

APPENDIX A: EXCAVATION STABILITY

A.1 Failure Mechanisms

There are three main failure mechanisms for open excavations:-

1st Mechanism: Hydraulic Failure due to Flow of Groundwater Towards the Excavation

If the groundwater pressure exceeds the supporting fluid pressure inside the excavation the resulting hydraulic force will be destabilizing and hydraulic failure is very likely. Critical situations could be:-

- encountering a confined aquifer with high groundwater level
- saline groundwater (with high specific weight) in combination with low weight slurry (e.g. polymer fluid mixed with fresh water and without a significant fines content)
- sand or gravel lenses in fine soils or soils that are enclosed by previously completed panels where the groundwater pressure will rapidly increase
- a loss of slurry pressure due to a piston effect if the tool is withdrawn too quickly or is not properly designed (bypass channel too small)

It is critical that the support fluid pressure sufficiently exceeds the groundwater pressure during all construction phases.

2nd Mechanism: Single Grains or Small Groups of Grains Falling off the Excavation Walls

If grains at the excavation walls cannot be kept in place this may result in a successive failure of the excavation.

Grains are pushed against the wall by the horizontal flow force $i \cdot \gamma_F \cdot V$. This flow force is a mass force which results from the hydraulic gradient i within the volume V of the considered grains.

In case of a bentonite suspension with a yield strength this mass force may be applied by static shear stresses after the penetration has stagnated. The horizontal flow force mobilizes an upward friction force which must be greater than the gravitational force of the grains (with buoyant specific weight under supporting fluid) to prevent sliding. It is essential that a suitable seal is maintained at or within the excavated surface.

3rd Mechanism: Failure Body Sliding on a Shear Plane

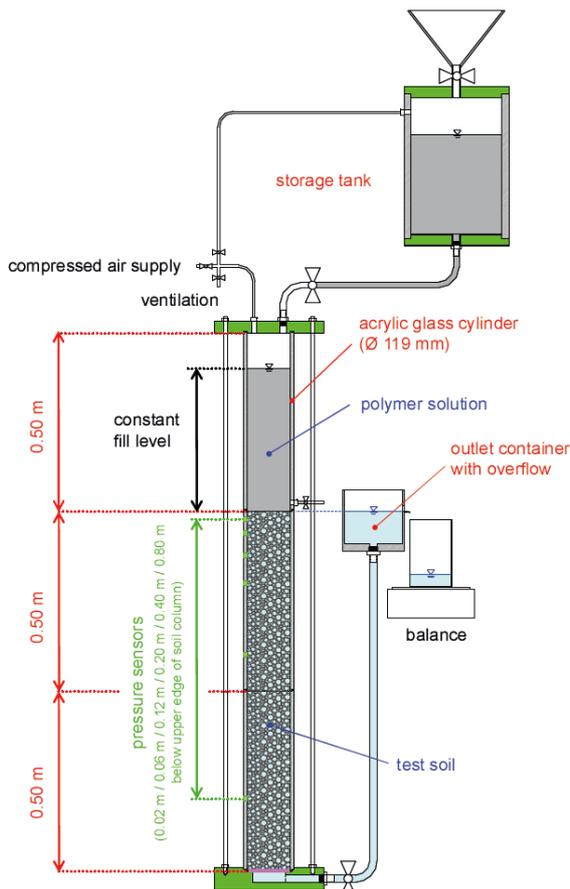
If the hydraulic supporting force falls below a critical limit a failure body may slide on a shear plane.

This could be a failure body according to DIN 4126 (see Figure A.1 with critical angle of shear plane ϑ_a , gravitational force G , variable load p , shear force Q and shear forces T in the lateral faces). Other failure body geometries should be considered if conditions are complex (e.g. inclined ground surface or layered ground). A reduction of the trench length (l_r in Figure A.1) increases the influence of the lateral shear forces (T) and the level of safety. For a circular excavation, a failure body as shown on the right side of Figure A.1 may be considered. *Note: a 3D failure body model naturally covers "arching effects".*

Experience in Equivalent or Unfavorable Conditions

Experience in equivalent or similar conditions may be a quick and easy method to evaluate the stability of an excavation. Additionally, experiences should always be taken into account for first assessment and plausibility checks even if other methods of stability checks are used. It is important to mention that the comparison of project conditions is often difficult. Stability is influenced by many factors such as geometry of the excavation, support fluid parameters (e.g. components, dosage, quality of mixing water, mixing technique), soil properties (e.g. layers, porosity, permeability, shear strength), ground water level, external loads, depth of guide wall or casing, execution time etc.

Analytical Stability Checks



Analytical stability checks allow all relevant parameters of influence to be taken into account and to detect failure mechanisms, to optimize design and to compare the performance of different products in an objective way.

The calculation of penetration lengths, hydraulic gradients and support forces requires the determination of rheological parameters (e.g. power law parameters to describe pseudoplastic rheology). This can be achieved with the flow test shown in Fig. A.2 that also allows the hydraulic head loss along the penetration length to be measured. Similar tests may be performed if the calculation for a support fluid is done using a stagnation gradient (fluid with yield strength).

The time-dependent penetration of a support fluid based on rheological parameters may be calculated according to Lesemann [2016, DOI: <http://doi.org/10.3846/13bsgc.2016.035>].

Figure A.2 : flow test (LESEMANN, 2016)

For calculating trench stability according to DIN 4126, "Trench" software is available from GGU Software.

APPENDIX B: SUPPORT FLUID TESTS

B1. Density

For support fluids, the most usual instrument for density measurements is the mud balance. The instrument consists of a cup rigidly fixed to a scale arm fitted with a sliding counterweight or rider (Figure B.1). In use the whole unit is mounted on a fulcrum and the rider adjusted until the instrument is balanced. The fulcrum must be placed on a horizontal surface. Specific gravity can be read from an engraved scale. It should be noted that the instrument may have three scales in addition to the specific gravity scale but none of these scales is required for civil engineering work.

As the balance was developed for the oil industry, the range of the instrument is wider than necessary for civil engineering works.

The balance may be checked by measuring the water density which has to be equal to 1.00.

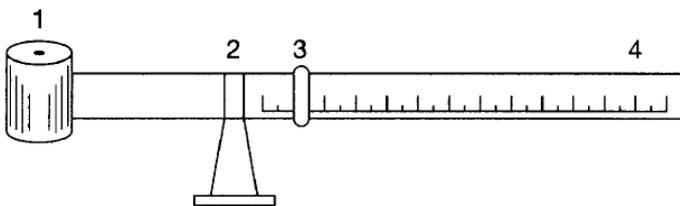


Figure B.1 – Schematic diagram of the mud balance: (1) mud cup, (2) fulcrum, (3) rider, (4) scale.

The density of many polymer support fluids is close to that of water and the mud balance is not sensitive enough. It is therefore recommended that density is measured using a weigh balance with a suitable container calibrated for volume (Jefferis and Lam 2017).

B2. Marsh viscosity

The Marsh funnel is the simplest instrument for routine assessment of support fluid flow behavior. The test procedure is simply to pour a freshly stirred sample of support fluid through the screen to fill the funnel to the underside of the screen **at the scribe line** (a volume of 1.5 liter). Then measure the time for the discharge of 946 ml (1 US quart) of support fluid from the funnel (Figure B.2). The result is quoted as Marsh funnel seconds. The Marsh funnel time in seconds cannot be directly converted to a viscosity. All Marsh Funnel times quoted in this Guide are for 946 ml.

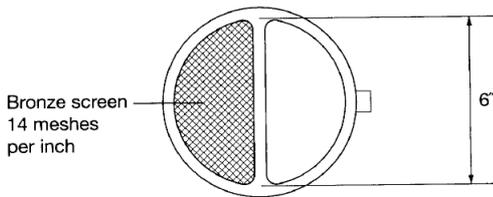
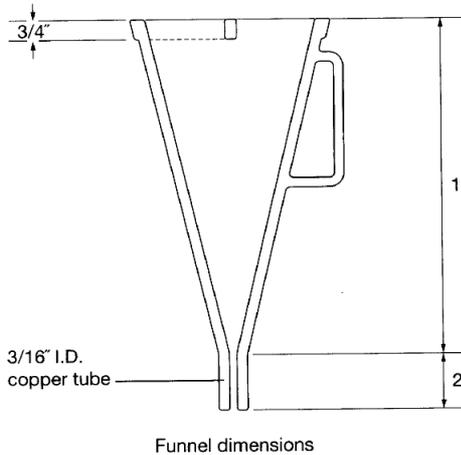


Figure B.2 – The Marsh funnel.



The funnel may be checked by measuring the flow time for water. For clean water at 21 °C (70 °F) the times should be as follows:-

- For 946 ml – 25.5 to 26.5 s
- For 1000 ml – 27.5 to 28.5 s

No adjustment of the funnel is possible, and if readings outside the above ranges are obtained it must be assumed that the funnel (or the stopwatch) is damaged. Nevertheless a higher water test value could highlight the funnel cleaning need.

B3. Filter Loss/Filter Cake

Filter loss will be significant for support fluids as they are all segregation processes that lead to loss of product volume. At its simplest, filtration is a pressure-driven process whereby a particulate system, when pressurized against a permeable formation, deposits a filter cake which accretes with time under pressure and which controls the rate of loss of water. The filtration is controlled by the loss of liquid (water) through a solid system – a filter cake – while bleeding is controlled by the behavior of a fluid system.

The standard apparatus used for filter loss measurement is the American Petroleum Institute filter press apparatus developed for testing drilling fluids (API 13B 2003). The instrument consists of a 3 inch diameter cell with a detachable base in which a filter paper supported on a wire mesh can be fitted as shown in Figure B.3. The filter paper is a Watman hardened filter paper with 2.7 μm openings. In the standard test the volume of filtrate collected from a support fluid sample subjected to a pressure of 100 psi (689 kN.m⁻²) for 30 minutes is measured.

The thickness of the cake is measured at the end of the test, and the permeability of the cake can be estimated by a function of the applied pressure.

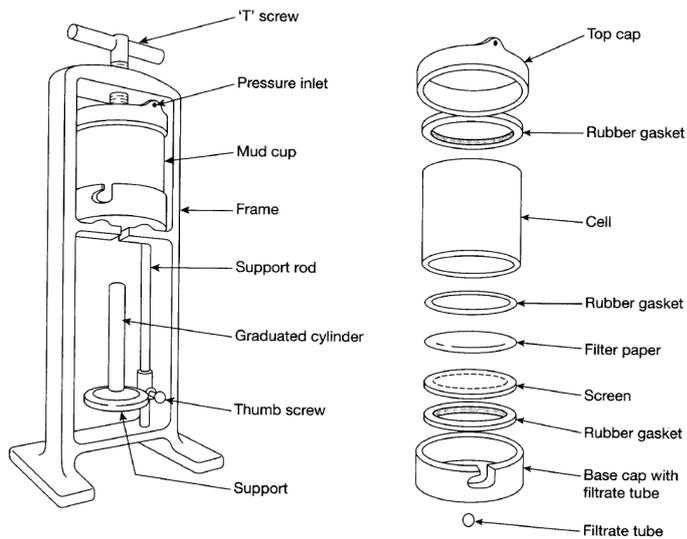


Figure B.3 – Standard filter press and mud cell assembly.

B4. pH

pH is a measure of the acid or alkaline nature of a material. pH 7 is neutral; below 7 is acid; above 7 is alkaline. pH may be measured with a glass electrode and a matched millivolt meter or with pH papers.

The relative acidity or alkalinity of a liquid is conveniently expressed as pH. Defined as the negative logarithm (to the base 10) of the hydrogen-ion concentration, pH units decrease with increasing acidity by a factor of 10.

$$\text{pH} = -\log[\text{H}^+]$$

where $[\text{H}^+]$ is the hydrogen ion concentration in moles per liter. At room temperature, the ion product constant of water, K_w , has a value of 1×10^{-14} mol/L.

$$K_w = [\text{H}^+][\text{OH}^-] = 1.0 \times 10^{-14}$$

For pure water, $[\text{H}^+] = [\text{OH}^-] = 1.0 \times 10^{-7}$ and hence, $\text{pH} = 7$.

pH may be measured with a glass electrode and a matched millivolt meter or with pH papers.

With an electrode it should be possible to measure the pH of pure solutions to a repeatability of better than 0.05 pH unit, though it will be necessary to calibrate the electrode with a buffer solution prior to test. Ideally two buffer solutions should be used with a pH range that brackets the expected pH of the support fluid. But the use of an electrical pH meter may be regarded as excessive and reserved for laboratory situations.

With pH papers, by selecting narrow range papers it is possible to measure pH to 0.1 unit. When testing suspensions, to avoid masking the colour with deposited solids apply the suspension to one side of the paper and read the colour from the other. It is also possible to test the filtrate from the filter loss test to avoid colouration problems. The pH paper must be stored in a sealed container to protect it from ambient humidity.

B5. Sand Content

During the excavation the support fluid density will increase due to suspension of soil. This density provides a measure of the total amount of soil in the support fluid but no information as to whether this is sand, silt or clay.

The sand content test is designed to measure the bulk volume of sand (strictly material coarser than 200 mesh US, 0.075 mm, 75 μm) in a given volume of fluid. The apparatus consists of a tapered graduated tube, a small 200 mesh US sieve and a funnel (Figure B.4). To carry out the test, a fixed volume of support fluid is washed on the

screen and the volume of retained soil is measured as a fraction of the original support fluid volume. The result of the test is quoted as the sand content.

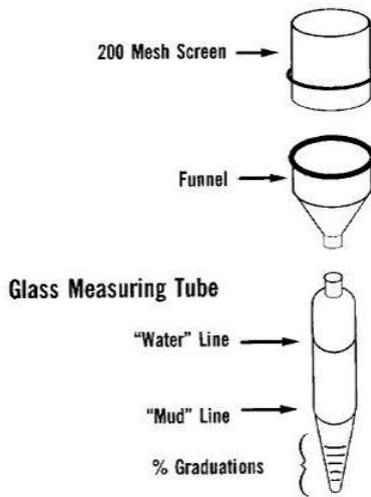


Figure B.4 – The sand content test equipment.

B6. Gel Strength

Gel strengths are determined in the two-speed direct-indicating viscometer by slowly turning by hand the driving wheel on the top or side of the instrument and observing the maximum deflection before the gel breaks. The same procedure is followed in the multispeed viscometer, except that the cylinder is rotated at 3 rpm with the motor.

The maximum deflection is the gel strength. Gel strengths are measured after allowing the mud to stand quiescent for any time interval of interest, but they are routinely measured after 10 s (initial gel strength) and 10 min. The dial reading gives the gel strength in pounds per hundred square feet.

The thixotropy is characterized by the gel "0" and the gel "10".

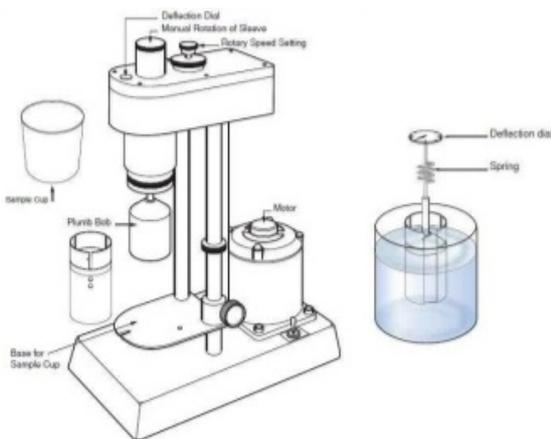


Figure B.5 – Fann viscometer

B7. Effective Yield Point

This test setup is standardized in DIN 4127. The so-called Ball Harp is used to determine the effective yield point of support fluids according to the former version of DIN 4126 and is still in use due to its uncomplicated and fast method of measuring the yield point of a suspension.

The Ball Harp equipment consists of a set of 10 glass and steel balls with different diameters. They are attached with polyamide threads to a common disk, the disk can be mounted on a drill stand. The fluid sample is placed beneath the balls and stirred up with a mixer for about one minute to disintegrate thixotropic solidifications, then the ball set is dipped slowly by use of the drill stand's lever, in order to avoid dynamic effects.

Depending on the previously measured density of the support fluid, each ball is assigned to a specific critical effective yield point, at which it would just be buoyant. Balls, whose critical yield point is below the fluid's yield point, float on it (thread bent). The critical effective yield points of all balls are displayed in a table for all consecutive ball numbers and all fluid densities between 1.02 and 1.70 g/cm³ [64 to 106 lb/ft³] and yield points between 3 and 200 N/mm² [435 to 29'000 psi]. The effective yield point of the support fluid can thus be estimated between the critical yield point of the ball with the largest number which is still floating and the critical yield point of the ball with the smallest number which is immersed.

Two sets of balls, a cup filled with fresh water for cleaning purposes and a cold air fan allow for continuous measurement of incoming probes.

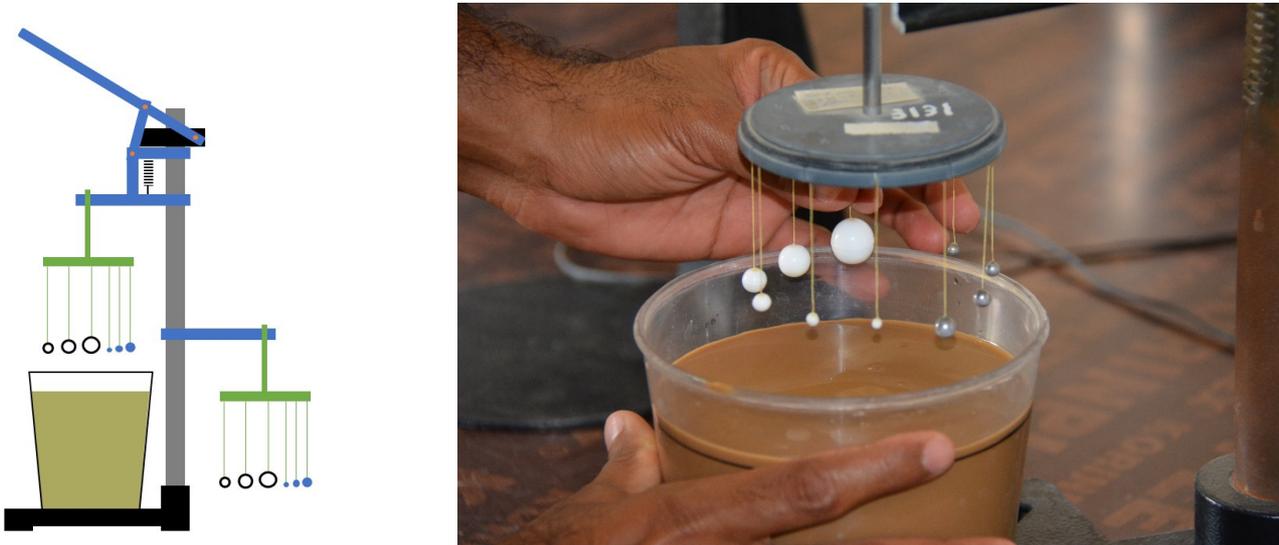


Figure B6: Ball Harp Test According to DIN 4127

B8. Calcium

Hardness in water is caused by the presence of calcium ions, magnesium ions, or both. As their concentrations increase, water becomes harder. The combined concentration of calcium and magnesium is frequently referred to as total hardness.

Temporary Hardness

Temporary hardness is a type of water hardness caused by the presence of dissolved bicarbonate minerals (calcium bicarbonate and magnesium bicarbonate).

Permanent hardness

Permanent hardness is hardness (mineral content) that cannot be removed. Ions causing permanent hardness of water can be removed using a water softener, or ion exchange resin.

Total Permanent Hardness = Calcium Hardness + Magnesium Hardness

The calcium and magnesium hardness is the concentration of calcium and magnesium ions expressed as equivalent of calcium carbonate.

Hardness can be quantified through instrumental analysis, an individual test kit, or through the use of test strips specifically formulated for making these measurements.

1. A colorimeter passes a white light beam through an optical filter which transmits only one particular color or band of wavelengths of light to the photodetector, where it is measured. The difference in the amount of colored light transmitted by a colorless sample (blank), and the amount of colored light transmitted by a colored sample, is a measurement of the amount of colored light absorbed by the sample. In most colorimetric tests, including hardness, the amount of colored light absorbed is directly proportional to the concentration and is reported by the meter.
2. Test strips are typically produced from plastic, with chemically impregnated pads on the end. These pads are designed to react with specific ions and produce a specific color change. Once a test strip is reacted and a color is developed, the strip is then compared to a printed color chart. The color chart is specifically designed to represent color reactions at various concentrations. Matching the strip to the closest color match produces a concentration reading.

B9. Resistivity

The resistivity (Ωm) of a support fluid is influenced by the dissolved salts (ppm) or (gpg, grain per gallon) in the water portion and the insoluble solid material contained in the water portion. The greater the concentration of dissolved salts, the lower resistivity of the solution. Unlike metals, the resistivity of a solution decreases as temperature increases. The resistivity is measured and controlled to permit better evaluation of formation characteristics, fluids, and filtrates. The determination of resistivity involves the measurement of resistance to the flow of electrical current through a sample of known configuration. In the direct-reading resistivity meter, the resistance measurement is converted to resistivity in ohm meters.



Figure B6: Analogy and Digital Resistivity meters

B10. Chlorine

Usually not all chlorine exists as free chlorine. It depends how much organic matter, particularly nitrogenous organic matter, is present. The chlorine reacts with ammonia or organic amines to form chloramines. This chlorine is called combined chlorine. Chloramines have lower disinfecting power than free chlorine but have the advantage of being more persistent.

1. **Titration: Iodometric method.** For higher levels of chlorine an iodometric titration is sometimes used. This method tests for total chlorine. The chlorine in the test solution oxidizes some iodide that has been added. This forms an iodine complex that then reacts with an indicator like starch. The solution is titrated with a reducing agent back to a clear colour. This method is subject to interferences from other oxidizing agents that may be present apart from chlorine.
2. **Test strips** are typically produced from plastic, with chemically impregnated pads on the end. These pads are designed to react with specific ions and produce a specific color change. Once a test strip is reacted and a color is developed, the strip is then compared to a printed color chart. The color chart is specifically designed to represent color reactions at various concentrations. Matching the strip to the closest color match produces a concentration reading.
3. **DPD method.** The most common method for free chlorine is the DPD method. At near neutral pH chlorine oxidises the DPD to form a magenta coloured compound. However this method only works for low chlorine levels up to approx 10 ppm. At higher chlorine levels the reaction proceeds beyond the magenta coloured compounds with a 'bleaching out' of the deeper colour.
4. A colorimeter passes a white light beam through an optical filter which transmits only one particular color or band of wavelengths of light to the photodetector, where it is measured. The difference in the amount of colored light transmitted by a colorless sample (blank), and the amount of colored light transmitted by a colored sample, is a measurement of the amount of colored light absorbed by the sample. In most colorimetric tests, including chlorine, the amount of colored light absorbed is directly proportional to the concentration, and is reported by the meter.
5. **Amperometric method:** In this method, chlorine is measured by a sensor probe containing the electrolyte potassium chloride (KCl). The chlorine present in the water moves across the membrane on the bottom of the probe and reacts with the KCl to generate an electric current. The probe measures the current produced to determine the level of chlorine. The stronger the current, the higher the level will be of present chlorine.

B11. Chloride

There are several methods for determining the chloride content.

1. **Titration**
 - a. **(Silver Nitrate Solution)**The Chloride concentration determined by titration uses a silver nitrate solution to remove the chloride from solution as AgCl in the form of a white precipitate. The endpoint of the titration is detected using a potassium chromate indicator. A potassium chromate indicator is used to react with the excess of AG forming Ag_2Cr_4 present after all Cl^- is out of solution.
 - b. **(Mercurimetric Determination).** In nitric solution chloride ions are titrated with mercury nitrate solution against 1,5-diphenylcarbazon as the indicator, forming slightly dissociated mercury chloride in the process. At the titration end-point, excess mercury ions react with the indicator to form a blue-violet complex. The chloride concentration is determined from the consumption of titration solution
2. **Test strips** are typically produced from plastic, with chemically impregnated pads on the end. These pads are designed to react with specific ions and produce a specific color change. Once a test strip is reacted and a color is developed, the strip is then compared to a printed color chart. The color chart is

specifically designed to represent color reactions at various concentrations. Matching the strip to the closest color match produces a concentration reading.

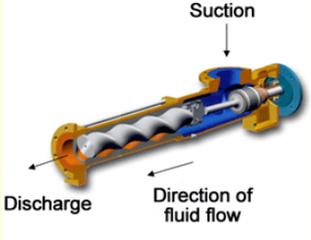
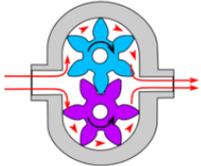
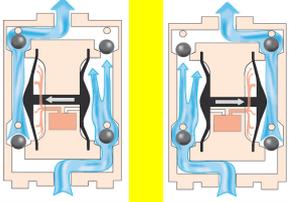
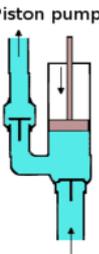
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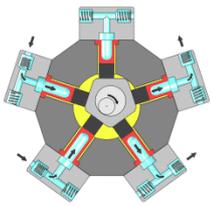
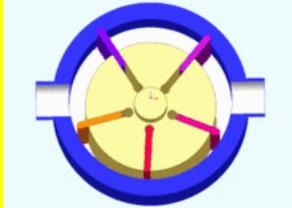
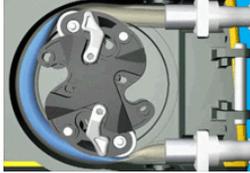
APPENDIX C: TYPES AND PROPERTIES OF PUMPS

Positive displacement pumps

Positive displacement pumps draw fluid into a compartment at the inlet and move it to an outlet for discharge, most typically using a rotary, reciprocating, or diaphragm method to move fluid.

Table C.1 – Positive Displacement Pumps

Type of Pumps	Schematic	Brief Description
Rotary Lobe		This type of positive displacement pump based on the counter rotation of pumping elements or lobes (without making contact) within a chamber. Liquid flows into the cavity and is trapped by the lobes as they rotate. Liquid travels around the interior of the casing in the pockets between the lobes and the casing, it does not pass between the lobes. Finally, the meshing of the lobes forces liquid through the outlet port under pressure.
Progressing cavity pump		This type of positive displacement pump is also known as an eccentric screw pump or cavity pump. It has a long helical rotor sitting in a twin helix casing or stator (usually made of rubber). When the rotor is set in motion the eccentric shaft creates multiple cavities that “progress” along the stator pushing the fluid towards the discharge side.
Screw Pump		As the pump rotates, the intermeshing of the two screws along with the pump housing forms chambers. These chambers fill with the pumped fluid and move it from the suction side to the higher pressure discharge side.
Rotary Gear Pump		As the gears rotate they separate on the intake side of the pump, creating a void and suction which is filled by fluid. The fluid is carried by the gears to the discharge side of the pump, where the meshing of the gears displaces the fluid. The mechanical clearances are extremely small.
Reciprocating Diaphragm Pump		The diaphragm pump uses a combination of the reciprocating action of a diaphragm (rubber, thermoplastic, teflon) and suitable valves on either side of the diaphragm to pump a fluid.
Reciprocating Piston or Plunger Pump		This type of positive displacement pump uses the movement of a piston or plunger to vary the holding volume within a sealed chamber, thus producing a pressure differential. On the up stroke the cavity fills with the fluid sucked from an inlet, on the down stroke the fluid is ejected from the outlet. Each movement of the plunger produces a pulse. Depending on the design of the pump it may use single or multiple pistons or plungers.

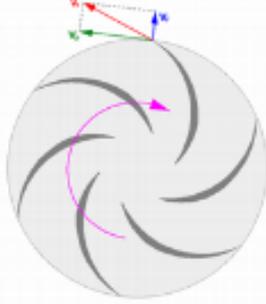
<p>Radial Piston Pump</p>		<p>This is a positive displacement pump with multiple pistons each with its own chamber. The pistons are organised symetrically around an exccentric axis drive that, when put in motion, extends or retracts the pistons and draws in/displaces out the fluid from chambers.</p>
<p>Rotary Vane</p>		<p>A rotary vane pump is a positive-displacement pump that consists of vanes mounted to a rotor that rotates inside a cavity. The vanes are allowed to slide into and out of the rotor and seal on all edges, creating vane chambers that do the pumping work. On the intake side of the pump, the vane chambers are increasing in volume. On the discharge side of the pump, the vane chambers are decreasing in volume, forcing fluid out of the pump. The action of the vane drives out the same volume of fluid with each rotation.</p>
<p>Peristaltic</p>		<p>This positive displacement pump is based on using rollers on a rotating axle to compress a hose or flexible tube thus pushing the fluid along its length.</p>
<p>Flexible Impeller</p>		<p>A flexible impeller pump is a positive-displacement pump that, by deforming impeller vanes, draws the liquid into the pump housing and moves it to the discharge port with a constant flow rate. The flexibility of the vanes enables a tight seal to the internal housing, making the pump self-priming, while also permitting bi-directional operation.</p>

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Centrifugal Pumps

Centrifugal pumps use a rotating impeller to create a vacuum in order to move fluid. The pump’s impeller rotates within the housing and reduces pressure at the inlet. This motion then drives fluid to the outside of the pump’s housing, which increases the pressure enough to send it out the discharge.

Axial flow centrifugal pumps have a curved propeller-shaped impeller, whereas the impeller on a radial flow centrifugal pump looks more like a fan.

<p>Centrifugal Pump</p>		
<p>Centrifugal Pumps</p>		<p>A rotating impeller is set in a chamber. The fluid enters the chamber close to the rotating axis of the impeller and is accelerated outwards to the outlet point. The faster the impeller revolves the higher the velocity of the liquid at the vane tip and the greater the energy imparted to the liquid. These pumps are very useful for colloids as they promote faster mixing by defragmenting the particles passing. These pumps are not as suitable</p>

		for polymer based fluid with long chains as the impellers work as knives cutting the chains.
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Table C.2 – Centrifugal Pumps

Nearly all pumps fall within these two categories. However, positive displacement pumps come in a wider variety such as gear, lobe, peristaltic, screw, and many other types of pumps as described above.

Care should be taken when using centrifugal pumps for polymer applications as the chains can be sheared by the action of the impeller.

Suppliers literature for any pumps (including pumping curves) should be consulted during the pump selection. Example curves are discussed below.

<p>Flow Rate versus Pressure</p>	<p>Centrifugal pumps have varying flow depending on pressure or head, whereas the positive displacement (PD) pumps have more or less constant flow regardless of pressure.</p>	
<p>Flow rate versus viscosity</p>	<p>Another major difference between the pump types is the effect viscosity has on the capacity of the pump. The flow rate chart shows how the centrifugal pump loses flow as the viscosity goes up but the PD pump's flow actually increases. This is because the higher viscosity liquids fill the clearances of the pump causing a higher volumetric efficiency. This chart shows the effect of viscosity on the pump flow. When there is a viscosity change there is also greater line loss in the system. This means it is necessary to calculate the change in pump flow from the first chart for this pressure change.</p>	
<p>Efficiency versus pressure</p>	<p>The pumps behave very differently when considering mechanical efficiency. The efficiency chart to the right shows the impact of pressure changes on the pump's efficiency. Changes in pressure have little effect on the PD pump but a dramatic one on the centrifugal.</p>	
<p>Efficiency versus viscosity</p>	<p>Viscosity also plays an important role in pump mechanical efficiency. Because the centrifugal pump operates at motor speed, efficiency goes down as viscosity increases due to increased frictional losses within the pump. Efficiency often increases in a PD pump with increasing viscosity. Efficiency rapidly drops off for the centrifugal pump as viscosity increases.</p>	

Net Positive Suction Head requirements	Another consideration is NPSHR. In a centrifugal pump the NPSHR varies as a function of the flow which is determined by pressure and viscosity as discussed above. As pressure and viscosity have less effect on a PD pump, NPSHR varies mainly as a function of flow which is determined by speed. The lower the speed of a PD pump the lower the NPSHR.	
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Table C.3 A Comparison between Positive Displacement and Centrifugal Pumps

APPENDIX D: SEDIMENTATION OF SOIL PARTICLES IN SUPPORT FLUIDS

This Appendix gives fuller details of the derivation of the settling velocities shown in *Table 2, Section 3.1* of the Guide. For ease of reference, this Table is reproduced below as *Table D1*.

The rate of sedimentation in a support fluid will depend on the size and shape of the particle settling and the properties of the support fluid.

The effective weight of a particle in a support fluid is given by the particle volume and density difference between the particle ρ_s and the support fluid ρ_l thus:-

$$\text{Weight in fluid} = \frac{\pi d^3 g}{6} (\rho_s - \rho_l)$$

where d is the particle diameter and g is the acceleration of gravity.

According to Stokes law the drag force D on a particle of diameter d in a Newtonian fluid (that is a fluid for which shear stress is proportional to shear rate) is given by:-

$$D = 3\pi\mu dv$$

where μ is the dynamic viscosity and v is the particle settling velocity.

By equating the weight of a particle in a fluid and the drag force, the settling velocity of particles can be assessed. *Table D1* shows examples of settling velocities of spherical particles of specific gravity 2.65 in water at 20°C (viscosity, 10^{-3} Pa s, 1 cP). For comparison, *Table D1* also shows indicative settling velocities in a 0.015 Pa s (15 cP) fluid (the apparent viscosity at high shear rates may be of the order of 0.015 Pa s for a bentonite slurry) and an example of PHPA polymer support fluid.

Soil type	Particle size	Particle size	Settling velocity in water, viscosity 1 cP	Settling velocity in a Newtonian support fluid of viscosity 15 cP	Settling velocity in PHPA polymer support fluid
	microns	mm			
CLAY	2	0.002	<0.1	<0.1	<0.1
SILTS	6	0.006	0.12	<0.1	<0.1
	10	0.01	0.32	<0.1	<0.1
	20	0.02	1.29	<0.1	<0.1
	60	0.06	12	0.8	<0.1
SANDS	100	0.1	32	2.2	<0.1
	200	0.2	95	8.6	<0.1
	600	0.6	>200	78	4
	1000	1	>200	170	40
	2000	2	>200	>200	>200
GRAVELS	6000	6	>200	>200	>200
	10000	10	>200	>200	>200

	20000	20	>200	>200	>200
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Table D1 Estimated Spherical Particle Settling Velocities in m/hr (values in italics represent Reynolds numbers >1)

Notes to Table D1:-

Settling velocities less than 0.1 m/hr are shown as <0.1 as particles settling at velocities of 0.1 m/hr and less are unlikely to deposit any significant amount of material at the base of an excavation.

Similarly velocities >200 m/hr are shown as >200 as all particles with such velocities are likely to settle sufficiently rapidly that they are removed in normal base cleaning operations.

All diameters are Stokes' diameters i.e. for non-spherical particles diameters are those of the equivalent spherical particle with the same settling velocity.

For particle settlement, Stokes law is not valid for Reynolds numbers > 0.1 though it gives reasonable results for Reynolds numbers up to 1. As the Reynolds number increases beyond 0.1, the flow regime becomes progressively more turbulent and inertial effects become progressively more important. For Reynolds numbers >1, settling rates can be estimated from published drag coefficient data and are shown in italics in Table D1. For Re>1, a drag coefficient approach has been used to develop the velocities in Table 1. For this the effective weight of a particle in a settling fluid is equated to the drag on the particle as follows:-

$$\frac{\pi d^3(\rho_s - \rho_l)g}{6} = C_D \frac{\pi d^2}{4} \frac{\rho_l v^2}{2}$$

There are a number of empirical equations for the Drag coefficient, C_D for a falling sphere, for example:

$$C_D = \frac{24}{Re} + \frac{3}{\sqrt{Re}} + 0.34$$

Where the Reynolds number is:

$$Re = \frac{\rho v d}{\mu}$$

For the PHPA polymer support fluid, the fluid is assumed to be pseudoplastic and to follow the Carreau model with a consistency coefficient of 0.3 Pa s (300 cP), and a power law index of 0.3 with an upper Newtonian threshold viscosity of 19 Pa s (shear rates less than 10^{-3} s^{-1}) and a lower Newtonian plateau viscosity of 0.007 Pa s (shear rates greater than 10^3 s^{-1}). These data approximate to those for the 0.6 kg/m³ fluid shown at Page 240 of Lam and Jefferis (2018) (*Polymer Support Fluids in Civil Engineering*, ICE Publishing).

For non-Newtonian fluids such as PHPA support fluids, the estimation procedure for settling velocities is subject to many uncertainties and the settling velocities given in the table should be taken only as indicators of the order of magnitude of the settling velocity.

It should be noted that many polymer systems are designed to inhibit soil dispersion. Soils excavated under such fluids may not disperse to clay and silt sizes but remain as larger cut soil lumps - at least not until the polymer has penetrated into the lumps.

Table D1 does not give an indication of settling velocities in bentonite slurries as the properties of such fluids can vary very greatly. However, the impact of an important feature of bentonite support fluids, gelling, can be assessed. Gelling allows small particles to be held in suspension rather than settle. The minimum particle size d which will be held in a fluid of yield stress, τ , is given by Chhabra R.P. and Richardson, J.F. (1999):-

$$d = \frac{\tau}{Yg(\rho_s - \rho_l)}$$

There is considerable variation in the value of Y in the literature ranging from about 0.04 to 0.2. Thus for example if the gel strength of the slurry, $\tau = 5 \text{ Pa}$, and ρ_s and ρ_l are 2650 and 1023 kg/m³ respectively, d may be in the range 1.6 to 7.8 mm and thus such particles may not settle. This can lead to a build of silts and sands in support fluids (in addition to clays). As the solids concentration increases and the suspended particles come into closer proximity, settlement will be slower than predicted by Stokes law. Also if fines are present the gel strength may increase further slowing or stopping sedimentation. These effects can lead to slurries with high and unusable viscosities and densities.

Water, sometimes used as a support fluid, has no gel resulting in fast particle settlements (see Section 4.7 of the Guide).