What can particle size data tell us depositional environments

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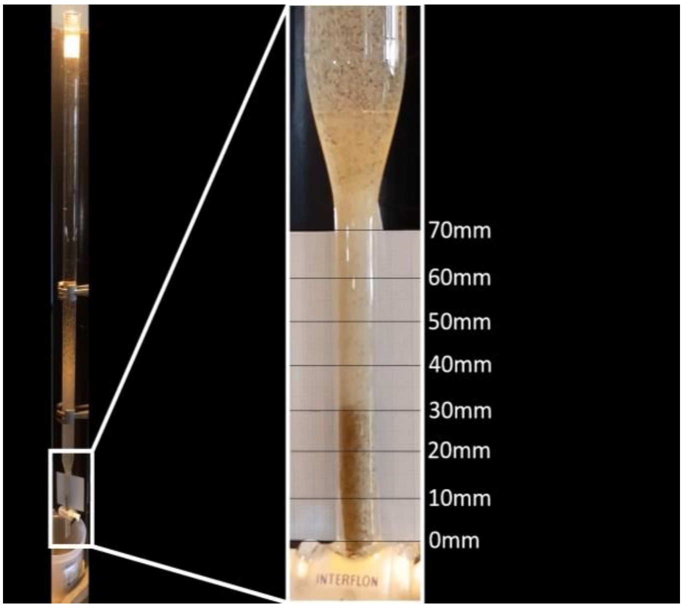
(Activity adapted from ENVS120 Experiments in Physical Geography, University of Liverpool)



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1. Introduction

The proportions of different grain sizes within a sediment sample can provide information on the method and mechanisms of deposition. The main technique for the determination of these particle size distributions is sieving. However, particle shape, composition and moisture can influence the results, especially in the smaller grain sizes. A preferred technique is the use of the settlement properties of particles in a fluid (water or air). This technique is particularly useful as the sediment samples were initially deposited from some kind of fluid medium.

Here, the principle of Stokes' law may be applied to quantify the proportion of different grain sizes present in a sediment sample by utilising their differential settling velocities. In this case, the coarser sediments will settle faster due to their larger size whilst the finer size fractions will take progressively longer to settle as the grain size decreases. Different depositional environments can thus be recognised by the particle size characteristics of their sediments. This is because gravity, air, ice, rivers and the sea erode, transport and deposit sediments in subtly different ways. Particle size analysis is a very useful technique in the reconstruction of past environments, and for determining the characteristics of processes that are just too dangerous to monitor directly (e.g. storms and tsunamis). One excellent example of where this may be applied is distinguishing beach and river sands, which can be identified on the basis of the particle size distribution sorting and skewness (Figure 1).

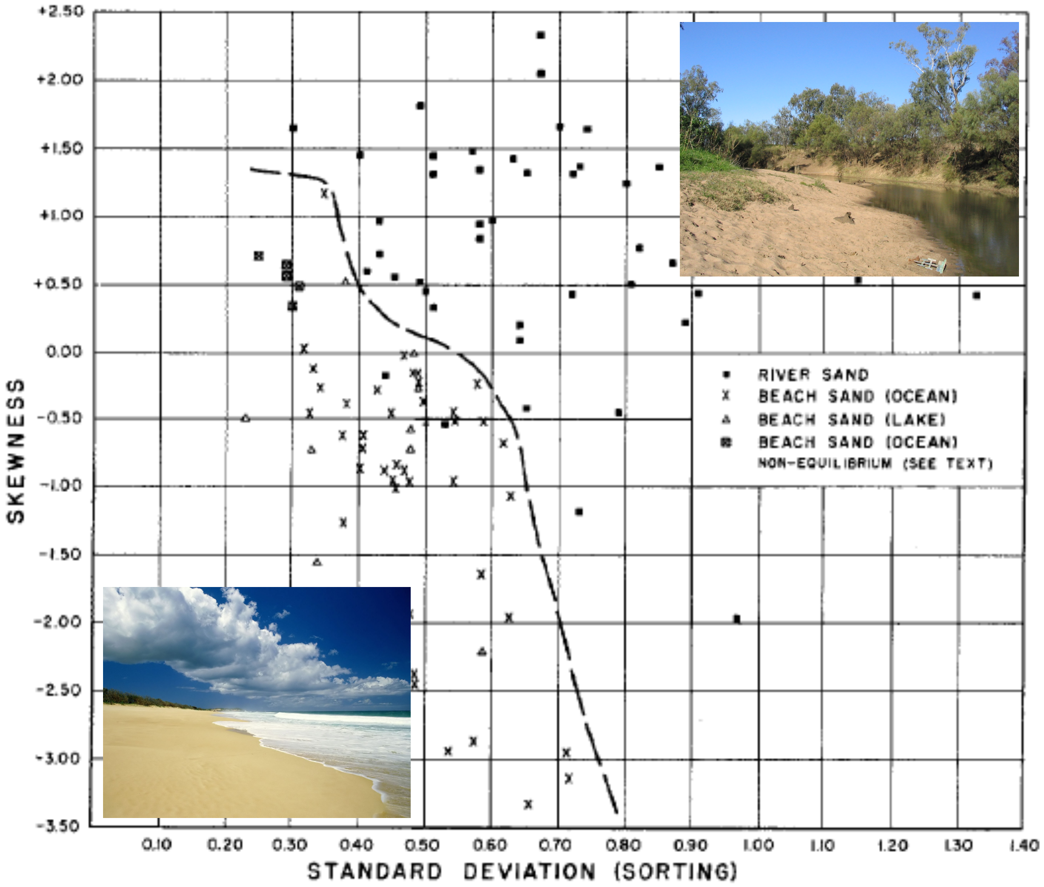


Figure 1: Typical particle size distribution statistics for river and beach sands. After Freidman, G.M. (1961), Journal of Sedimentary Petrology, 31, 514-529.

In the above example, beach sands are well sorted and negatively skewed due to constant winnowing of fines by wave action. In contrast, river sands are more poorly sorted and positively skewed due to settling of fines from suspension when flow velocity decreases. In this activity you will collect particle size data experimentally using settling velocities to investigate the principle that the depositional energy of particles is a function of their size. There is opportunity to test this approach on sediment samples of unknown origin.

1.1. Particle settling and Stokes' Law

Stokes' law is one of the most important law in hydrodynamics and geomorphology as it can help describing the deposition of sediments in a Newtonian fluid. Stokes' law states that the rate at which a particle or grain settles, its **settling velocity**, is proportional to particle size, hence larger particles settle faster in a fluid. More specifically, other factors are involved, such as fluid viscosity, particle and fluid density and particle size:

$$V_g = \frac{g\, d^2\, (\sigma - \rho)}{18\mu}$$

where:
V_g = settling velocity of a particle (cm/s)
g = acceleration due to gravity (approx. 9.8 m/s^2)
σ = particle density (g/cm^3)
ρ = fluid density (g/cm^3)
μ = viscosity (g/s.cm)
d = particle diameter (mm or ϕ)

In the simplest terms (if viscosity, fluid and particle density, and gravity remain constant) Stokes' law states that the rate at which a particle or grain settles is proportional to particle size, hence larger particles settle faster in a fluid.

Though from the equation above you can note that other factors are involved, such as fluid viscosity, particle and fluid density, and particle size. Especially grain size properties such as size, shape, roundness, composition, density etc. will introduce a significant difference in the settling of grains which appear to be the same general size. As a result, the amount of time it takes for grains of a certain size class to settle will be subject to a considerable level of variability.

It is an essential element of scientific observation to assess or **quantify** the significance of this variability. This can be achieved through **measures of dispersion**, i.e. how much do the results spread around a mean value. One of the simplest measures of dispersion is the **standard deviation** (Figure 2). Of 100 measurements of settling velocity, 68 of them will be clustered within plus or minus one standard deviation of the mean value, and 96 within two standard deviations. As a result, standard deviation is a good measure of dispersion or variability within the dataset.

1.2. Characteristics of grain populations

Particle Size, or Grain Size, in geomorphological studies are critical element of any geomorphological, sedimentological, pedological, Quaternary (and many more) study. They are some of the most fundamental ways in which we can describe environments and processes that operate within ithem. There are three ways the sediment grain size can be described; in mm, using phi scale, or using descriptive terms.

1.2.1. The Phi scale

Particle Size, or Grain Size, in geomorphological studies is generally measured on the Phi (ϕ) scale (Table 1). This was proposed by Krumbein (1934) in the Journal of Sedimentary Petrology, volume 4, pages 65-77. Krumbein highlighted the problems with plotting the sizes of particles in a sediment sample using a linear scale:

- *Difficult to express a wide range of grain sizes on a linear axis*
- *Information in finest fractions can be lost – yet this information is often the most important*

A logarithmic scale was proposed to overcome these problems, where $\log_2$ provides most effective way of expressing most particle size ranges. Furthermore, because the finest sizes, i.e. fractions of mm, provide a significant proportion of geomorphological and sedimentological information, a negative logarithm (e.g. $-\log_2$) enables geomorphologists to work with positive rather than negative values.

The Phi (ϕ) Scale

$$\phi = -\log_2 D$$

where, D = grain diameter (mm)

Table 1: Phi scale and its association with grain size.

Diam. (mm)	**0.125**	**0.25**	**0.5**	**1**	**2**	**4**	**8**	**16**	**32**	**64**	**128**
-log₂ (ϕ)	**3**	**2**	**1**	**0**	**-1**	**-2**	**-3**	**-4**	**-5**	**-6**	**-7**

When you first use the phi (ϕ) scale, it may seem counter-intuitive. However, you soon get used to the fact that large ϕ values indicate the finest particle sizes. Similarly, the largest particle sizes have a high negative ϕ value. Just take a little time to acquaint yourself with the above table, and get used to talking about decreasing particle size when the ϕ value increases. Many researchers try to get around this by referring to an "increasing ϕ value", but it is much better to state "decreasing particle size".

1.2.2. Mean Grain size

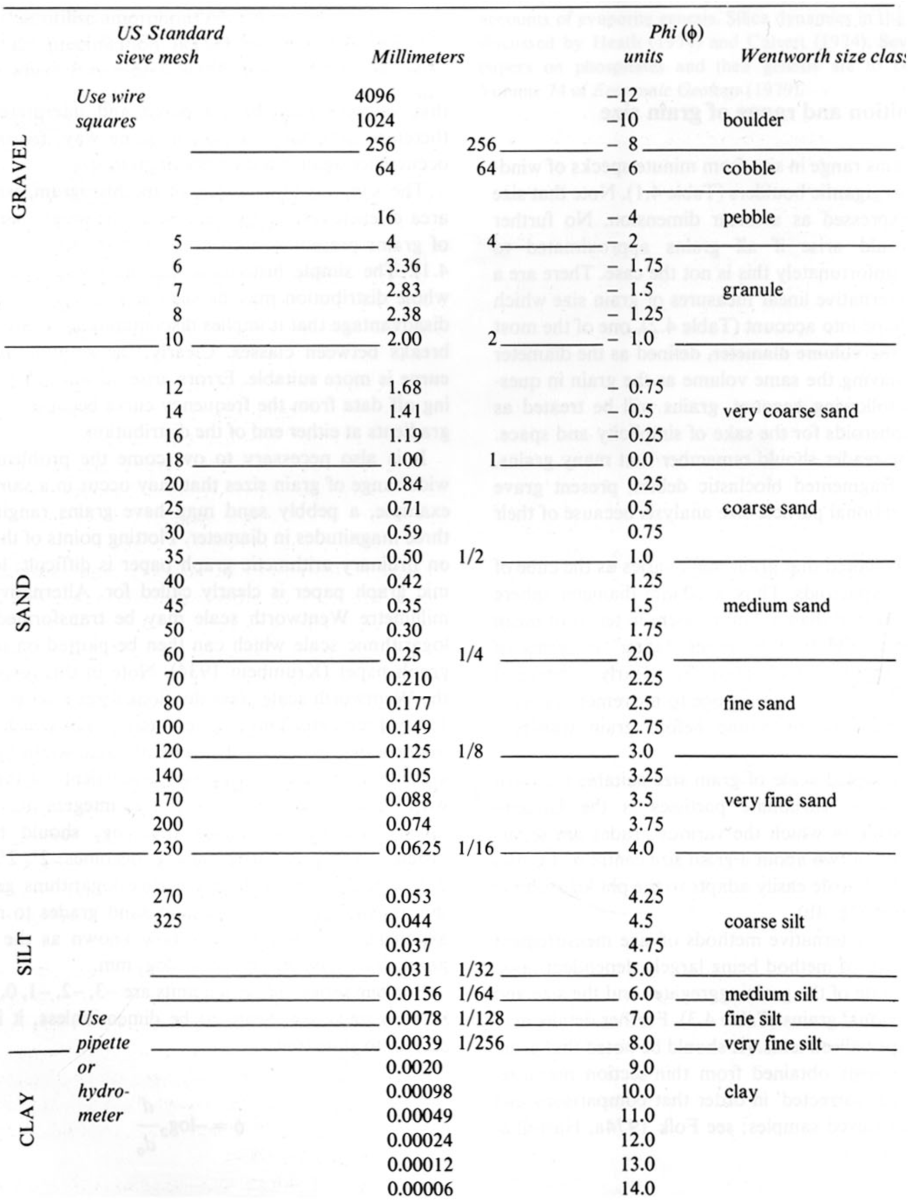
Mean grain size (μ) is the average size of a particle in sample, i.e. the sum of all the measurements divided by the number of measurements. Mean grain size may be provided in metric system (mm), phi scale, or using descriptive terms following Udden-Wentworth size classification scale (Figure 2). Mean grain size gives an indication of the weight force applied by the depositional medium (i.e. depositional energy) and interpreted in terms of the depositional environment. For example, boulders are the largest particle and high energy to move them such as landslides, earthquakes, glaciers. On the other hand, clay is the smallest grain size and requires really low energy environment to settle out such as lake.

1.2.3. Standard deviation or sorting (σ)

Sorting is a measure of dispersion of grain sizes on either side of mean value. In this case, sorting can be considered as the sedimentary equivalent of standard deviation – and is often given the same symbol to denote it (σ). Using normal distribution (Figure 2) we can calculate that 68.3% of data is located within ±1σ of the mean, whilst 95.5% is found ±2σ of the mean. Better sorted samples have a lower sorting value, i.e. the extent of dispersion either size of the mean is less (narrower peak). Therefore, sorting can be indicative of the uniformity of sediment processing during deposition; high σ = poor sorting, e.g. diamicton; how σ = good sorting, e.g. aeolian sand. As with mean grain size, sorting is also measured in phi (ϕ) units.

Table 2: Sorting classes.

phi (φ) Size Range	**Verbal Description of Sorting**
under .35 phi	very well sorted
0.35 - 0.50 phi	well sorted
0.50 - 0.71 phi	moderately well sorted
0.71 - 1.0 phi	moderately sorted
1.0 - 2.0 phi	poorly sorted
2.0 - 4.0 phi	very poorly sorted
over 4.0 phi	extremely poorly sorted



	US Standard sieve mesh	*Millimeters*		*Phi (ϕ) units*	*Wentworth size clas*
GRAVEL	*Use wire squares*	4096		-12	
		1024		-10	boulder
		256	256	-8	
		64	64	-6	cobble
		16		-4	pebble
	5	4	4	-2	
	6	3.36		-1.75	
	7	2.83		-1.5	granule
	8	2.38		-1.25	
	10	2.00	2	-1.0	
SAND	12	1.68		-0.75	
	14	1.41		-0.5	very coarse sand
	16	1.19		-0.25	
	18	1.00	1	0.0	
	20	0.84		0.25	
	25	0.71		0.5	coarse sand
	30	0.59		0.75	
	35	0.50	1/2	1.0	
	40	0.42		1.25	
	45	0.35		1.5	medium sand
	50	0.30		1.75	
	60	0.25	1/4	2.0	
	70	0.210		2.25	
	80	0.177		2.5	fine sand
	100	0.149		2.75	
	120	0.125	1/8	3.0	
	140	0.105		3.25	
	170	0.088		3.5	very fine sand
	200	0.074		3.75	
	230	0.0625	1/16	4.0	
SILT	270	0.053		4.25	
	325	0.044		4.5	coarse silt
		0.037		4.75	
		0.031	1/32	5.0	
		0.0156	1/64	6.0	medium silt
	Use pipette or hydro-meter	0.0078	1/128	7.0	fine silt
		0.0039	1/256	8.0	very fine silt
CLAY		0.0020		9.0	
		0.00098		10.0	clay
		0.00049		11.0	
		0.00024		12.0	
		0.00012		13.0	
		0.00006		14.0	

Figure 2: The Udden-Wentworth size classification scale

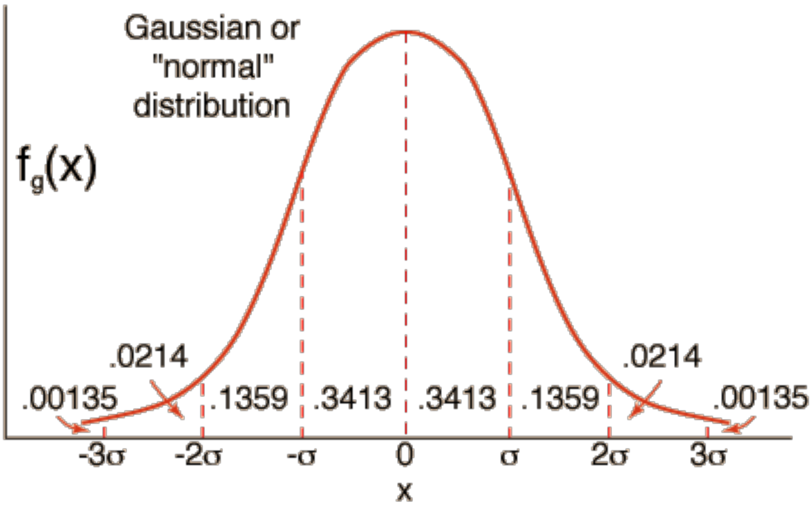


Figure 3: A Gaussian Distribution Function

1.2.4. Skewness

Skewness is another measure that uses the basic statistics associated central tendency of the data. It uses the relationship between mean and median (and mode) to assesses how symmetrical curves are. Symmetrical curves have a value of 0.00 and mean = median = mode (Figure 3). Where mode < median < mean the most values are clustered around the left tail of the distribution while the right tail of the distribution is longer; this is described right-skewed or **positively skewed**. In the opposite scenario where mode > median > mean values are concentrated on the right side of the distribution while the left tail of the distribution is longer; this is described as left-skewed or **negatively skewed.**

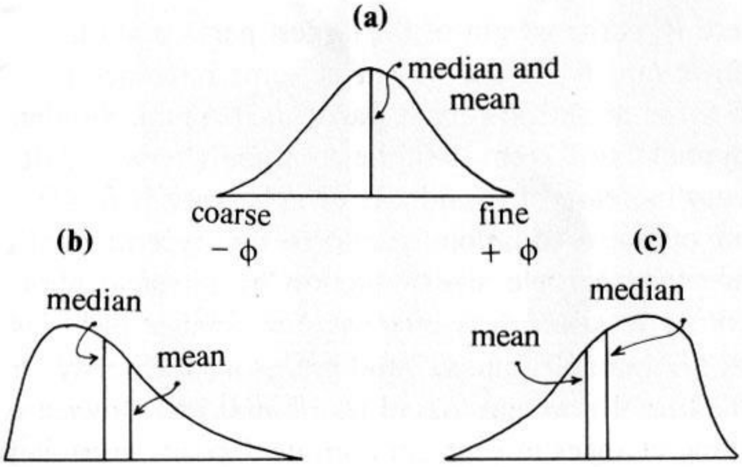


Figure 4.2 To illustrate skewness of distributions. (a) symmetrical distribution, (b) positive skewness, (c) negative skewness.

Figure 4: Graphical illustrations of degrees of skewness

When interpreting skewness in the context of particle size samples with an excess of fine grain are positively skewed (and can be described as a **Fine Skewed**). Conversely sample with an excess of coarse grains are negatively skewed (and can be described as **Coarse Skewed**). This a very powerful descriptors of grain size distributions. Positive skew tends to be the result of deposition from suspension, e.g. river silts, whilst negative skew tends to result from winnowing or erosion (lag deposits), e.g. beach sands. Skewness is a dimensionless parameter, its numerical limits lie within the range of +1.00 and –1.00.

Table 3: Skewness classes

Skewness	**Verbal Description of Skewness**
from +1.00 to +0.30	strongly fine skewed
from +0.30 to +0.10	fine skewed
from +0.10 to -0.10	near symmetrical
from -0.10 to -0.30	coarse skewed
from -0.30 to -1.00	strongly coarse skewed

1.2.5. Kurtosis

This is a measure of the ‘Peakedness’ of a particle size distribution, i.e. the ratio between the sorting in the "tails" of the curve and the sorting in the central portion. If the central portion is better sorted than the tails, the curve is said to be excessively peaked or **leptokurtic**; if the tails are better sorted than the central portion, the curve is deficiently or flat-peaked and **platykurtic**. Kurtosis is a dimensionless parameter.

Table 4: Kurtosis classes

Kurtosis Value	**Verbal Description of Kurtosis**
under 0.67	very platykurtic
0.67 - 0.90	platykurtic
0.90 - 1.11	mesokurtic
1.11 - 1.50	leptokurtic
1.50 - 3.00	very leptokurtic
over 3.00	extremely leptokurtic

2. Lab safety and Equipment

There are no specific safety issues	**Be aware that other practicals taking place near your bench may involve hazardous materials or equipment**
Working above head height	**If you need to additional height to work with the Emery (settling) tube, use the steps available. DO NOT climb on the seats or the benches**

- **Emery Tube, often known as a settling tube**. This 80 cm-long tube enables you to settle grains of both known and unknown size through water, using Stokes’ law as the basis for the settling of particles of different grain size. It is important to know the length of the settling cylinder. You can measure the length of the cylinder using a measuring tape; start measuring from the water surface to the bottom where sediments will settle. *Use the same water level during each experiment by filling the cylinder with the same quantity of water.*

- **Sediment samples of known grain size**. For the first part of the practical, these known sizes are used to examine the relationship between settlement time, settling velocity and particle size. These sediments are located in the foil trays and range in size from 1 ϕ to 4 ϕ (at 0.5 ϕ intervals)

- **Sediment samples of unknown origin**. There are six different samples of unknown origin. These are stored in glass vials.

- **Stop watch**. Used to time the settling of known grain sizes and to mark-off how much sediment has accumulated in the bottom of the Emery tubes at given times.

- **Spirit level**. To check the Emery tube is vertical.

- **Wash bottle of deionized water**. For topping up the Emery tube to the 80 cm mark and for dislodging and residual particles held by surface tension.

- **Plastic beaker**. For collecting water and sediment when you wash out the Emery tube.

- **Strips of paper and sellotape**. During the second part of the practical, these strips of graph paper are attached to the lower part of the Emery tube to track how much of the sample has accumulated after given settlement times.

- **Graph paper**. 1 mm graph paper for plotting settlement time against grain size.

- **Probability graph paper**. This is used to plot the cumulative frequency distribution graphs of the unknown sediment samples.

3. Experiment A: Settling velocity and particle size analysis of known grain size

For the settling velocity you will be using the Stoke's Law and Emery Tube. It is a very simple apparatus with which to investigate the settling of grains in a fluid. It is of known length, therefore the time taken for grains to settle can be considered as a measurement of distance per unit time in cm s^{-1}, i.e. velocity.

The part of the practical enables you to:

- investigate the reproducibility of results
- plot graphs and undertake calculations to illustrate analytical uncertainty
- explore the relationship between grain size and settling velocity

3.1. Experiment A Procedure

1) Check that the Emery tube is vertical (using the spirit level) and clear of any sediment (tapping the top of the tube will encourage any sediment residue to fall). Using a wash bottle, top up the water level in the Emery tube to the mark (80 cm above the tap).
2) There are a total of seven samples of known grain size in the foil trays, at 0.5 ϕ intervals between 1.0 ϕ and 4.0 ϕ. For each known grain size, in turn, select **a few** grains (less than 20) place them on a folded strip of paper. Release these grains into the top of the tube and simultaneously start the stop watch. Ignore the few grains held on the water by surface tension. Record the time (in seconds) for the arrival of the grains at the base of the tube. Take the time of arrival or ***the main group of grains***. Carry out this procedure five times to obtain a mean settlement time and a corresponding standard deviation.
3) After each grain size run, open the tap, flush out the grains into the plastic beaker and top up the tube as before.
4) Repeat the entire procedure for all the known grain sizes.
5) Enter your settlement times into EXCEL worksheet 'Settling_cylinder.xlsx' (with perhaps a row for each grain size, and a column for each repeat). In new columns further to the right on your worksheet, calculate the corresponding settling velocity, V_g, for each of these, using the formula:

$$V_g = \frac{\text{settlement length}}{\text{mean settlement time}} \quad (\text{cm s}^{-1})$$

6) From this you can calculate the mean and standard deviation of settling velocity, using Excel (=STDEV() function). Add these as extra columns to your settling velocity data.
7) Now create a scatter plot in EXCEL with ϕ on the *x*–axis and settling velocity on the *y*–axis. Add a bar to show the standard deviation for each.

8) Finally, add a trend line to your data points. This should not to be a straight line of best fit, but a trend line that more sensitively passes close to or through all the mean settlement times. A curved or quadratic line may be more appropriate for this.

To add error bars:

- Select the bar chart, and click on Design>Add chart element>More error bar options
- Under *Error amount*, select *Custom*, for the *positive error value* select your standard deviation column on the worksheet. For the *negative error value* do the same.
- On the scatter plot, click on the horizontal error bar, and delete it.
- In this case, it doesn't make sense to have "horizontal" error bars as the diameter are "known" values.

3.2. Experiment A Questions: Settlement time and settling velocity

From the plot and the results from the above analysis, please complete the following:

a. With reference to your first graph, briefly comment on the observed relationship between mean settlement time and grain size.

b. Again, from the first graph, does the variability in settlement time change with grain size, i.e. does the standard deviation increase with decreasing grain size?

c. From your table of settling velocity calculations, do your data confirm or contradict Stokes' law?

There is a general rule in geomorphology that sediments of a certain size will settle on the bed of a river or, indeed, any flow when the effective flow velocity is just below that of the particle's settling velocity, i.e. the forces directed downwards are greater than those directed upwards and along. Thus, particle settling velocity (calculated from size measurements) may be used as an approximate guide to the velocity of the flow from which the sediments were deposited. With this in mind, give estimates of flow velocity for depositional media that have deposited sediments with a mean particle size of:

a. 1.2 ϕ

b. 2.3 ϕ

c. 3.7 ϕ

To do this, you will find it helpful to draw lines from these particular particle sizes on your graph to the trend line and then across to the settlement time axis. From these settlement times, use the formula as before to calculate settling velocity as a proxy for flow velocity. You should also consider the sources of uncertainty in your determinations of settlement time and settling velocity. Are they due to the slope of the line or the uncertainty in the original data from which the trend line was obtained?

4. Experiment B: Settling velocity and particle size analysis of unknown grain size (optional extra)

In the second part of the practical, the aims are to:

- investigate the use of settling for determining particle size distributions
- plot graphs and undertake calculations to investigate particle size characteristics
- understand how particle size statistics may be used in the interpretation of the nature of deposition

4.1. Experiment B Procedure

1) Check that the Emery tube is vertical and clear of any sediment (tapping the top of the tube will encourage any sediment residue to fall). Using a wash bottle, top up the water level in the Emery tube to the mark (80 cm above the tap). Run off water through the tap if the tube is overfull.

2) Attach a strip of graph paper to the narrow section at the base of the tube using Sellotape (Figure 5). Mark on the graph paper strip where the top of the tap section is.

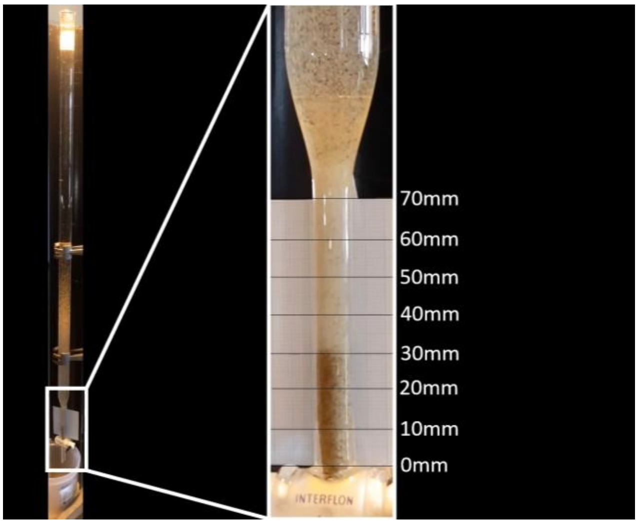
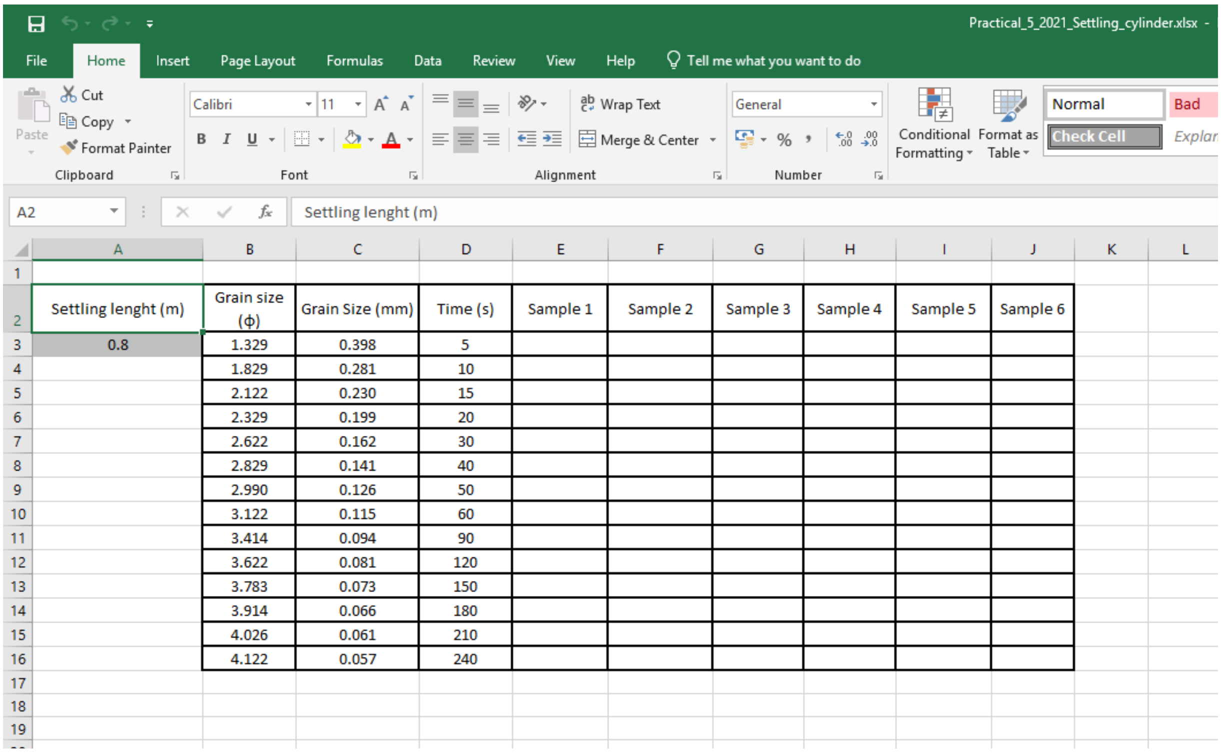


Figure 5: Graph paper attached to the bottom of the tube

3) Select one of each of the six different sediment samples in sample bags. For each sample, complete the following procedure:

a Open the excel file ‘Settling_cylinder.xlsx’ (Figure 6). Complete the excel file inserting in column A (grey cell) the settling length (in m). Column D uses Stokes law to calculate the time required for a given grain size to travel the settling length that you have inserted in the grey cell. **Make a note of the time intervals in column D.**



A2 Settling lenght (m)

Settling lenght (m)	Grain size (ϕ)	Grain Size (mm)	Time (s)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
0.8	1.329	0.398	5						
	1.829	0.281	10						
	2.122	0.230	15						
	2.329	0.199	20						
	2.622	0.162	30						
	2.829	0.141	40						
	2.990	0.126	50						
	3.122	0.115	60						
	3.414	0.094	90						
	3.622	0.081	120						
	3.783	0.073	150						
	3.914	0.066	180						
	4.026	0.061	210						
	4.122	0.057	240						

Figure 6: Worksheet for data collection

b Add the sediment to the tube and start the stop watch.

c The sediment will gradually settle down the tube and accumulate in the narrow section at the base. Record the height of the accumulated sediment at the time intervals shown in **Column D of the Excel file** by marking the graph paper strip.

d When all the sediment has settled, remove the graph paper strip and flush out the tube into the plastic beaker. Create a second version of the table and record the measurements in Excel as cumulative percentage using the following equation:

$$\frac{\text{Height of sediment at each time interval}}{\text{Final height at the end of the experiment}} \times 100\ (\%)$$

4) Repeat steps 3 to 6 for each sample

5) To plot results use graph paper with a probability scale, again orientated portrait.

Note: It is recognised that a large proportion of the information regarding the depositional characteristics of a sediment sample is contained at the finest and coarsest ends of the grain size distribution. As a result the probability scale provides equal weighting to the coarsest 5%, the middle 90% and the finest 5% of the grain sizes.

6) For each sample plot a diagram of grain size in ϕ on the *x*–axis against cumulative percentage on the *y*–axis. You should be able to plot the results from two samples on a single sheet of probability paper.
7) Connect each data point by straight lines - do not smooth out the curve.
8) For each sample, read off and record the grain size in ϕ (from the probability paper) for the percentiles given in the Table 5 and add them to 'Settling_cylinder.xlsx'.

Table 5: Grain size at given percentiles (read these from the probability paper)

Percentile	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
5%						
16%						
25%						
50%						
75%						
84%						
95%						

8) Using the values collected in Table 5, calculate the summary statistics of mean grain size, sorting, skewness and kurtosis in combination with the equations below (Folk and Ward, 1957) and record in Table 6 and the 'Settling_cylinder.xlsx' spreadsheet. These values can then be used in conjunction with Figure 2 and Tables 2-4 to classify the samples using the Udden-Wentworth Scale.

$$\text{Mean} = \frac{(16\% + 50\% + 84\%)}{3}$$

$$\text{Sorting} = \frac{(84\% - 16\%)}{4} + \frac{(95\% - 5\%)}{6.6}$$

$$\text{Skew} = \frac{(16\% + 84\% - 2(50\%))}{2(84\% - 16\%)} + \frac{(5\% + 95\% - 2(50\%))}{2(95\% - 5\%)}$$

$$\text{Kurtosis} = \frac{(95\% - 5\%)}{2.44(75\% - 25\%)}$$

Table 6: Particle Size Statistics

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Mean ϕ						
Sorting ϕ						
Skewness						
Kurtosis						

4.2. Experiment B Questions: Can you tell whether the samples are from a beach or a river?

From the results from Experiment B and with reference to the material given in the introduction to this practical, complete the following:

a. Classify your samples according to Figure 2 and Tables 2 through 4, tabulating your findings.

b. Compare the mean grain size, sorting, skewness and kurtosis of your sediment samples, e.g. which is the coarsest, which is the better sorted, etc.

c. Interpret the characteristics of the environment of deposition for each sample, e.g. "Sample 3 was deposited in a high energy environment where the flow exhibited a low variation in flow velocity, in which setting from suspension dominates (i.e. coarse grained, well sorted, positively skewed, leptokurtic)". You may like to use Figure 1 if you find it helpful in your interpretation.