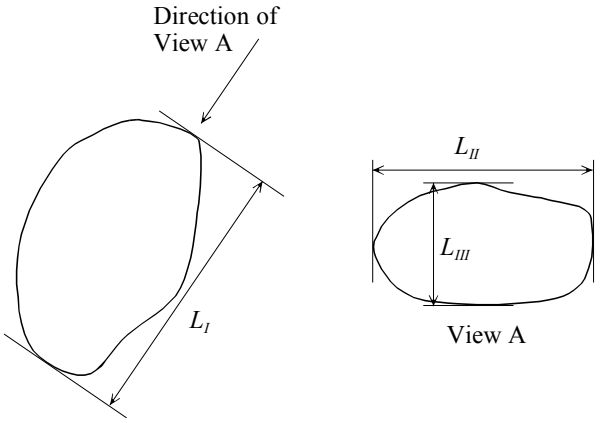


Figure 5. Principal particle dimensions

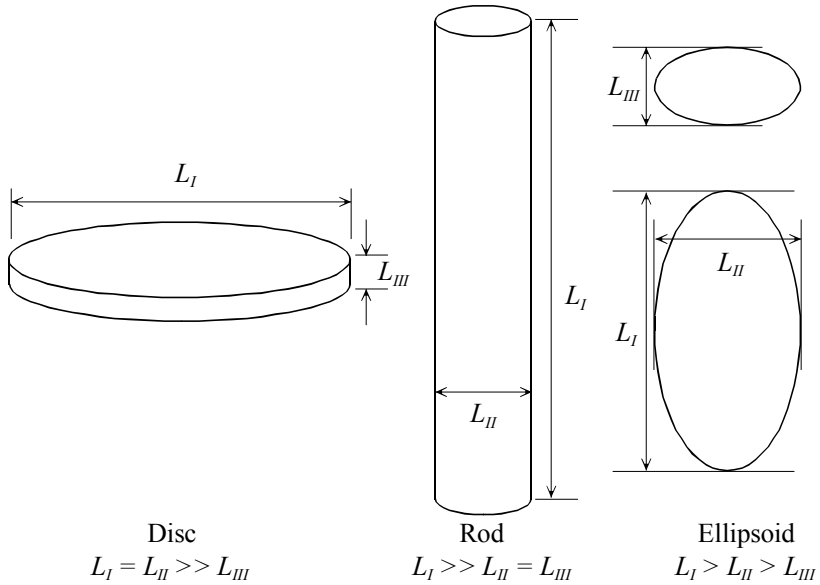


Figure 6. Idealised non-spherical particles

3.5 Theoretical differences between D_{SPOS} and D_{sieve}

For spherical particles ($L_I = L_{II} = L_{III}$), Equations 1 and 2 indicate that $D_{SPOS} = D_{sieve}$. For non-spherical particles, analytical expressions can be developed for the discrepancy between D_{SPOS} and D_{sieve}. Two idealized non-spherical particle shapes are considered here; flat platey particles ("discs") and elongated rod-like particles ("rods") (Figure 6). The characteristic aspect ratios, $R_{I/II}$ and $R_{II/III}$, of these particles are shown in Table 1. The resulting values of D_{SPOS} and D_{sieve} are derived as follows.

The value of D_{sieve} for a rod is trivial; it is equal to the diameter of the rod, L_{II}. The value of D_{sieve} for a disc is found by considering the particle to fit tightly across the diagonal of a mesh aperture with the shortest principal dimension in the plane of the mesh. The value of D_{SPOS} for a rod is found by assuming that all particles are aligned with the flow direction. The projected area, $L_I L_{II}$, is converted to an equivalent circle of diameter D_{SPOS}.

The value of D_{SPOS} for a population of identical discs is more complicated to derive. Although it can be assumed that all discs pass the sensor with a diameter aligned parallel to the flow, the axis of rotational symmetry can be aligned in an arbitrary direction. The result is that a *distribution* of particle sizes is recorded even if all the particles in the population are *identical*. The projected area of a disc can vary from $L_I L_{III}$, if the axis of rotational symmetry is perpendicular to the direction of the sensor beam, to $\pi L_I^2/4$ if the axis of rotational symmetry is parallel to the sensor beam. These two values correspond to the projected area of the edge and the face of the disc respectively. If the axis of the disc is aligned at angle θ to the sensor beam, the projected area of the disc, A_{proj}, assuming that $L_I >> L_{III}$ is given by Equation 3.

A simple procedure to deduce an equivalent mean particle size for a large number of randomly oriented particles would be to evaluate the mean value of A_{proj} for the range θ from 0 to $\pi/2$. However, this area-based mean value is neither the mean value of the distribution of D_{SPOS}, nor is it the more useful $D_{50\%}$ passing size on a plot of cumulative volume vs. particle size. A more useful approach is as follows. The value of D_{SPOS} recorded for a disc aligned at θ is found from Equation 3 by considering an equivalent circle of equal projected area, with diameter D_{SPOS} (Equation 4).

$$A_{proj} = \frac{\pi L_I^2 \sin\theta}{4} \qquad [3]$$

$$D_{SPOS} = L_I \sqrt{\sin\theta} \qquad [4]$$

From Equation 4, the volume contributed by this disc, vol_{SPOS}, to the volume of the entire population can be found:

$$vol_{SPOS} = \frac{\pi D_{SPOS}^3}{6} = \frac{\pi L_I^3 \sin^{3/2}\theta}{6} \qquad [5]$$

The integral of Equation 5 for θ varying from 0 to $\pi/2$ is the total volume recorded for a population of evenly oriented discs. To find the 50% passing value of D_{SPOS}, Equation 5 is integrated for θ varying from 0 to $\theta_{50\%}$ such that the sum of this integral is half of the sum from 0 to $\pi/2$. The value of D_{SPOS} corresponding to $\theta_{50\%}$ was found to be 0.94 L_I by numerical integration.

Table 1. Theoretical comparison of D_{sieve} and D_{SPOS} for different particle shapes

Particle shape	$R_{I/II} = L_I/L_{II}$	$R_{II/III} = L_{II}/L_{III}$	D_{sieve}	D_{SPOS}	D_{SPOS}/D_{sieve}
Sphere	1	1	L_I	L_I	1
Rod	>1	1	L_{II}	$L_{II}\sqrt{\frac{4R_{I/II}}{\pi}}$	$\sqrt{\frac{4R_{I/II}}{\pi}}$
Disc	1	$\rightarrow \infty$	$L_{II}/\sqrt{2}$	0.95 L_{II} [A]	1.34

[A] The $D_{50\%}$ passing value of the theoretical distribution of D_{SPOS}.

This theoretical analysis summarized in Table 1 suggests that elongated particles will appear larger when measured using an SPOS system compared to sieving. If an elongated particle is approximated as a rod of aspect ratio $R_{I/II}$= 1.5, the analysis described above predicts that D_{SPOS} = 1.38 D_{sieve}. A similar result is obtained for flat platey particles, with the analysis predicting that D_{SPOS} = 1.34 D_{sieve}.

4 PSS NICOMP ACCUSIZER 780 DRY SPOS SYSTEM

4.1 Key components

The Accusizer 780 dry powder system consists of two units connected by serial link to a PC, on which the control software is mounted (Figure 7). The PC is connected to a counter box, which samples the output signal from the laser diode at high frequency, identifying and counting the spikes created by passing particles. A typical measurement run lasts 180 seconds, during which many thousands of particles are sized. The Accusizer software cumulates the measured particles in 512 logarithmically spaced size bins.

The counter box is connected to the Dry Powder Feeder (DPF). The DPF is connected to a vacuum supply and contains a plumbing system that draws air through an intake nozzle past the laser diode sensor. The sample is placed on a vibrating feeder, which introduces the particles in a controlled manner into the air stream via the intake nozzle (Figure 8). A feedback system between the counter box and the vibrating feeder regulates the sample flow rate. The sample is separated from the air stream after passing the sensor, and is gathered in a collection flask for subsequent recovery.

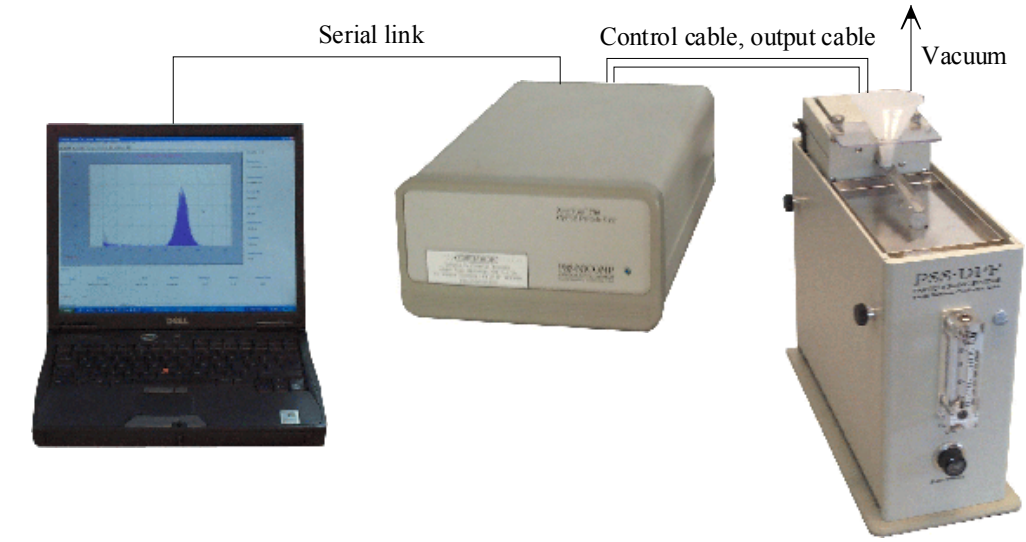


Figure 7. Schematic diagram of PSS Nicomp Accusizer 780 dry SPOS system

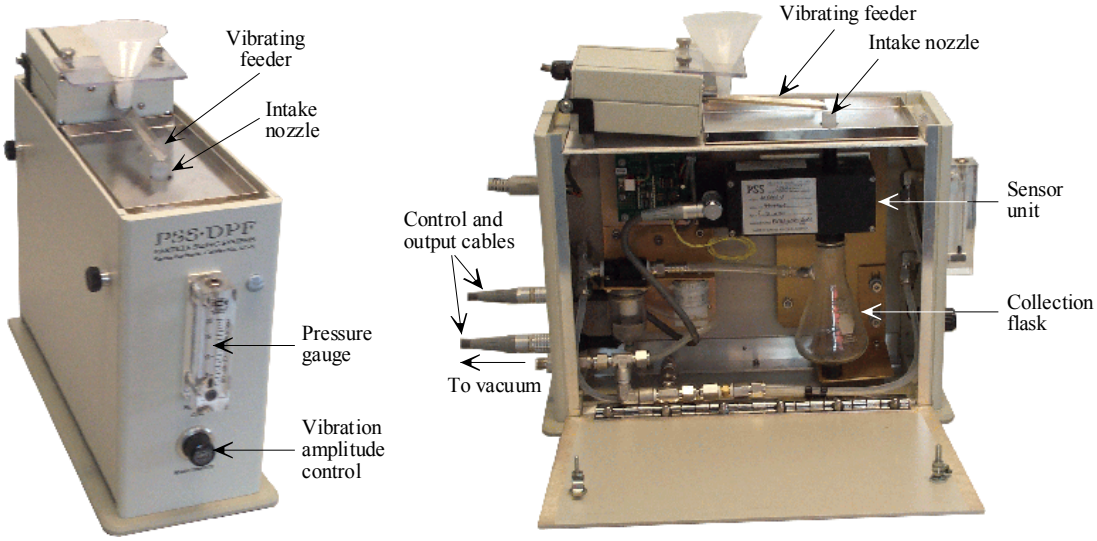


Figure 8. PSS Nicomp Accusizer 780 Dry Powder Feeder (DPF)

The baseline voltage, v_b, (when running the system in extinction mode) recorded in the absence of particles is typically 7.0-7.2v after cleaning of the inner window of the sensor. However, after a long measurement run, this baseline voltage is reduced by the influence of dust particles that accumulate on the window, blocking out the laser light. This effect is only significant on the large (5µm – 5mm) sensor unit fitted to the CUED Accusizer. The air flow rate through this large orifice is not sufficiently large to clean dust particles from the chamber surface. Smaller sensor orifices, more typical of SPOS applications, suffer less from dust accumulation.

4.2 Calibration procedure

The Accusizer 780 is calibrated by relating pulse height, v_p, to particle size. The calibration procedure involves passing known single-sized particle standards (glass balls or ceramic beads) through the machine. The most commonly measured pulse height is linked to particle size. A typical calibration consists of 7-10 standards, between which a spline interpolation is fitted.

The factory calibration, and a subsequent calibration carried out by the Author at CUED, are shown in Appendix A. The slight difference between the two calibrations is attributed to the differing intake nozzles used in each case. The DPF unit was fitted with a non-standard nozzle after installation at CUED, which led to a slight change in the sensor response. All data presented in this report, except for Figure 9, was obtained using the CUED calibration curve (ID number cam9904909e.sns).

4.3 Influence of sensor cleanliness on performance

A series of trials were conducted to examine the influence of sensor cleanliness on the measured PSD. A sample of Fraction C Leighton Buzzard silica sand was passed through the DPF 6 times. For the first three measurement runs (J37-J39), the sensor was initially slightly dirty, with a baseline extinction voltage of 6.3v (Figure 9). For three subsequent runs (J40-J42) the sensor was thoroughly cleaned to a baseline extinction voltage of 6.9-7.1v. Within each set of three runs the results are highly repeatable, but a clear difference exists between runs using a different baseline voltage.

Figure 10 illustrates schematically the source of this apparent error in the case of a very dirty sensor. The output voltage from the sensor is assumed to be proportional to the mean brightness over its area. A single particle is shown passing a clean sensor and a dirty sensor. The baseline voltage, v_b, changes as the sensor becomes dirty. Also, the pulse height, v_p, of the spike changes. However, the pulse height divided by the baseline voltage remains constant even when the sensor is dirty.

The conventional approach of SPOS systems is to calibrate pulse height, v_p, against particle size. However, as the sensor becomes dirty, the pulse height created by a given particle becomes smaller. Therefore the apparent size of a given sample reduces with reducing sensor cleanliness. This effect can be explored by back-calculating the pulse heights that correspond to the D_{50} sizes measured in runs J37-J42, using the factory calibration curve of pulse height vs. particle size. The back-analysed values of pulse-height for the D_{50} particle in runs J37-42 are plotted against the baseline extinction voltage on Figure 11.

The data of pulse height against baseline voltage falls on an approximately straight line passing through the origin. This observation agrees with the simple model shown in Figure 10 in which the *fractional* reduction in sensor output is related the obscured area, rather than the absolute reduction in sensor output. However, the straight line relationship shown on Figure 11 remains a hypothesis. The linearity of this relationship is not confirmed for a wide range of baseline voltages.

The influence of sensor cleanliness on apparent particle size can be overcome in two ways. Either, a modified version of the calibration procedure can be used, in which the fractional reduction in sensor voltage is related to particle size. This approach is currently being introduced to the control software by the Accusizer manufacturer, PSS Nicomp, as an optional mode. However, it should be noted that this approach relies on the linearity of the relationship hypothesized in Figure 11.

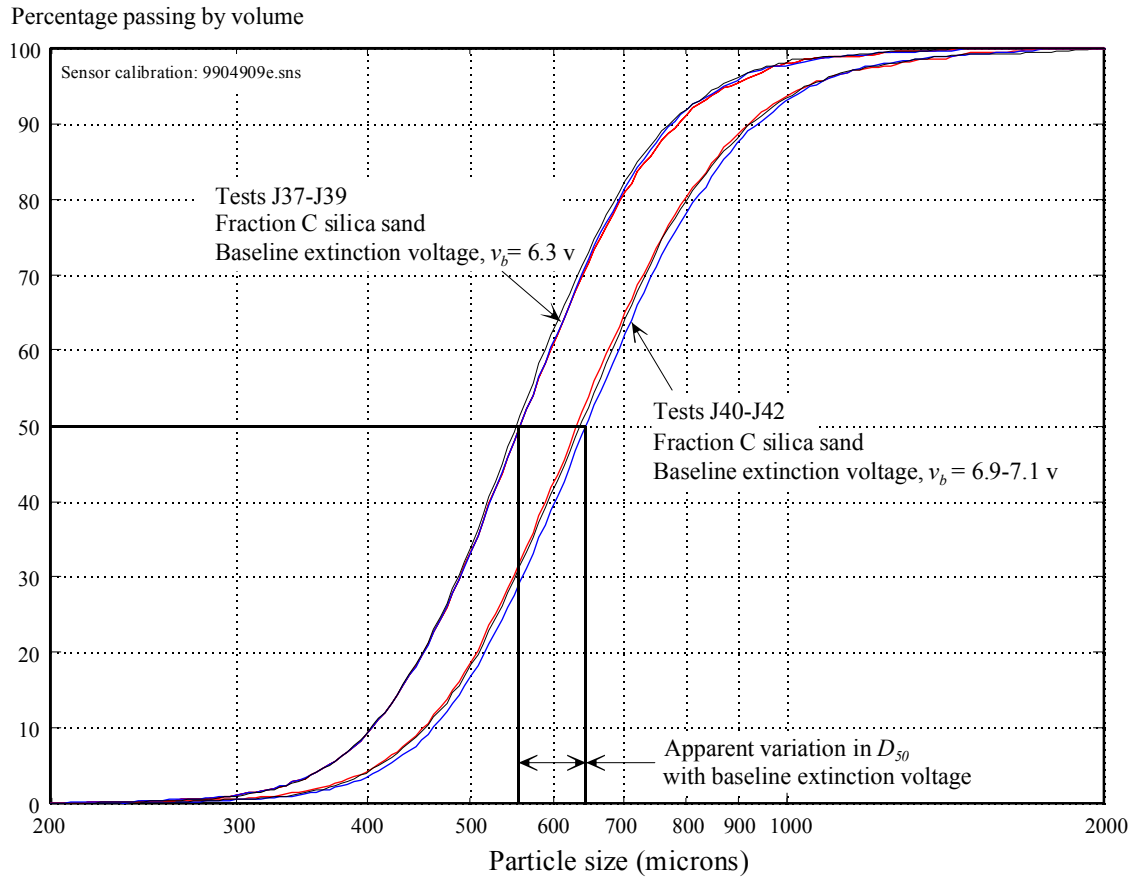


Figure 9. The influence of baseline voltage on apparent particle size

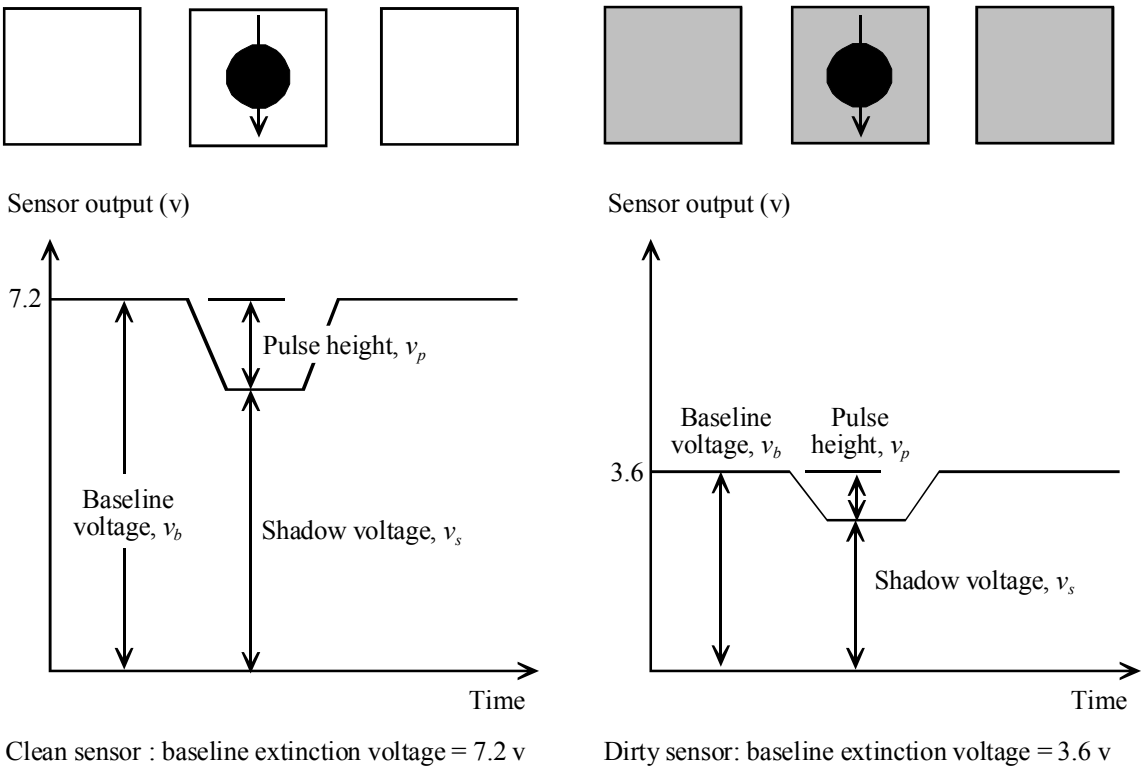


Figure 10. Schematic diagram of the influence of baseline voltage on pulse height

Alternatively, thorough cleaning between runs can be used to ensure the baseline voltage remains close to the maximum value. A procedure for cleaning the inner window of the sensor is described in Appendix B.

Care should be taken to ensure that the sensor remains clean at the end of a run as well as at the beginning. Measurement runs using samples with a high fines content lead to a relatively rapid build up of dust on the sensor window. A sample size of around 1-2g and a run period of around 60 seconds should be sufficiently short to prevent a loss of sensor cleanliness. Although this sample size is relatively small, since the SPOS method simply measures every particle, the sample need contain only enough particles to be representative of the parent soil. Riffling should be used to create representative small samples from a large volume of material.

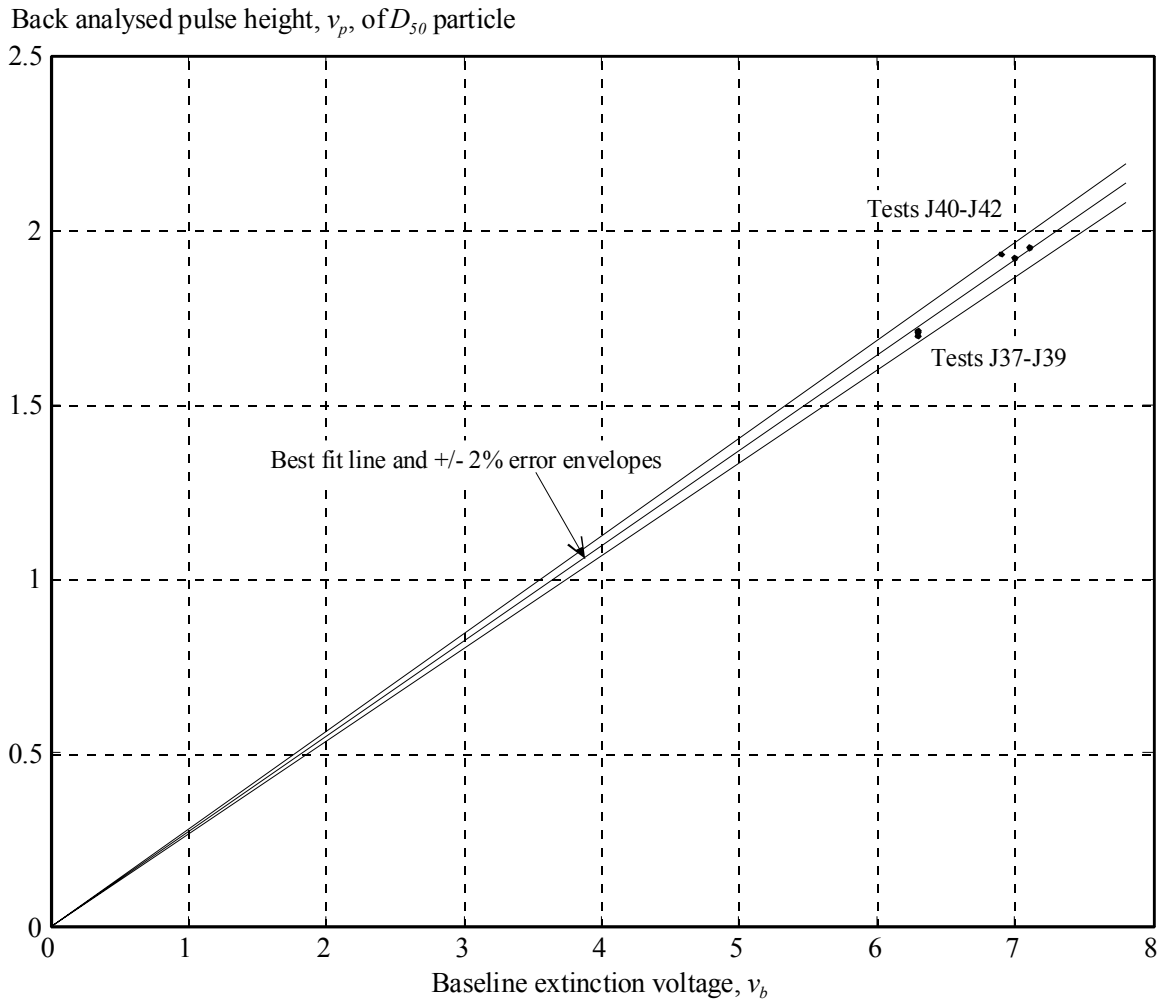


Figure 11. The variation of pulse height with baseline voltage for a given particle.

5 A COMPARISON OF SPOS AND SIEVING

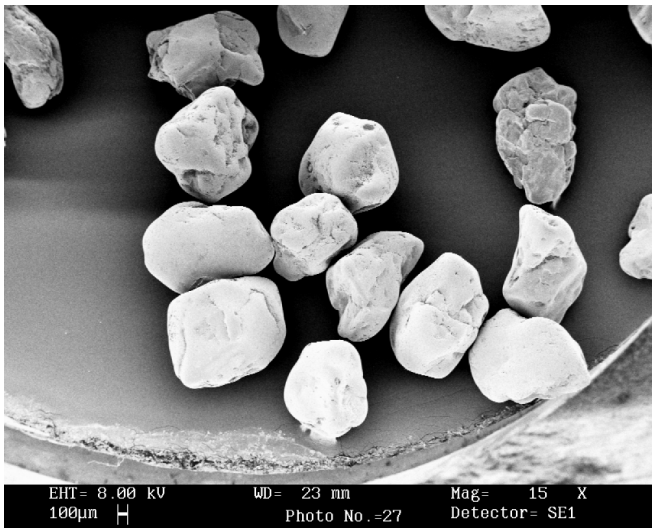
A series of tests were conducted to compare the performance of the SPOS system and conventional dry sieving. Three sands were tested using each method; the three sands were Fractions B and D of Leighton Buzzard silica sand, and Dog's Bay carbonate sand. Scanning Electron Microscope (SEM) photographs of these sands are shown in Figure 12.

Firstly, a large sample of each sand was sieved following the British Standard BS1377 (1990) procedures described by Head (1992). The sands were retrieved from the sieves and re-mixed. A Quantachrome micro-riffler was used to produce 4 small representative samples (typically of mass 2-3 g). These samples were sized using the Accusizer 780.

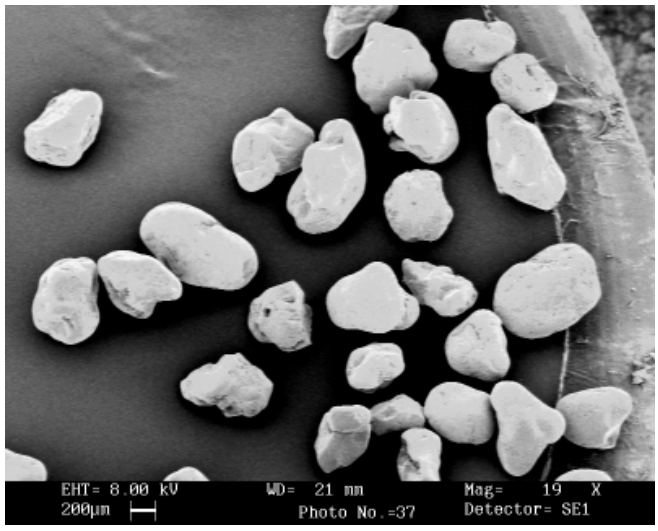
Although Agrawal *et al.* (1991) suggest that new particle sizing techniques should not be 'validated' against conventional techniques, it is valuable to make some comparison between the two techniques to allow a degree of equivalence to be assessed. Figures 13-15 show the PSD curves measured by each method for the three test sands.

It should be noted that these PSD 'curves' have been constructed by joining adjacent data points (size bins) by a straight line. The sieving results could be smoothed by fitting a spline or drawing in a curve by eye. The SPOS results have the appearance of a curve since the size axis consists of 512 logarithmically-spaced bins. This contrasts with the 7 BS sieve sizes distributed between 63μm and 1.18mm, of which only 2 or 3 retain significant quantities of material.

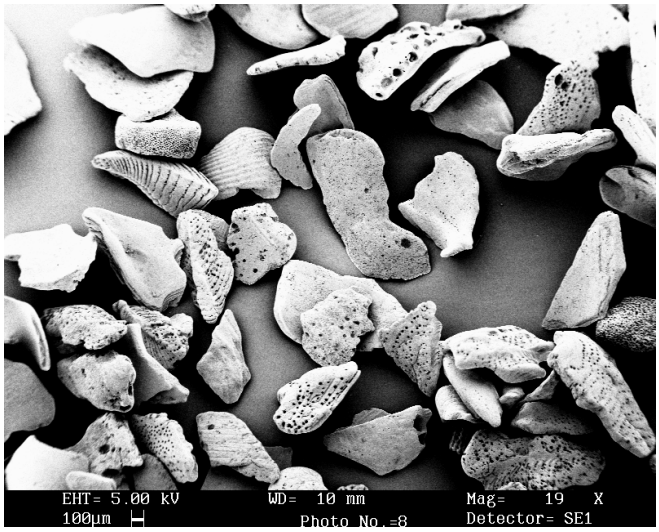
The repeatability of the SPOS method, and the reliability of the riffling technique, is demonstrated by the overlying curves of the 4 representative samples of each sand. There is a consistent difference between the SPOS and sieve sizes predicted for each sand. D_{SPOS} is typically 20-40% greater than D_{sieve}. This difference is within the range predicted by the theoretical analysis in Section 3 for slightly elongated particles. Measurements of particle size gathered from sieving and SPOS methods are not equivalent.



a) Fraction B Leighton Buzzard silica sand (Sentenac *et al.*, 2001)



b) Fraction D Leighton Buzzard silica sand (Bowman, 2002)



c) Dog's Bay carbonate sand (Bowman *et al.*, 2001)

Figure 12. SEM photographs of test sands

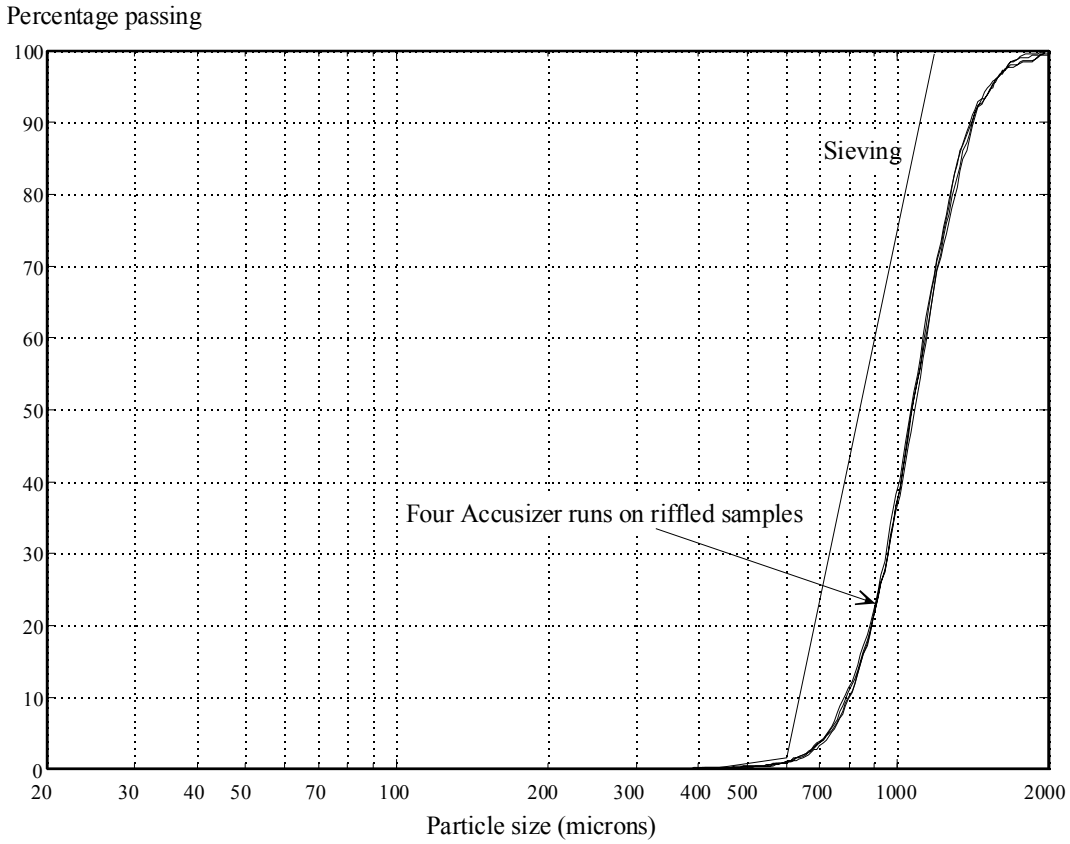


Figure 13. Comparison of SPOS and sieving: Fraction B sand

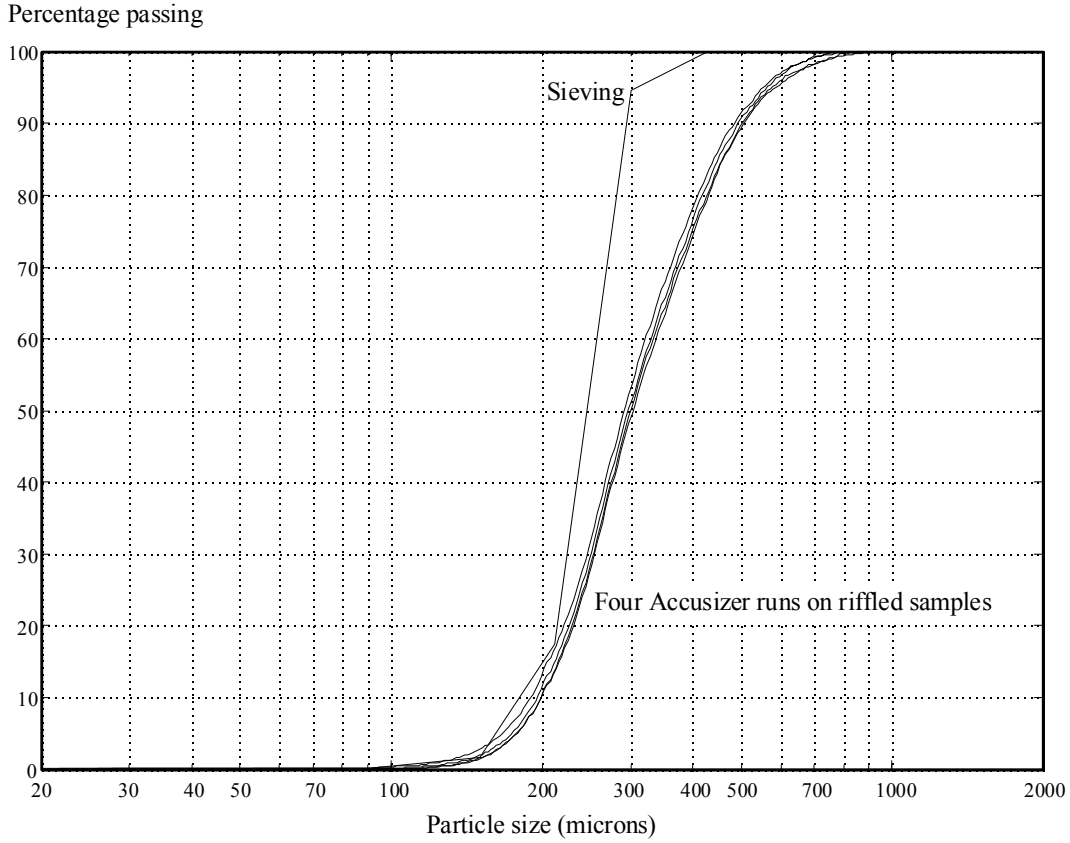


Figure 14. Comparison of SPOS and sieving: Fraction D sand

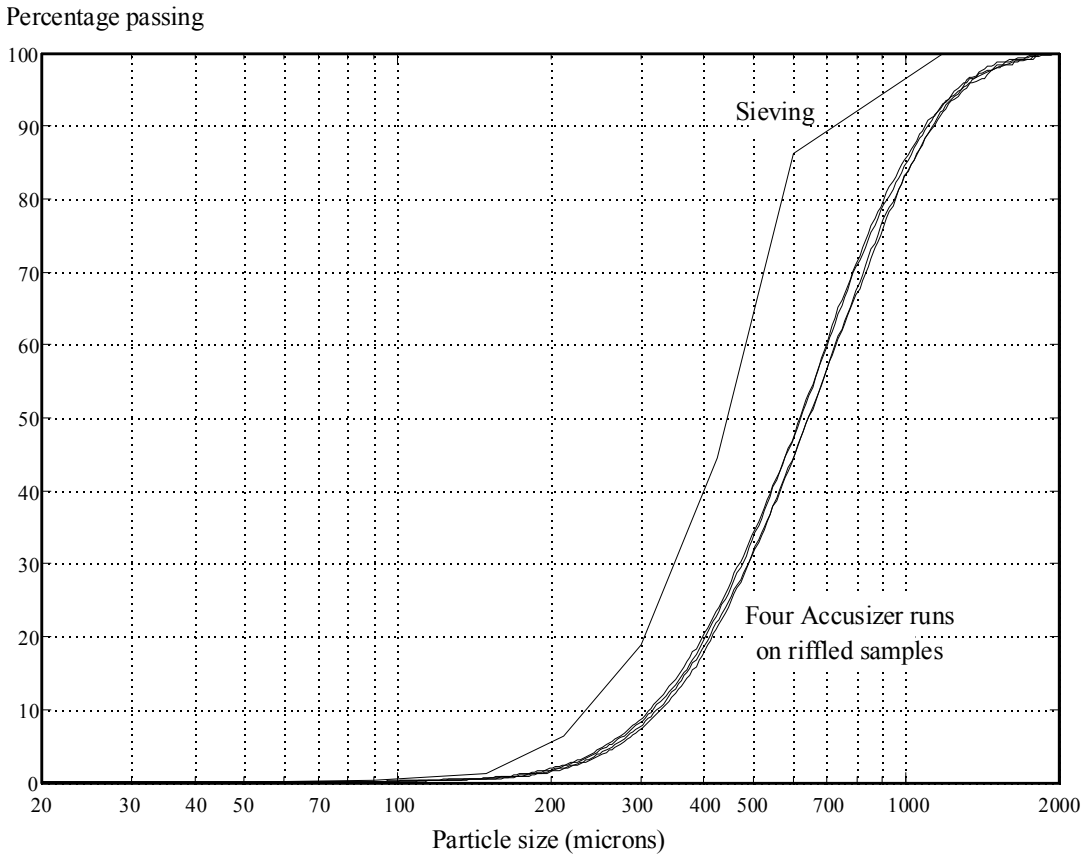


Figure 15. Comparison of SPOS and sieving: Dog's Bay sand

6 SPOS ACCURACY AND RESOLUTION

To examine the accuracy and resolution of the SPOS method, two additional tests were carried out. The first test involved a comparison of the measured and theoretical PSD of a sample consisting of two components, both of which had been previously sized. The two components were 0.5g of Fraction E and 1.0g of Fraction D Leighton Buzzard silica sand. Runs A1 and A2 on Figure 16 show the PSD of the each component. The components were recovered after these runs and mixed. The resulting sample was measured during Run A3. The theoretical distribution found by combining the raw data from Runs A1 and A2 is very similar to the measured distribution, with a maximum discrepancy of ≈1.5% passing for a given particle size.

The second test aimed to examine the resolution of the system when detecting a small tail of fine particles, as created by particle breakage during a loading event. Fractions C and D of Leighton Buzzard silica sand were used. Two reference runs were conducted,

in which samples of Fractions C and D alone were tested (Runs B1, B2 & B3 on Figure 17). The sample of Fraction C was then repeatedly tested after the addition of very small quantities (<<0.1g) of Fraction D. In order for this test to be successful, careful recovery of the sample was required to ensure that no particles, in particular the finer fraction, were lost. To check that the sample recovery process did not involve the loss of the fine fraction, two reference runs (B2 & B3) of the Fraction C sample were made. These reference runs overly each other almost exactly in Figure 17.

After completion of Run 3, a small quantity of Fraction D was added to the Fraction C sample, equal to about 1% of the original sample by mass. The combined sample was resized (Run B4). A further additional quantity of Fraction D was then added, and the run repeated (Run B5).

Figure 17 shows the progressive enlargement of the fine 'tail' on the sample PSD as the sample is 'spiked' with fine material. The addition of ≈1% by mass of fine material is clearly detected. An alternative way of expressing this observation is that a 20% reduction in the "$D_{1\%}$" size can be easily identified.

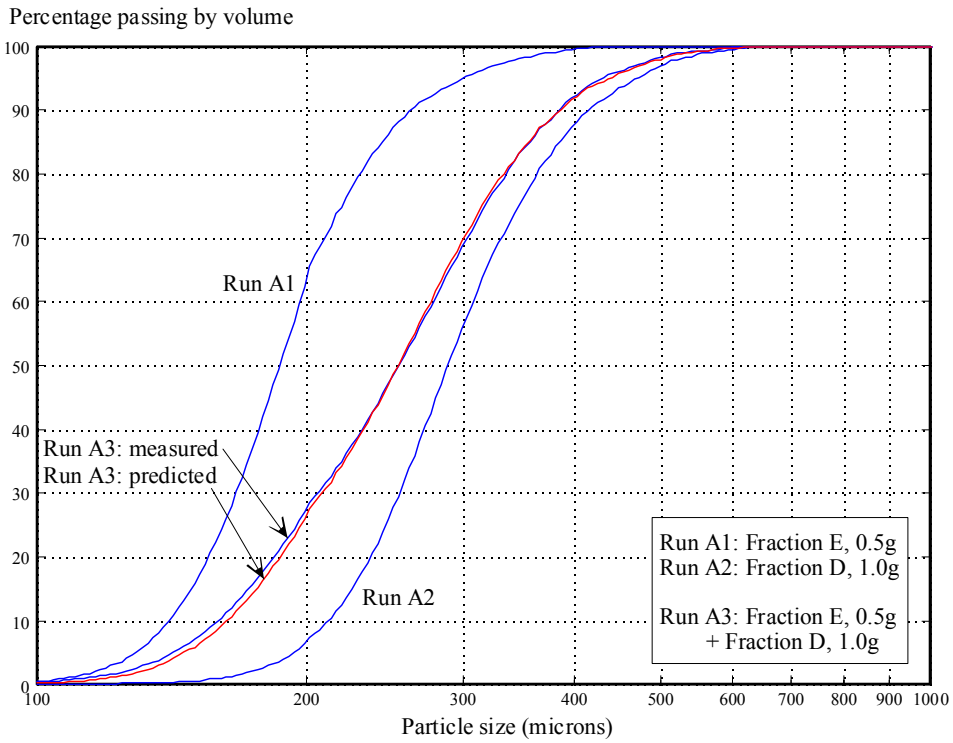
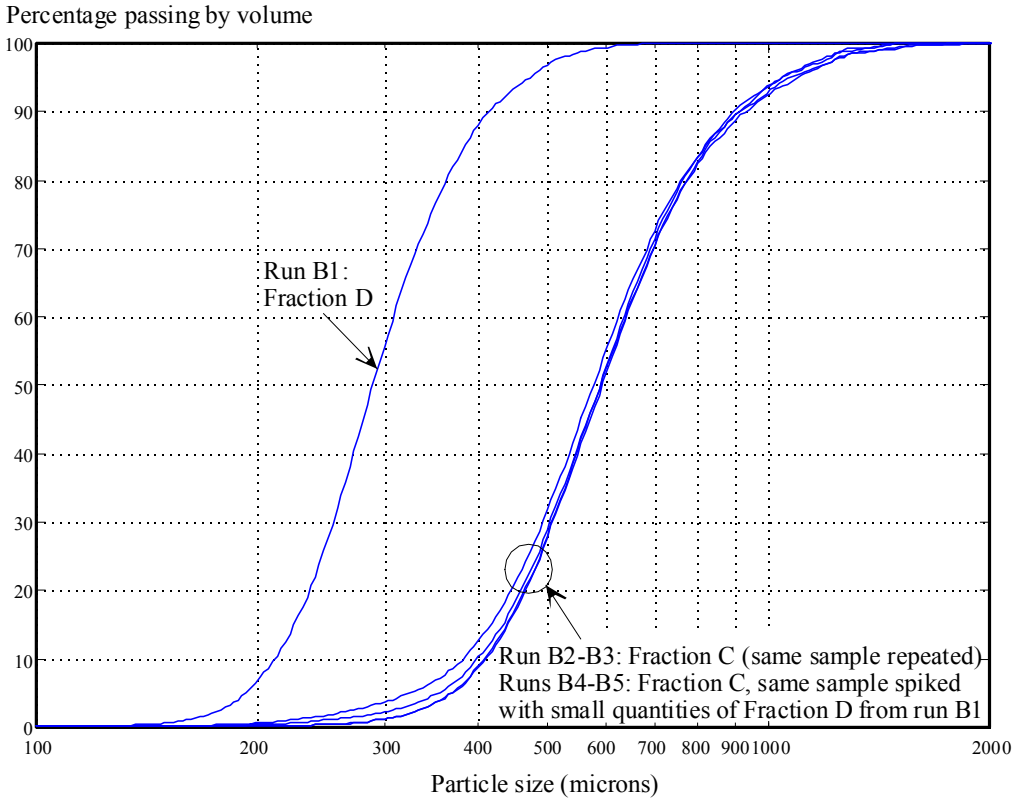
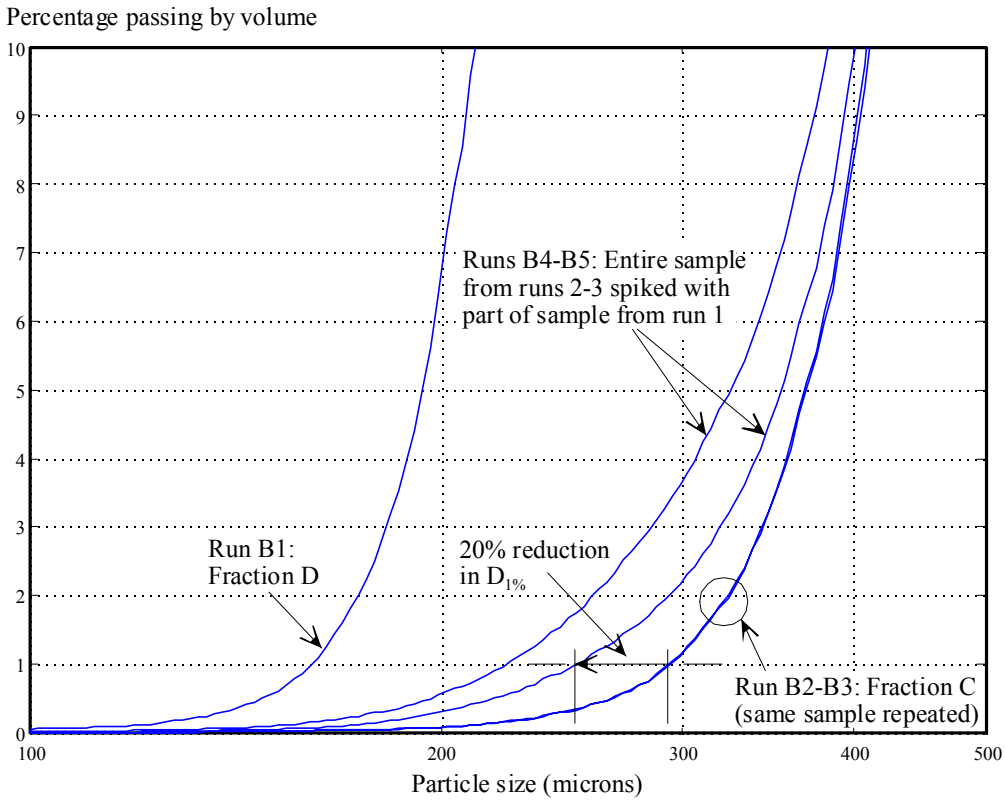


Figure 16. A mixed sample: theoretical and measured PSD



a) Entire PSD curve



b) Enlargement of 'tail' on PSD

Figure 17. The detection of a 'tail' of fine particles

7 CONCLUSIONS

A new technique for measuring the Particle Size Distribution (PSD) of soil, known as Single Particle Optical Sizing (SPOS), has been evaluated. Compared to sieving or sedimentation, this modern technique of particle size determination requires a reduced sample volume, and provides better resolution of particle size.

Different definitions of particle size are implicit in these different measurement techniques. A simple theoretical analysis has been used to examine the possible differences in apparent particle size for different particle shapes. A series of tests were conducted to compare the results obtained from sieve analysis and the SPOS method. It was found that for typical laboratory sands, the SPOS method oversizes particles compared to sieving by 20-40%, as predicted by the theoretical analysis described in Section 3. Measurements of particle size gathered from sieving and SPOS methods are not equivalent.

However, since neither of the definitions of particle size implicit in each method can be considered as 'correct', this exercise does not represent a 'validation' or otherwise of the SPOS method. Excellent repeatability was observed when sizing multiple samples obtained by riffling the sieved batches of sand, demonstrating the reliability of both the SPOS method and the preparation of samples by riffling.

Two further series' of tests were conducted to examine the performance of the SPOS method. Firstly, an assessment of the accuracy of the method was made by combining two previously tested samples. The measured PSD of the combined sample showed excellent agreement with the expected PSD calculated by summing the measured PSDs of the separate components.

Secondly, the ability of the SPOS method to detect a small fraction of fine material, as created by particle breakage during a loading event, was assessed by the progressively 'spiking' a sample of coarse sand with fine particles. Multiple tests of the sample prior to addition of the fine material revealed excellent repeatability. Repeated testing of the

sample after each addition of fine material revealed that an evolution of a 'tail' in the finest 1% of the material could be clearly distinguished by the SPOS method.

In conclusion, the SPOS method is a fast, repeatable and accurate method of soil particle size determination. Since the technique requires only small volumes of sample it is particularly suited to the assessment of changes in PSD during geotechnical model or element testing.

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APPENDIX A: CALIBRATION CURVE

A calibration curve for extinction mode operation was obtained by PSS using the original intake nozzle. This curve is labeled on Figure A1 as 9904909e.sns. A subsequent calibration carried out by the Author at CUED using the non-standard 2.5mm diameter intake nozzle is labeled as curve cam99049090e.sns. These labels correspond to the calibration filenames.

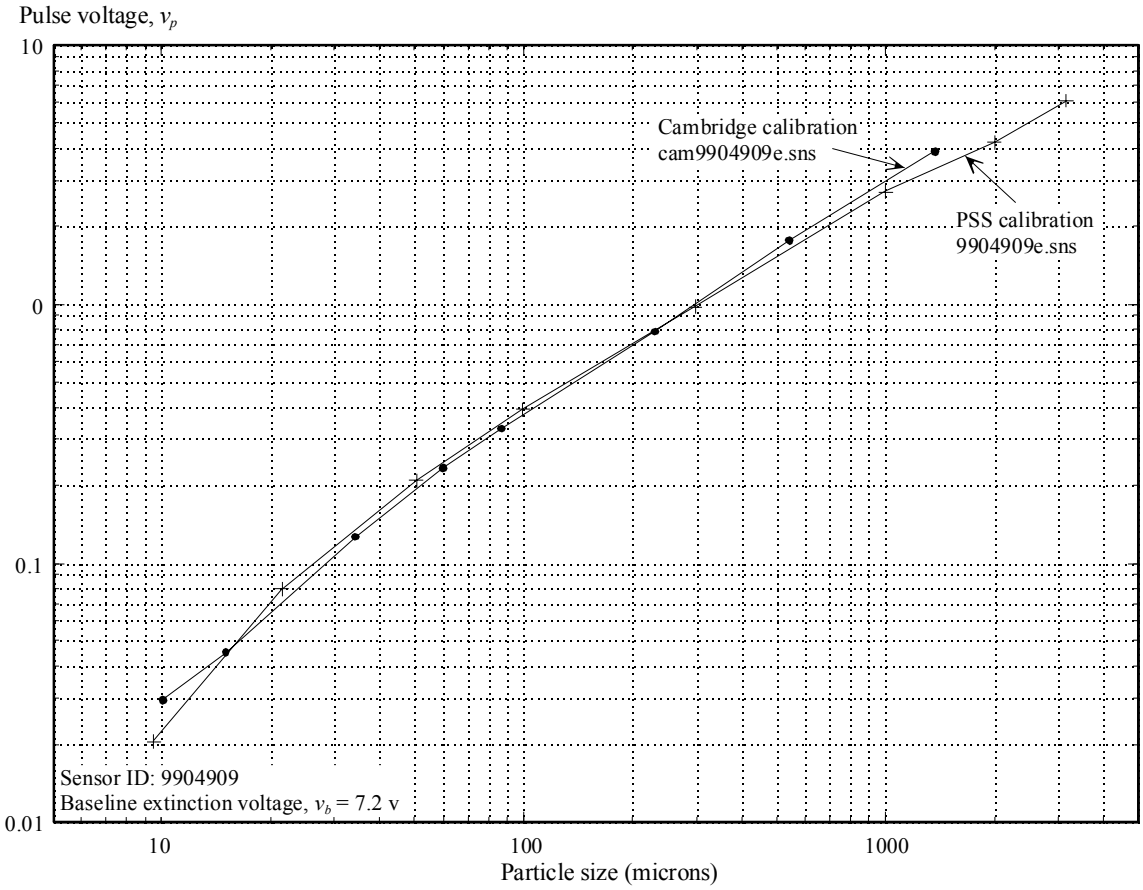
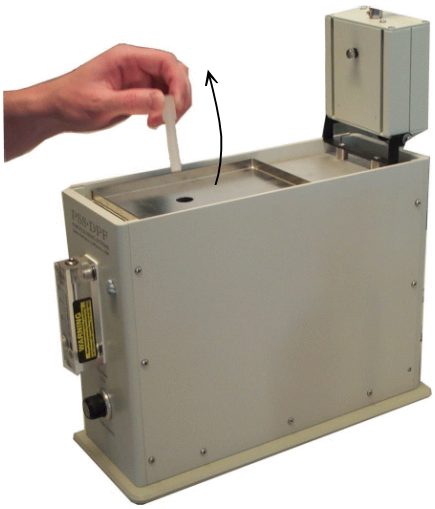


Figure A1. Accusizer 780 calibration curves.

APPENDIX B: CLEANING PROCEDURE

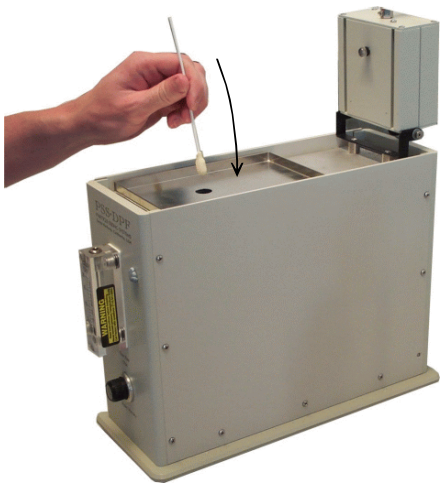
The following procedure is an efficient technique of cleaning the 5µm-5mm sensor installed in the DPF unit.

1) Remove the intake nozzle from the DPF unit

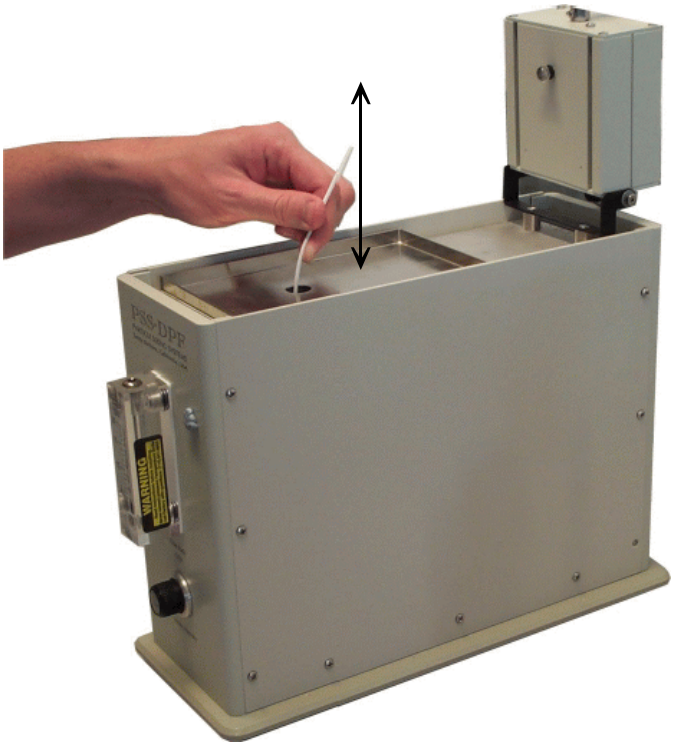


2) Activate the high flow rate cleaning cycle (Alt-F2)

3) Introduce a dry foam-tipped bud (RS catalogue number 494-562) to the bottom of the intake hole. This point is level with the inner window through which the laser diode beam passes. At this point the sensor baseline voltage should drop to 0 v. since the bud is completely obscuring the beam.



4) Wipe the bud up and down whilst pressing against one side of the inner window. Continue this procedure around the entire perimeter of the window.



5) Retract the bud and check the baseline extinction voltage. If this value has not reached 7.0 v., repeat step 4.

6) Replace the intake nozzle.