critical value, there will be sedimentation in the pipeline (**figures 1.20-21**). The critical velocity is determined by a number of factors and is explained in chapter 5. The critical velocity is the lower limit of the dredging process.

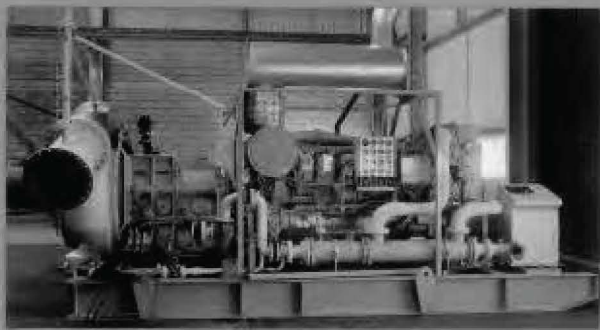
1.9 Pumps and drives

So far, we have identified pump and pipeline characteristics as the determining factors in the pumping process. However, despite their importance, they are not the only factors determining the installation's output characteristics. The combination of the pump and the drive (**figures 1.22-23**) together generate combined characteristics: the "pump characteristics", which are discussed in chapter 8.

The presence of solids usually affects the performance of a centrifugal pump. At a given flow rate and speed, the pressure head will increase while the efficiency of the pump will decrease. These variations are determined by the nature of the soil and the density of the mixture. Chapter 6 looks at the effect of solids on pump performance in more detail.

A certain pressure is required to transport the mixture at a given velocity through the pipeline. This pressure is delivered by the action of the centrifugal pump. The point where pump and pipeline characteristics intersect is the "working point" of the pump installation. Chapter 9 describes how to calculate this working point.

In the case of a cutter suction dredger, discharge distance varies during the dredging project. Pipeline resistance as well as dredger production changes accordingly. Placing a booster in the discharge line *(***figure 1.24**) can maintain dredger output over longer discharge distances. Chapter 9 discusses the positioning and construction of boosters.


1.22 Pump driven by a diesel engine


1.23 Centrifugal submerged pump driven by an electromotor


1.24 Floating booster station

1.10 Monitoring the process

The transport of solids in pipelines is a well-established technique. However, both operational and economic control can be improved if the correct instruments are utilised. Since the amount of solids transported is a function of velocity and the concentration of the mixture, both these factors limit the progress of work. Therefore, monitoring mixture velocity and concentration is essential for dredging efficiency. A number of methods have been developed specifically for this purpose.

The inductive flow rate indicator can be used to measure the velocity of the mixture in the pipeline. Other types of instrument with ultrasonic transducers are available for this purpose, but there are doubts over their accuracy. A radioactive concentration indicator has been developed to measure the solids concentration (**figure 1.25**). To date, this is the only instrument that

1.25 Integrated concentration and flowrate transmitter

1.26 Worn impeller

1.27 Dewatering is a natural part of the rainbowing process

can be employed satisfactorily for pipelines.

1.11 Wear

Wear is an important consideration in the design and operation of slurry systems, as it affects both the initial capital cost and the life of components (**figure 1.26**). Unfortunately, in the case of many mineral slurries, it is by far the most difficult problem to evaluate. It is usually assumed that pump performance is reduced by wear. However, quantitative data from service experience about this effect is limited.

Wear in a slurry pipeline can be attributed to two main factors: chemical corrosion; and mechanical abrasion or erosion. These may be isolated or combined. For example, fine coal slurries are said to be corrosive, while phosphate slurries are said to be erosive. Nearly all soils in dredging practice are of the erosive type. Some iron concentrate slurries are thought to be both. The corrosion scale or oxide film on the pipe wall generated by the oxygen in the slurry is eroded by fine but heavy solid particles. In chapter 10, we discuss wear in general and take a more detailed look at the effect of wear on pump performance and dredger output.

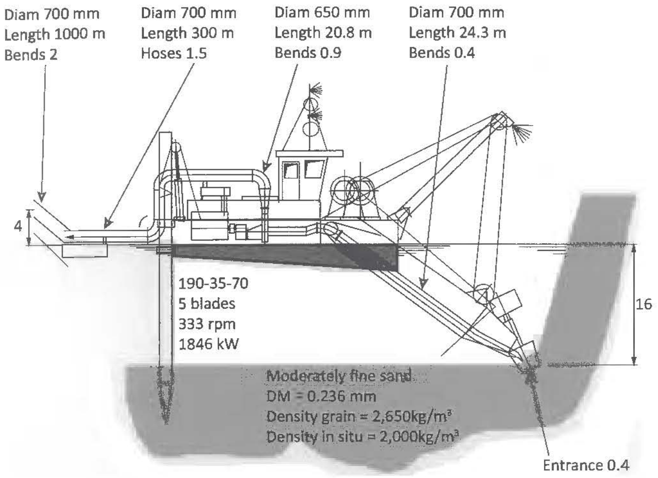
At the end of the transport chain, the solid material is separated from the fluid by a process known as dewatering. Not all slurry systems require dewatering facilities (**figure 1.27**). Those used for limestone slurry, for example, do not. However, the majority of the other materials must be treated in some way prior to final use. In most dewatering systems, the principal parameters are the grain size distribution, the behaviour of the material during the treatment process, the water content of the solid matter, the feasibility of recycling the water, and the need to store the product.

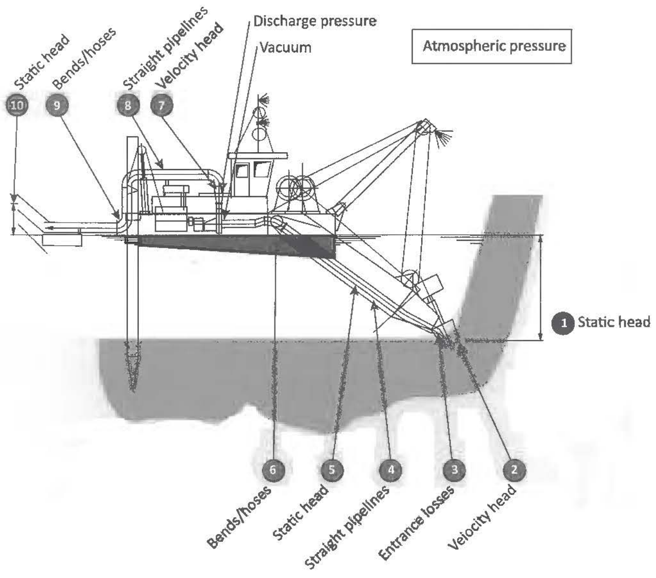
Equipment for dewatering slurries includes vibrating screens, centrifuges, vacuum filters, cyclones and concentrators.
In dredging, complete dewatering is not so important. The water content is usually reduced until the bearing capacity of the ground is delivered only by the solid fraction.

Explaining the hydraulic transport of sand/water mixtures combines theory, which means explaining physical phenomena, and calculations to obtain an idea of the effect of these phenomena on dredger output.

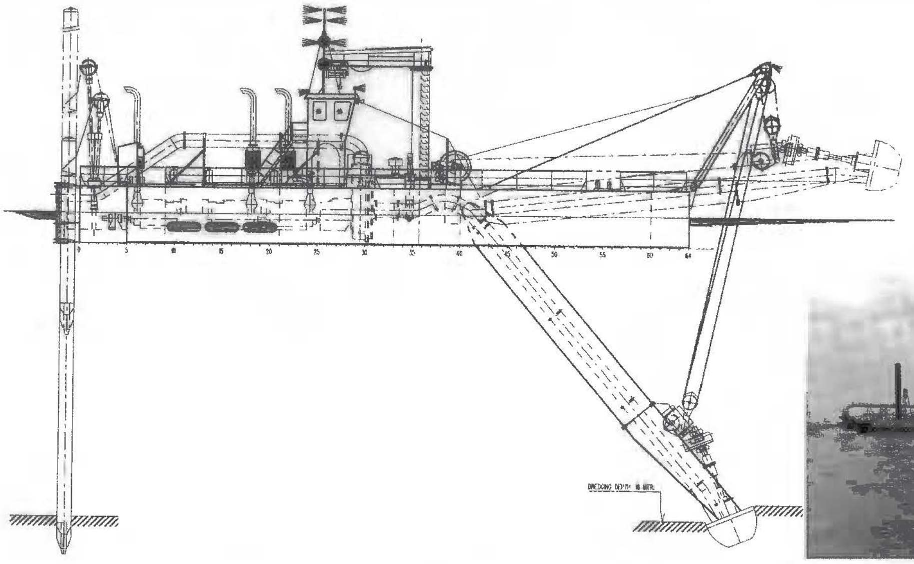
1.12 Intermezzo: information for the calculations

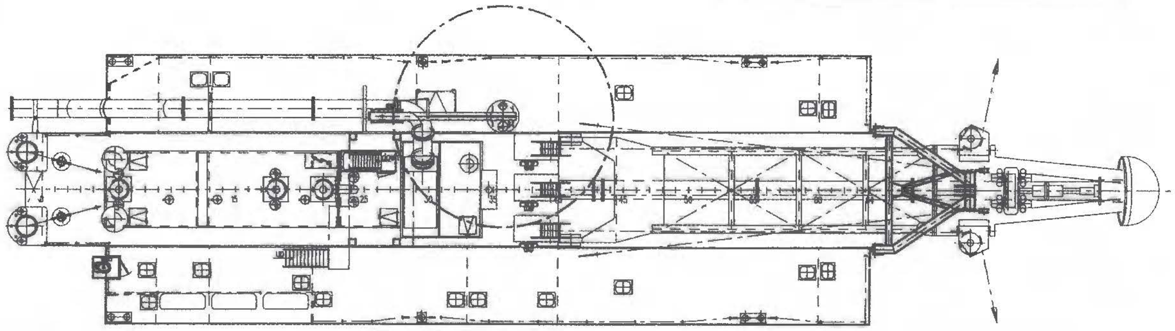
The information required to calculate dredger output is detailed in the table on this page. The first figure below contains the same information. The bottom figure illustrates the different pressure losses in the hydraulic system. We will also look at how to calculate these losses. Page 16 details a datasheet of the IHC Beaver® 3800 cutter suction dredger, which was chosen as the example for our calculation.





Description	Dimension	Unit
DREDGE PUMP		
Diameter impeller	1,900	mm
Width of impeller	350	mm
Diameter suction opening	700	mm
Number of blades	5	
Speed	333	rpm
Available power	1,846	kW
Constant torque		
SUCTION SIDE		
Dredging depth	16	m
Diameter of suction line	700	mm
Length of suction line	24.3	m
Factor entrance	0.4	
Factor bends/hose	0.4	
Centre pump below water	0	m
SOIL		
Moderately fine sand		
Average diameter	236	µm
Density grain	2,650	kg/m³
Density in situ	2,000	kg/m³
DISCHARGE SIDE		
Diameter discharge on board	650	mm
Length on board	20.8	m
Factor bends	0.9	
Diameter floating pipe line	700	mm
Length floating pipe line	300	m
Factor for hoses	1.5	
Diameter shore pipe line	700	mm
Length shore pipe line	1,000	m
Factor for bends	2	
Elevation	4	m





Features
- Completely assembled and fully tested afloat before delivery
- Simple, rapid assembly and dismantling
- Ready for operation on arrival at site
- Standard design, which implies early delivery and low price
- Spare parts available from stock
- Transportable by road or sea
- Reliable hydraulic system
- Fresh water engine cooling system
- Efficient in terms of fuel consumption
- One-man operation
- Wide range of optional equipment available

Principal particulars
- Length overall, ladder raised : 44.50 m
- Length over pontoons : 32.00 m
- Breadth : 10.32 m
- Depth : 2.97 m
- Main pontoon : 20.00 x 4.30 x 2.97 m
- Side pontoons : 29.50 x 2.95 x 2.95 m
- Mean draught with full bunkers approx. (standard execution) : 2.05 m
- Maximum standard dredging depth : 16.00 m
- Internal diameter of suction tube : 700 mm
- Internal diameter of discharge pipes : 650 mm
- Total installed power : 2809 kW (3820 hp)
- Total dry weight approx. : 360 t

Dredgepump
- Type : IHC 1900-350-700, double walled
- Power at shaft : 1846 kW (2510 hp)
- Prime mover : 2 Caterpillar 3512 DI-TA in tandem position developing 2 x 954 kW (2 x 1298 hp) continuous power at 1,600 rev/min. Specific fuel consumption 216 g/kW/hr.
- Dredgepump driven through combined pump block/ reduction gearbox

Auxiliary power
(Cutter, winches, spuds)
Caterpillar 3512 DI-TA developing 876 kW (1190 hp) continuous power at 1,600 rev/min. Specific fuel consumption 216 g/kW/hr.

Harbour set
(Satrting air compressor, bilge pump, generator, hydraulic emergency pump)
Deutz F3L912 developing 25 kW (34 hp) at 1500 rev/min.

Electric installation
- Voltage 24 V
- Capacity 460 Ah
- Voltage 220/380 V AC 50 Hz
- Capacity 25 kVA

Cutter
- Type : IHC 2200-550, 6-bladed with serrated edges
- Power at shaft : 552 kW (750 hp)
- Diameter : 2380 mm
- Maximum speed : approx. 31 rev/min

Winches

	Ladder winch	Swing winches
- Line pull, 1st layer (kN)	: 240	240
- Max. line speed (m/min)	: 25	20
- Wire diameter (mm)	: 36	36
- Drum diameter (mm)	: 750	750

- All winches have independent hydraulic drive
- The two swing winches are supplied with wires of 150 m and anchors of 2500 kg.

Spuds
- Length : 21.4 m
- Diameter : 800 mm
- Weight : 12,110 kg.

Spud hoisting rams
- Force : 534 kN
- Ram stroke : 2.50 m
- Spud stroke : each time approx. 3.65 m

Swing width with 35° swing each side
- At max. dredging depth : 42.5 m
- At min. dredging depth : 51 m

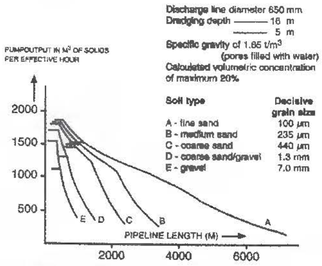
Deck crane
- Lifting power : 80 kN
- Outreach : 4.25 m

Classification
Bureau Veritas Class I, ✠ 3/3, Coastal Waters
Engine installation after construction • MOT

Tools
Special tools for connecting and disconnecting pontoons and cutter ladder, and for maintenance of dredgepump and diesel engine, are supplied

Optional equipment
- Anchor booms
- Tilting facilities for spuds
- Wedge piece for very small min. dredging depth
- Spud carriage
- Increased dredging depth
- X-mastree installation
- Swivel bend
- Non-return valve
- Valve in discharge line
- Vacuum relief velve
- Production measuring equipment
- Towing facilities
- Bilge water separator
- Airconditioning or central heating
- Accommodation

IHC Holland reserves the right to amend dimensional or other data given in this publication, without prior notice



1.13 Literature

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2. Important soil parameters

2.1 Introduction

The term "slurry" describes a mixture that consists of both solid and fluid phases, and behaves differently to a pure fluid. In most cases, the fluid employed as a vehicle is water, although many others are also suitable. Before designing a hydraulic system for the transportation of solids, it is necessary to understand the behaviour of the two-phase slurry mixture. Slurries can usually be divided into two types: settling and non-settling. Settling slurries are also known as heterogeneous suspensions and are found in a wide range of commercial applications, from dredging to coal transport. The dimensions of the grains are usually the point of difference between these two flow types.

The nature of the solid being transported plays a key role in each individual slurry project. Therefore, it is important to first determine the characteristics of the solid and establish how they will affect the performance of pumping equipment. Obtaining and analysing representative samples, as well as collecting and analysing the soil at its source before the dredging process, must be carried out by reliable methods. Only then can reproducible and optimum results be achieved.

Dredging is more than just transporting the slurry. Excavating and dumping are also part of the production process. The successive phases of the dredging process include:

- disruption of the soil cohesion by loosening with cutting tools or high pressure water jets
- entering of the soil into the hydraulic system
- transportation of the soil through a pipeline
- deposition of the material in barges, dumping site or reclamation point
- further processing of the soil by either compacting, or dewatering and/or grading.

The nature of the soil plays a vital role in all of these phases. In the majority of cases, it will determine the entire approach to the dredging project, including operation methods and equipment.

The analysis of the solid is governed by the purpose for which it is undertaken. The tests conducted to determine the dredgeability of a soil (**figure 2.1**) are not the same as the tests carried out to establish pipeline resistance (**figure 2.2**), even if it relates to the same soil. For the purpose of this chapter, we do not focus on the dredgeability of a soil. Instead, we concentrate on the tests that are designed to collect information on the parameters affecting hydraulic transport.
These parameters, such as grain size, grain density, grain shape and viscosity, influence the minimum transport velocity, pipeline resistance, pump characteristics and wear in the system.

2.1 Soil in situ before excavation and...

2.2 ...on the shore following transportation by pipeline. The test to establish the dredgeability of soil before excavation is different to those carried out to determine pipeline resistance after excavation

2.3 Clay in the cutter demonstrates its cohesive properties

2.4 Incoherent materials include gravel and sand

The soil characteristics also determine the type of transport. Fine material is usually transported as a non-settling or slowly settling slurry, and coarse material as a heterogeneous slurry. The characteristics of the transport materials are a function of the geometric, kinematics, physical and chemical properties of the soil.

Unfortunately, the distinction between settling and non-settling slurries is not always clear. The classification not only depends on the dimensions of the grains but also on the duration the particles remain in the pipeline, determined by the ratio pipeline length/mean flow velocity. Therefore, a relatively slowly settling slurry that flows in a long horizontal pipe would be classed as a "settling" slurry, whereas a faster-settling slurry that flows through a short length of horizontal pipe could be considered a "non-settling" slurry. In the latter example, there is insufficient time for the solids to settle.

2.2 Classification of the soil

Soils can be divided into three main groups. These are dealt with in the following sections.

2.2.1 Coherent ductile material

Coherent ductile materials, such as clay, have particle diameters of up to 16 µm. They are mostly transported as non-settling or slowly settling slurries. Both Newtonian and non-Newtonian fluid patterns can occur. Important parameters for these types of materials include: viscosity and yield-stress; density; water content; and shear strength.

Clays can be broadly defined as those minerals that dominantly make up the colloidal fraction of soils, sediments, rocks and waters. The term "clay" can be used to describe particle size or mineralogical context. This main group can be divided into two sub-groups: one consisting of rock fragments with diameters smaller than 2µm; and the other consisting of silt with grain diameters ranging from 2µm to 16µm.

However, it is difficult to consider these sub-groups separately, as they are usually found together or as components of composite soils. The amount of clay mineral in a soil is often estimated by the total amount of material finer than 2µm.

Therefore, soils of this type should be referred to as "pseudo-coherent", because the particles in principle display little coherence. Purely sedimentary, these soils are simply sand and gravel, together with a substantial or large quantity of organic substances (humus) and/or carbonates. However, under the influence of various factors, including the water, organic substances and carbonates, significant cohesive forces can occur in these soils, producing cohesion of the particles. In clays with very fine particles, these cohesive forces can reach a magnitude that is suggestive of the mutual power of attraction of the molecules (**figure 2.3**).

Depending on the condition in which they are found, clays can be dealt with by cutting, scraping or digging, which means that vessels operating on these principles can dredge them. Clay with relatively low natural water content in the proximity of the plastic limit proves to be highly adhesive. With coherent, ductile material, the possibility of forming clay balls during hydraulic transport is important in relation to critical velocity and pipeline resistance.

The limits of plasticity, density and water content of the soil in situ, shear strength, soil structure and stratification, and the quantities of organic constituents are significant in this context. For hydraulic transport, the main parameters are viscosity (mixture), density of particles, humus content, grain distribution, particle shape, mineralogical composition, plasticity limits and shear strength.

The combination of the Atterberg limits and the water content determines how easily the soil will suspend in a watery environment. As well as soil mixtures, the other non-settling slurries are drilling mud; thick limestone slurries; sewage sludge; and quick-sand.

2.2.2 Incoherent material

Materials such as sand and gravel with a particle size between 63µm and 64mm are classed as incoherent materials (**figure 2.4**). Important parameters for the determination of incoherent materials include: the grain diameter; shape and density of particles; lime; and humus content. If lime is present and if the grains are a certain shape, a degree of cohesion can exist.

Once out of its cohesive state, sand that displays coherence is just as easy – or difficult – to deal with as sand that is not cohesive by origin. In this type of material, the initial process of petrifaction results in greater cohesion, and gradually leads to so-called "cemented sand". Where real petrifaction occurs, the result is "coherent consolidated material".

Medium-fine and very fine grades of sand, such as those with a grain diameter smaller than 125µm, can cause problems. Owing to the shape of the grains and/or the presence of lime, they are often highly cohesive, their natural slope is very steep and penetration is difficult. They can be dealt with by profile or hopper dredgers, equipped with water jet systems, although cutter suction dredgers may also be suitable.

Once in solution, these types of sand behave like mud and silt. They are problematic at settling in barges, hoppers and at the point of reclamation. It is even more difficult to draw the material up through the suction pipe of a cutter dredger,

2.5 Coherent consolidated material

2.6 'Dredging' peat by hand

2.7 Sampling with a grab

or to extract it with a bucket dredger. The fine particles suspended in water will not settle easily but gravitate towards the deepest areas. This means that cutter or bucket dredging can be accompanied by significant spillage.

For gravel and sand, the main parameter is grain distribution. Gravel is rarely transported by long pipelines because it can cause extreme wear. Wherever possible, barges or belt conveyors are used instead. This explains why bucket dredgers are preferred above suction reclamation dredgers for extracting gravel.

2.2.3 Coherent, consolidated material

This is the designation for rock-like material such as slate, granite and coral etc. (**figures 2.1 and 2.5**). Important parameters for the excavation of these materials include: unconfined compression strength; tensile strength; stratification; and weathering. Important parameters for hydraulic transport include: density; size; shape; distribution of the lumps; and the sensitivity for degradation.

Between these three main groups of materials lie broad areas of transition. For example, silt and mud, which have particle diameters between 16 and 63µm, can be found between the first and second group. The viscosity of the mixture to be transported is key for these soils, as is the mineralogical composition of the soil and its lime and humus contents.

Dredged spoil may contain gas as well as water and solids. This gas and spoil enters through the suction line in the pump and may cause a severe reduction in the manometric head of the pump. The composition of the gas in dredged material can vary widely, although it is usually a mixture of air and methane gas.

Methane is a flammable by-product of the decomposition of organic material in the absence of oxygen. Such organic material may include the remains of fish and other water creatures, or debris of plants and trees. Knowledge of the amount of organic material in clay and silt is extremely important.

Peat is a special material as it is highly compressible and has high plasticity. Peat is a heterogeneous mixture of partially colloidal decomposed organic matter (plant material), and inorganic minerals (clay and silt) that have accumulated in a water-saturated environment. It is usually a combination of the remains of several plant groups, rather than of a single group.

Its colour can vary from yellow to brownish black, depending on the degree of biological decay, mechanical disintegration of the plant fibres, and the presence of sediment. A water-saturated environment inhibits active biological decomposition of the plant material and promotes the retention of carbon that would normally be released as gaseous products of the biological activity. The result is an accumulation of organic material (**figure 2.6**).

Problems with the transportation of sedge peats (peats formed in wet habitats) can be attributed to their large pore volume, low volume weight (dry matter volume weights between 86 and 212kg/m^3 and wet in-situ density between 800 and 1,100kg/m^3), high moisture content, fibrous structure and high viscosity. A small reduction in the moisture content can result in a significant increase in viscosity. Peat is a very poorly flowing, bulky material, which easily arches in bins.

Finally, consolidated materials such as cemented sands, gravel and very soft types of stone can be found between incoherent and coherent materials.

In addition to these main groups and transitional areas there are many further mixtures. The most important parameter for the calculation of the pipeline resistance for settling slurries is the grain size distribution. Changes in grain size affect the settling characteristics and the flow properties of the material and therefore have a significant influence on the performance of slurry handling equipment.

2.3 Treatment of soil samples

In statistical terms, the purpose of sampling is to study the characteristics of a particular population. The size of the sample taken should be a good representation of the overall population.

Representative samples should be taken from the dredging site (**figure 2.7**) in order to obtain data about the types of soil, their properties, situation and the thickness of the layers. The method of boring is determined by both the specific characteristics to be investigated through analysis of the samples, and the nature of the soil. The degree to which the sample is disturbed is governed by the employed method.

In a completely undisturbed sample, the material properties do not change – the position and distribution of the particles and the tension in the soil remain as they were in-situ.
However, it is virtually impossible to obtain such a perfect sample.

The extent of a soil sampling operation largely depends on the objective for which the samples are taken. The uniformity (or otherwise) of the soil stratification, the risks and the experience previously obtained in the area also influence the operation. The more complex the soil structure, the more comprehensive the soil investigation must be. If little is known about the soil stratification at the start, a general investigation can provide preliminary indications for the nature and extent of the overall soil investigation.

The samples, together with the results of tests carried out in-situ, provide information about the properties of the soil. If the sample is to remain representative after transport and storage, it must immediately be placed in a well-sealed metal or plastic container.

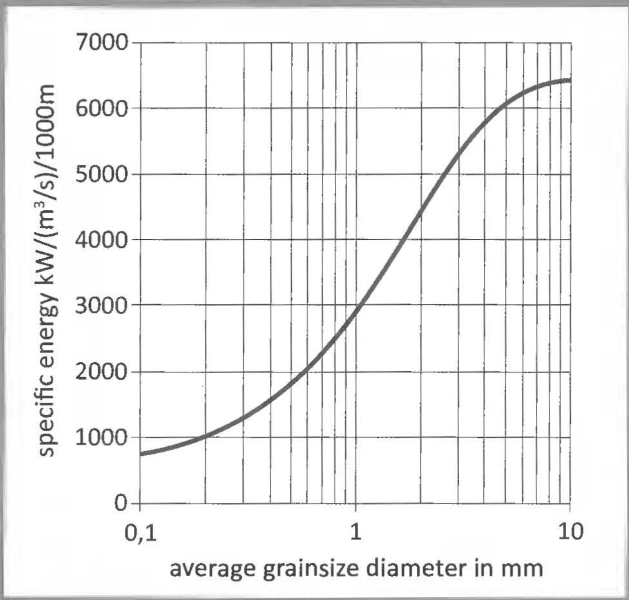
Samples of cohesive ductile material, such as clay, silt, peat, or sand with particles of cohesive ductile material, must be packed with as little air as possible in an airtight container to prevent drying-out. In many cases, coherent consolidated material must also be packed in an airtight container – preferably under water – immediately after sampling.
The properties of this soil type can change considerably if exposed to air (e.g. drying-out or crumbling). Every sample must immediately be labelled with the sample and bore numbers to enable identification.

When the boring has been completed, experts can immediately provide a description of the various soil strata. This gives an impression of the composition of the strata to be obtained during further sampling. If necessary, the pattern and/or number of bores can be modified. The description also helps the laboratory in determining the extent of the examination of the samples during selection and possibility for consultation. Some tests can be carried out on site immediately after obtaining the sample. Among these are the measurement of the density and the undrained shear strength of coherent ductile material.

Ensuring that the sample is representative of the bulk is usually the most important factor when measuring slurry properties. The only exception is when sampling is required to obtain specific local values of properties. A representative sample can be produced only if it is sufficiently large and all parts of the slurry have an equal probability of entering the sample.

The method of sampling depends on the type of slurry. Low viscosity homogeneous slurries can be sampled from free or bounded flows in pipes, open channels, or from vessels, relatively easily and in a representative manner, because the solids are homogeneously dispersed. Heterogeneous slurries must be maintained in a sufficiently turbulent state to prevent settling of the solids. Here, a representative sample can usually be obtained.

2.8 Waste and debris in the soil



2.9 Specific energy

2.10 Collection of sieves

The preferred sampler for slurry systems is a cross-sectional sampler operating in a free falling system. Line or point samplers are the only practical solution for closed, fully turbulent slurry stream systems. It should be ensured that the slurry is well mixed, and that the sampler operates isokinetically.

The risk of the presence of hazardous soil gases or chemical contamination is a significant factor in selecting the method of investigation. It is vital for the analysis to be carried out under strict health and safety guidelines, in order to prevent the creation of contaminants and their migration pathways, and in order to provide reliable samples for chemical analysis.

Before samples are passed to the laboratory, the possibility that they may be contaminated with harmful substances must first be ruled out. If such a possibility exists, appropriate safety precautions should be implemented and preliminary tests conducted in order to determine the nature of the contamination.

During maintenance dredging, the soil may be polluted with all kinds of waste and debris (**figure 2.8**).
To prevent blockage of the pump or the suction opening, removal of such rubbish before dredging begins is highly recommended.

2.4 Grain size distribution

The particle size distribution (PSD) of a soil is an important property, that affects the settling characteristics and flow properties of the material. Therefore, it has significant influence on the performance of slurry handling equipment.

The importance of particle size is illustrated in **figure 2.9**, presenting specific energy as a function of particle size. The specific energy is the required hydraulic power to transport a mixture flow of $1m^3/s$ solids with a density of $2,650kg/m^3$ over a distance of 1,000m. The calculations refer to the critical velocity, which is the minimum allowable velocity in the pipeline for a pipe diameter of 800mm and a mixture density of $1,300kg/m^3$. The larger the grain size, the greater the effects on pump performance and friction losses.
For example, fine gravel requires eight-times more transportation energy than fine sand.

There are many ways of defining the size of an equivalent particle: mass; projected area; diameter; or another appropriate measure. In the dredging industry, classification according to the particle diameter is used. The soil data that a dredging company may receive for tendering on a particular job may be limited to some particle size distributions.

Several methods are available for measuring grain size distribution, including:

- laser diffraction, giving a measure of volume
- sedimentation, giving a measure of mass
- microscopy, giving a measure of length
- gas adsorption, giving a measure of surface area
- sieving (screening), giving a measure of mass
- hydrometer, giving a measure of settling speed.

Each of these methods will define the "size" of a particle in different ways, for example a rod-shaped piece of porous coral would have very different "diameters" when measured using these techniques.

Two common methods for determining particle size are: sieve analysis; and hydrometer analysis. For the purpose of soil investigation as a prelude to dredging, the particle size distribution of sand and gravel is determined by a screen analysis.

The distribution of particle sizes larger than 74μm is determined by sieving (retained on the 200-mesh sieve), while the distribution of particles smaller than 74μm is determined by a sedimentation process using a hydrometer.

During sieve analysis, the dried particles are shaken on a sieve with square openings of a specified size (**figure 2.10**). However, some components of soil may hinder a correct execution of the sieving process. As well as having a specific mass that differs from quartz, carbonate material abrades quickly and could even dissolve in water. During the sieving process, the particle size of carbonate material may reduce, causing erroneous results. Therefore, the amount of carbonates should firstly be determined and removed. When carbonates react with hydrochloric acid, the gasses can be removed easily.

The characteristics of organic content differ from those of mineralogical matter. In addition, because organic material is lighter than quartz, the sieve result will be erroneous.
So, when it is present in substantial quantities, it must be removed before sieving. This is achieved by oxidation.

The sieve analysis, performed using a sieve tower (**figure 2.11**), records the weight of the material retained on each of the series of test screens (by percentage), with the largest holes at the top and the smallest holes at the bottom.
This method of screening is described in the ASTM-standard D422 [4].

The particle size of a soil is a tabulation of the percentage represented in each size range in relation to the total sample, usually shown as passing a given screen size and being

2.11 Sieve tower

retained on the next smaller screen. A complete screen analysis (**figure 2.12**) indicates the total size range of the particles and the uniformity or discontinuity of size distribution between the maximum and minimum sizes.
A grain size distribution gives a visual picture of the screen analysis. The shape of the curve and the gradient of any straight lines on the graph indicate the relative uniformity of the grain size distribution in the sample.

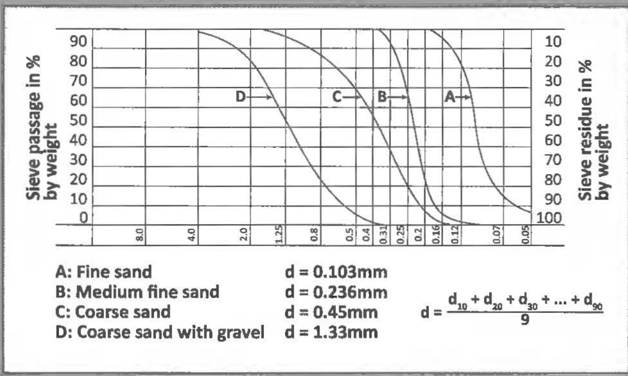
The mesh number, which is a common designation of sieves, is the number of wires per linear inch of sieve cloth. The 200-mesh sieve has a nominal aperture of 75µm and a nominal wire diameter of 52µm (**figure 2.13**). One well-known mesh series is the Tyler Equivalent (www.wstyler.com). Tyler mesh size indicates the number of openings or holes per square inch of mesh. A Tyler number 16 mesh for example, has 16 holes per square inch.

When calculating the size of the holes in a mesh, the thickness of the wires must first be taken into account, as this can cause significant differences in the particle size passing through screens. Thicker wire results in smaller holes, for example.

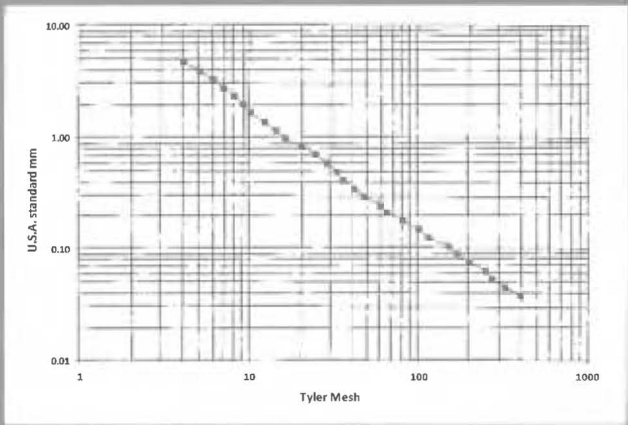
Sieving divides the sediment into volume frequency classes suitable for further analysis. This method measures a different characteristic of the particles than settling tube methods would. Instead, the latter measures the hydraulic properties of the particles. For very fine materials such as clay and silt, or when the grain size distribution of the material passing the Nr. 200 (74µm) sieve is of interest, the washing method may be used.

Pipette or hydrometer analysis is essential for finer silt and clay-sized particles. This type of analysis is performed if the grain sizes are too small for sieve analysis. In the hydrometer test, a dispersing agent is used in distilled or demineralised water. The basis for this test is Stoke's Law for falling spheres in a viscous fluid. A sample of approximately 50 grams is brought in suspension. After this, the density of the suspension is measured as a function of time. The percentage of soil remaining in suspension at the level at which the hydrometer is measuring the density can be calculated.

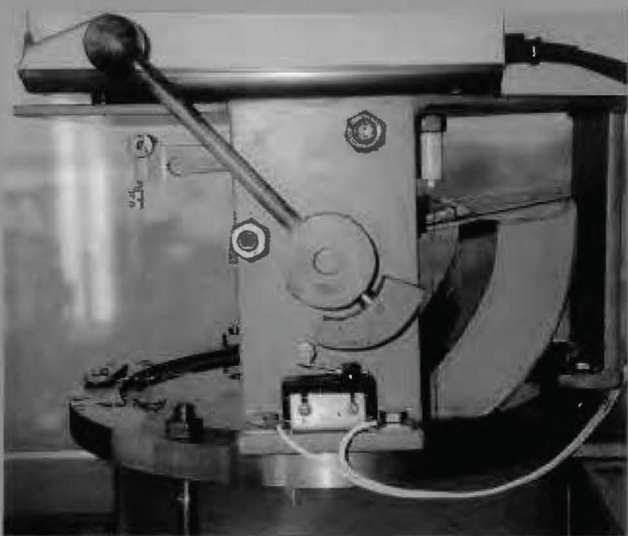
The diameter of a particle corresponding to the percentage indicated by a given hydrometer reading can be calculated according to Stoke's law. This is on the basis that a particle of this diameter was at the surface of the suspension at the beginning of sedimentation, and had settled to the level at which the hydrometer measured the density of the suspension. When the hydrometer analysis is concluded, a grain size distribution graph, such as **figure 2.12**, can be produced.



2.12 Grain size distributions



2.13 Comparison between Tyler Mesh and USA standard



2.14 Feeding mechanism of the sedimentation column

All standards for grain size distribution of sand and gravel samples are based on sieve analysis and this method is usually the most accurate for general analysis. However, one drawback of this process is that it can only be used for loose to weakly consolidated sediments. Soft sand grains such as fossils or meta-morphed rock fragments may be smashed on disaggregation. The size of unusually shaped or abnormal density grains cannot technically be recorded in hydraulic terms.

The method of dry sieving is time consuming, especially when wet samples have to be dried first. Sieving and weighing the individual fractions should be performed accurately to obtain a representative result. For laboratories and the aggregate industry, where quality control of the product is of great importance, the sieve analysis can be lengthy and expensive as well as tedious. The use of laboratory sieving machines has improved this slightly, but the results of the analysis usually take longer than an hour, during which time it would be possible to process a considerable amount of material.

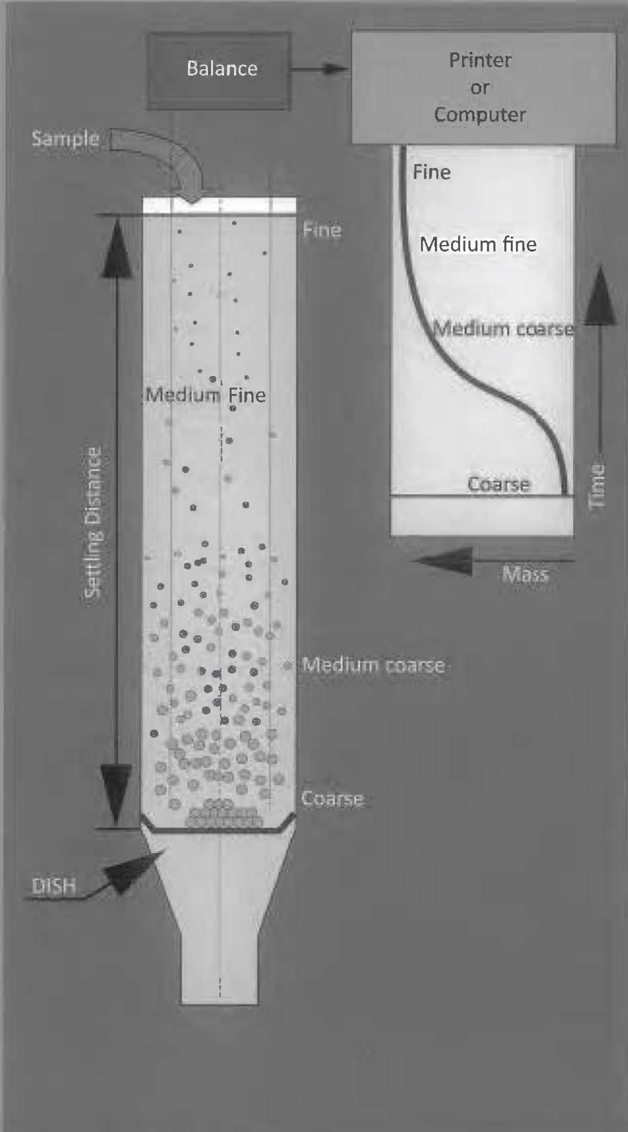
Alternative methods of analysis, such as the laser diffraction method, seem inappropriate for sand and gravel, because of the maximum limit of 1.25mm and the small volume of samples that can be processed.

Large sand particles settle quicker than small particles. Therefore, as long as the settling speed of a particle of a given size is known, an equivalent particle distribution can be found via a sedimentation test in a sedimentation column (**figure 2.15**).

At the top of the sedimentation column, just under the water level, is a small tray in which the sample is placed. By operating a feeding mechanism (**figure 2.14**) , the whole sample is tipped into the water and settles to the bottom of the column. At the bottom of the column is a small dish, which is connected to a weighing device. The weight of the sand deposited on the tray is measured as a function of time.

The settling velocity, which is also known as the terminal velocity, can be calculated by the length of the water column and the settling time. By comparing the settling speed of the unknown particles with the settling speed of particles whose diameters are known, the unknown particle size distribution can be found. For this reason, the settling speed/particle size ratio should first be calibrated with samples of known particle size distribution and grain form. This calibration is a simple process and is the basis for other analyses.

In **figure 2.16**, the relationship between settling velocity and diameter is given for Riversand, Meusesand, Biggelsand and



2.15 Sedimentation column with settling sand

Brekersand. The shape of the particles is important because it determines the friction of the particles, which is detailed in section 2.5. Non-spherical particles with small diameters have been observed to fall without changing orientation.
This means that the settling velocity for identical particles can vary between that of a fully broadside-oriented and a fully narrow side-oriented particle.

When a non-spherical particle falls in the turbulent drag region, it orientates itself into the position of greatest drag and then follows a sinuous path. Consequently, the settling velocity as a function of the grain size could vary for each location with its specific particle characteristics. **Figure 2.16** presents different settling velocities for spheres of glass, sub-angular sand such as Biggelsand, and angular sand such as Brekersand.

Through use of the sedimentation column, the measured diameters will differ from those measured with sieves.
In a sieve, the smallest dimension of a particle is determined. However, elongated particles will eventually pass a sieve if they have sufficient time. In the sedimentation column, the hydraulic diameter is measured and shape is expressed in the friction factor. This is an advantage for particles of unusual shape (plates or rods), density (heavies), or porosity (skeletal grains).

Sedimentation analysis is closer to a three-dimensional analysis, while sieving is only two-dimensional. When using the sedimentation column, particles are subject to three different laws, depending on their size (**figure 2.16**). For small particles (< 0.1mm), the viscosity is the main variable affecting the forces that act on a single particle settling in a fluid. The relationship between terminal settling velocity and grain size follows the formula of Stokes for laminar region:

$$w = 424 \cdot \left(\frac{\rho_s - \rho_w}{\rho_w} \right) \cdot d_s^2 \quad \text{mm/s } (d_s \text{ in mm})$$

For intermediate size particles (0.1-1mm), the terminal settling velocity follows the Budryck formula:

$$w = \frac{8.925}{d_s} \cdot \left(\sqrt{1 + 95 \cdot d_s^3 \cdot \left(\frac{\rho_s - \rho_w}{\rho_w} \right)} - 1 \right) \quad \text{mm/s } (d_s \text{ in mm})$$

The terminal velocity of coarse particles (>1mm), settling in the turbulent regime, follow the Rittinger formula:

$$w = 87 \cdot \sqrt{\left(\frac{\rho_s - \rho_w}{\rho_w} \right) \cdot d_s} \quad \text{mm/s } (d_s \text{ in mm})$$

The distribution curve is smooth, because it is derived from the constant data acquisition of the weight increase. This is more accurate than the sieve curves, where only the discrete points of the sieve diameters are known.

The settling velocity of an individual particle is influenced by the presence of other particles and decreases when concentration is greater. This hindered settling velocity is caused by the collision of particles and upward water flow in the space between particles, due to the settling of other particles.

This hindered settling strongly depends on the volumetric concentration of solids in the cloud. Equations for the calculation of hindered settling velocity are given in [19].
To prevent hindered settling in a sedimentation column, it is recommended to limit the sample to 100 grams.

The disadvantage of the sedimentation column is that its length is too short to test very coarse or high-density particles. It only takes a few seconds for them to reach the bottom, so accurate analysis is not possible.

There are various methods of dealing with different sized particles in hydraulic transportation systems. One method is to consider each size separately; another is to consider weighted mean values. For non-cohesive materials, most equations for the determination of the resistance in a pipeline are based on the decisive or mean grain diameter according to the Führböter formula:

$$d_m = \frac{d_{10} + d_{20} + d_{30} + \ldots d_{90}}{9} \quad \text{mm}$$

In the above equation, d_m is the arithmetic average of the grain diameters belonging to 10, 20 ...90% by weight on the sieve.

Another parameter, d_{50}, is the grain size diameter belonging to 50% by weight on the sieve. One half of all particles in a sample are larger than this diameter and one half of them smaller. This median grain size works well when a balanced grain distribution is encountered – the shape of the distribution curve above d_{50} is the mirror image of the curve below d_{50}. Soils with the same d_m or d_{50} can differ significantly in sorting and therefore, d_{50} as a soil parameter in isolation is not enough to characterise the soil. Some formulae also contain information about d_{85} or the ratio d_{10}/d_{90}.

Grain size is also used in the classification of materials. A general basis for the identification and classification of soils for dredging purposes is illustrated in table 2.1. A material with an average diameter of 0.055mm can be classified as coarse silt while a material with an average grain size of 0.7mm can be classified as coarse sand.

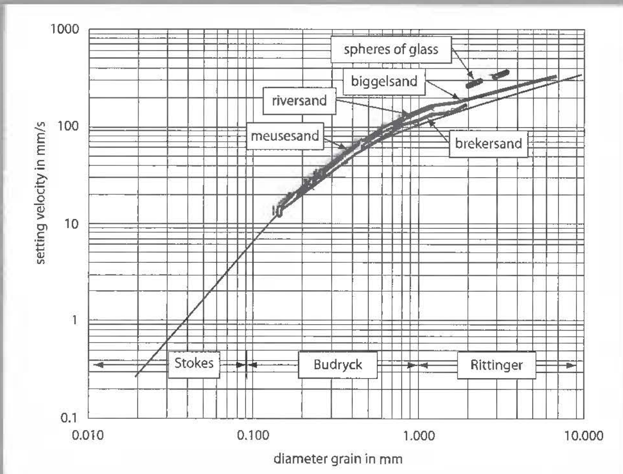
Materials that simultaneously contain silt, sand and gravel cannot be classified by the average grain size. For these materials, other classification systems have been developed.

Main type of soil		Particle size		
		Identification	mm	B.S.I. mesh
Boulders	Granular Non-cohesive		> 200	
Cobbles			200-60	(6)
Gravel		Coarse Medium Fine	60-20 20-6 6-2	3"- ¾" ¾"-¼" ¼"-No. 8
Sand		Coarse	2-0.6	8-25
		Medium	0.06-0.2	25-72
		Fine	0.2-0.06	72-200
Silt	Cohesive	Coarse	0.06-0.02	Passing Nr. 200
		Medium	0.02-0.006	
		Fine	0.006-0.002	
Clay			< 0.002	
Peat and organic soils	Organic	Generally identified by its black or brown colour. Often with strong organic smell and presence of fibrous or woody material. Firm or spongy in texture.		

Table 2.1: General identification and classification of soils for dredging purposes [3]

Grain size parameters can be listed with the use of a calculator or computer, without the need to draw a cumulative curve. However, this is risky and should only be done if an estimation is sufficient. Without drawing the curve, it is impossible to get an accurate "feeling of the data". It will be difficult to detect bimodality, or "shoulders" in the curves; experimental errors in weighing, including errors caused by faulty screens, for example; and genetic relationships that may occur through the actual inspection of the curves will be unnoticed.

N.B. The name sand does not automatically mean "quartz", although quartz is the most common type of sand.



2.16 Terminal velocity as function of the grain size for different sand types

2.5 Particle shape

Particle shape (**figure 2.18**) influences properties such as the flow ability of powders, packing of soil and interaction with fluids (settling velocity, critical velocity, abrasive wear and pipeline resistance). Although qualitative terms, including "angular" and "flaky", are provided in B.S. 2955, particle shape factors allow a quantitative assessment.

Figure 2.17 illustrates the classification of particle shapes according to Russell and Taylor. These researchers devised a comparative table detailing five classes of roundness, designated by the letters A to E, each of which subdivide into five grades, numbered one to five. Completing the table is, for each class, the designation of the shape, the degree of roundness expressed as a value, and a description of the particle shape class. The irregularities in the shape of the particles also play a part.

The best method of determining the shape factor of a grain is the measurement of its drag coefficient, compared to a spherical grain of the same weight. The deviation of a grain from a pure spherical shape causes a decrease in its settling velocity within a fluid.

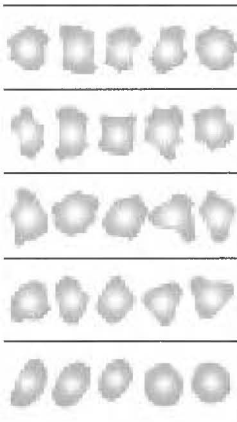
The shape factor is found by: SF = CD_{ball}/CD_{grain}

In the above formula, CD_{ball} is the drag coefficient of a sphere and CD_{grain} is the coefficient for an "angular" grain. The drag coefficient follows from:

$$w = \left(\frac{4}{3}\cdot g\cdot\frac{d_s}{C_D}\cdot\frac{\rho_s-\rho_w}{\rho_w}\right)^{0.5} \quad \text{mm/s}$$

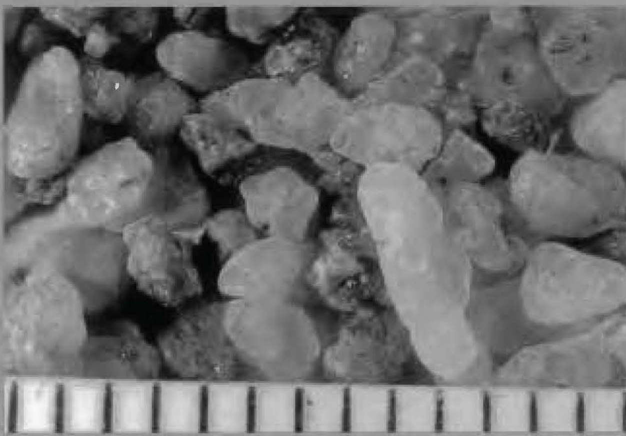
With a measured settling velocity (w [mm/s]), a known grain diameter (d_s), a known grain density (ρ_g) and a known density for water (ρ_w), it is possible to calculate the drag coefficient for a specific grain and to relate it to the known drag coefficient for a sphere with the same diameter. This allows for the calculation of the shape factor (SF) of the grain.

Figure 2.19 presents the results of tests [27] on angular Brekersand, sub-angular Biggelsand, Meusesand and Riversand. A sphere has a shape factor of 1. As could be expected for the same grain diameter, the shape factor for Brekersand is smaller than the shape factor for Biggelsand and the other kinds of sand. This results in increased wear in the pipeline and pump, as well as lower settling velocities. The shape also affects the settling velocity (**figure 2.16**) – the settling velocity of angular Brekersand is lower than for sub-angular Biggelsand.

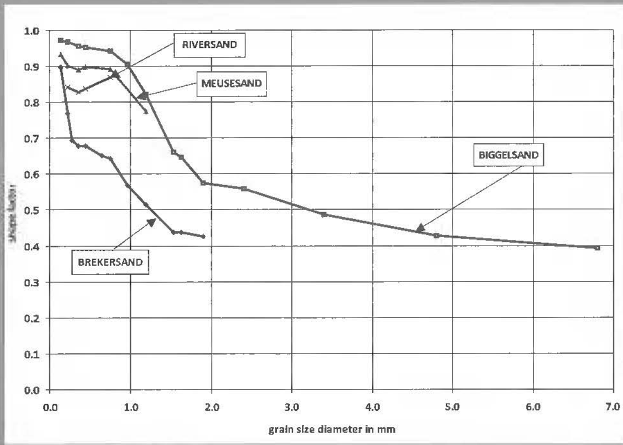


5 4 3 2 1	Names of classes	Degree of roundness	Description
	E Angular	0 - 0.15	Sharp corners sharply defined. Large embayments with numerous equally sharply defined embayments
	D sub-angular	0.15 - 0.25	Incipient rounding of corners. Large embayments preserved, small embayments smoother and less numerous
	C sub-rounded	0.25 - 0.40	Corners well rounded, large embayment weakly defined, small embayments few in number and gently rounded
	B rounded	0.40 - 0.60	Original corners are gently rounded, large embayments are only suggested, small embayments absent
	A well-rounded	0.60 - 1.00	Original corners and large embayments are no longer recognizable. Uniformly convex cutline (subordinate planar section possible)

2.17 Classification according to Rusell and Taylor



2.18 Grains of differing shape, size and mineralogical composition



2.19 Relationship between grain size and shape factor for different kinds of sand