SETTLING TUBE ANALYSIS OF SAND
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INTRODUCTION

For various reasons particle-size analysis of sediment is used in many fields of science and technology, a.o. earth sciences, agricultural and civil engineering. Relatively coarse-grained sediment like sand, with dimensions ranging from 0.06 till 2 mm, is analyzed almost exclusively by sieving. The size of particles in the silt and clay range (0.002 - 0.06 mm resp. smaller than 0.002 mm) commonly is derived from their settling velocity using Stokes' law; in this connection the important studies by Odén (1915, 1925) and Fisher/Odén (1924) are recalled.

Since the 1930's attempts have been made to remove this difference in analyzing technique by application of fall velocity analysis to sand-size sediment as well, using an empirical relation between size and fall velocity. A second and more important motive for the development of settling velocity analysis of sand is the surmise that the fall velocity of a particle might be a more fundamental property than its size as far as its behaviour in a stream is concerned. Hence, in studies on depositional environment of recent and ancient sediments settling velocity analysis is sometimes given preference to sieving (Reed et al., 1975; Emery, 1978). In this respect it is noted that in an alluvial stream the initiation of motion as well as the concentration distribution of suspended sediment with height are dependent on the ratio between shear velocity and fall velocity.

Thirdly, in some cases the amount of material available to sampling is very small, e.g. in flume experiments on selective transport and in studies on sedimentary structures (Emery, 1978; Grace et al., 1978). Unlike sieving settling velocity analysis permits -- and sometimes necessitates -- the use of small samples.

Fourthly, in settling velocity analysis the measurement process is continuous by nature. Therefore, more information is available than in the case of sieving, which is a discontinuous method. In addition, the application of a modern detection system and electronic data processing enables rapid analysis of a large number of samples in a short time.

This report does not deal with the problem of conversion of settling velocity to particle size when Stokes' law is no longer valid, but focusses on design aspects of settling tube systems, on some of the settling tubes developed in the past, and on a settling tube that recently has been developed at Delft University of Technology.
DESIGN ASPECTS OF SETTLING TUBES FOR SAND

In a properly functioning settling tube the actual fall velocity $w_a$ of a particle should closely correspond to its ideal fall velocity $w$, i.e. the velocity with which it would settle if no disturbing effects were present. These disturbances include (Fig. 1):
- effects of sample introduction,
- retarding effects because of proximity to the settling tube wall,
- concentration effects (hindered settling, settling convection).

*Fig. 1.* Ideal and actual settling velocity.

In fall velocity analysis of fine-grained sediment using water as sedimentation fluid, the initial condition consists of a uniform suspension (dispersed settling). Because of the relatively large fall velocity of quartz sand in water, ranging from 3 to 300 mm s$^{-1}$, the dispersed system of settling is not possible. The application of a sedimentation fluid with larger density and/or viscosity than water, attempted a.o. by Odén (1915) is not very practical; moreover, it is the settling velocity in water that usually is required. Therefore this discussion is limited to the
stratified settling system. In this case the particles start from a common level and become stratified according to their settling velocity (layer method).

The effect of sample introduction at the top of the settling tube can be minimized easily through the choice of a sample release method which ensures an evenly spread sample introduction and a minimum disturbance of the sedimentation fluid, e.g. a rotating disk (Plankeel, 1962) or a venetian blind device (Brezina, 1969) (Fig. 2).

![Diagram of sample introduction methods.](image)

**Fig. 2.** Sample introduction methods.

Due to the finite extent of the sedimentation fluid the drag on a falling particle is increased, causing a reduction of the settling velocity (Fig. 1). However, usually the wall effect is small in comparison with the effects of particle interference (concentration effects).

In Fig. 1 two kinds of concentration effects have been indicated, viz. hindered settling and settling convection. Hindered settling is the phenomenon that the settling velocity of a particle in an evenly distributed suspension is smaller than its ideal fall velocity, the decrease in fall velocity being due to the counterflow of the suspending fluid upward through the falling sediment. A recent discussion of the nature and the stability of hindered settling is given by Thacker/Lavelle (1977, 1978). The second concentration effect, called settling convection after Kuenen
(1968), occurs in a nonhomogeneous suspension. When certain particles are in close proximity to each other (clusters), they fall at a relatively large velocity (Stenhouse, 1967; Brezina, 1972). Both particle concentration and fluid viscosity will be relevant to the occurrence and the duration of existence of these faster falling clusters.

Assuming sediment concentration and fall velocity in the suspension to be continuous functions of time and position, Kranenburg/Geldof (1974) derived an estimating procedure for the magnitude of hindered settling and of settling convection when settling tube dimensions and sample volume are given. Application of this procedure to some existing settling tubes for stratified settling led to the conclusion that settling convection seems to be more severe than hindered settling. Experiments in a test model of a settling tube with samples of varying volume showed that settling convection is indeed the dominant concentration effect (Geldof, 1978).

Neither the settling tube volume nor the sample volume can be chosen at will. The length of the settling tube is confined to the available height, while both the length and the diameter are related to the detection method (see next chapter). Another constraint is due to sampling effects: a reduction of the sample volume results in increasing inaccuracy, especially of the fast tail of the settling velocity distribution. Moreover, it is important to minimize the amount of work involved in sample splitting.

The selection of the method by which the time of arrival of the falling particles at the bottom of the settling tube is detected, is related to both the settling tube dimensions and the sample characteristics. The selection procedure is dealt with in next chapter.
CHOICE OF DETECTION METHOD

Before considering the question how to select an appropriate detection method, some well-known methods are mentioned in brief (Fig. 3). These methods vary strongly as far as accuracy, cost and ease of operation are concerned.

Fig. 3. Detection methods.

**Volume**

In the volumetric method, which is the oldest and most simple one, the falling particles are collected in a so-called accumulation section with an inner diameter that is considerably smaller than the settling tube diameter and with a length which is not negligible compared with the settling
Fig. 4. Van Veen settling tube, a) dimensions, in mm, b) recording of accumulated sediment; after van Veen, 1936, Figs. 138 and 140.

tube length (van Veen, 1936; Emery, 1938; Colby/Christensen, 1956; Poole, 1957). The height of the top of the accumulated sediment is recorded visually (Fig. 4), often using optical and mechanical aids (Colby/Christensen, 1956) (Fig. 5).

To achieve sufficient resolution the diameter of the accumulation section is small. Colby/Christensen (1956) state that the best results are obtained when the total height of accumulation for one sample is between 25 and 100 mm; they advise a diameter of the accumulation section between 2 and 10 mm depending on particle size. Given this small diameter a contracting section with a length between 15 and 25% of the settling tube length is necessary.

The volumetric method has the attraction of simplicity; also it can be used in places where no electricity is available. However, the drawbacks of the method are often outweighing these advantages.

In the first place the design seems to include an inconsistency. A settling tube is intended to separate the particles physically according
to their ideal fall velocity. Directly after the sample introduction concentration effects cannot be avoided completely, therefore the length of the settling tube should be large enough to attain the required degree of dilution of the suspension over the major part of this length. In the contracting and accumulation sections the suspension is concentrated again, leading to the occurrence of concentration effects. Now the total length of these sections is not small in comparison with the settling tube length, consequently concentration effects cannot be neglected during a large part of the settling time causing deviations from the ideal fall velocity.

Secondly, the time that the arrival of a particle is detected is a function not only of its fall velocity, but also of the distribution of fall velocities occurring in the sample: the length of the particle trajectory may vary by 2 to 5% depending on the total height of accumulation of a sample. Similarly the particle trajectory length depends on the number of samples analyzed before the sediment is removed from the accumulation section. Both defects can only partly be compensated for by calibration (which should be attempted after it is made clear that an alternative method is
beyond reach).

Moreover, the visual detection method does not seem to be very suitable for the analysis of a large number of samples in a short time.

Weight

Since 1939 a settling tube similar to the one of van Veen (1936, 1937) is used in the sedimentpetrological laboratory of an oil company in Amsterdam. Soon after its introduction, however, the volumetric method of detection is replaced by a weighing method (Doeglas/Brezesinska Smithuysen, 1941; Doeglas, 1946). The apparent weight of the sediment particles accumulated on a balance pan at the bottom of the settling tube is recorded as a function of time (Fig. 3). Like in the apparatus used by Odén (1915) for fall velocity analysis of fine-grained sediment, the balance pan is suspended by a wire connected to a balance near the top of the settling tube. As the pan diameter is nearly equal to the settling tube diameter, which usually varies between 0.1 and 0.2 m, a considerable mass of water is moving with the pan (Rietdijk, 1974). This is highly relevant to the delay time of the weighing method.

Various ways of weight detection have been used (Fig. 6). The balance method is applied by Doeglas/Brezesinska Smithuysen (1941), Doeglas (1946), Plankeel (1962), Bienek et al. (1965), Sengupta/Veenstra (1968), Gibbs (1972). The sediment weight on the pan can also be measured by means of strain gauges on the beam from which the pan is suspended (van Andel, 1964; Felix, 1969; Gibbs, 1974; Flemming, 1976; Thiede et al., 1976). Brezina (1972) applies an underwater balance in which the pan is supported by leaf springs and the movement of the pan is measured by inductive displacement transducers. A similar way of pan suspension and of detection of pan movement is applied in a settling tube developed (independently from Brezina's design) at Delft University (Rietdijk, 1974; Slot, 1977; Geldof, 1978); however, in other respects this settling tube, which will be discussed in detail in next chapters, differs significantly from the instrument of Brezina (1972).

Weight detection by an underwater balance has the advantage of avoiding the use of suspending wire(s), which vibrate when large particles strike the pan and which are subject to surface tension at the air–water interface. Moreover, unlike weight detection by strain gauges, the application of an underwater balance as described, does not involve interaction between the sensing
element and the pan suspension.

\[
\begin{align*}
\text{(electro-) balance} & \quad \text{strain gauge} \\
\text{wire} & \quad \text{leaf spring} \\
\text{pan} & \quad \text{inductive displacement transducer} \\
\text{magnet & coil}
\end{align*}
\]

(Brezina, 1972) (DUST)

**Fig. 6.** Weight detection methods.

**Differential Pressure**

A suspension of particles in a settling tube causes a hydraulic head at a certain level that differs from the head in the case of clear water by

\[
\frac{V}{A} + \frac{V_s}{A} \Delta
\]

in which \( V \) = total volume of particles in the sample,

\( V_s \) = total volume of particles that are present above the level of measurement,

\( A \) = area of the settling tube cross-section,
\[ \Delta = \frac{(\rho_s - \rho_f)}{\rho_f} = \text{relative apparent density of particles.} \]

The first term allows for the addition of volume and is a constant. The second term, which reflects the contribution of sediment density, is a function of time as \( V_s = V_s(t) \). When the fastest settling particle of a sample is still above the level of measurement then \( V_s = V \). Thereafter \( V_s \) gradually decreases to zero according to the fall velocity distribution of the sample.

Theoretically it is also possible to derive the average density of the sediment particles from the ratio between the values of differential pressure at the moments that \( V_s = V \) and \( V_s = 0 \).

The measurement of differential pressure was introduced by Wiegner (1918) in the case of dispersed settling of silt and clay particles. Zeigler et al. (1960) applied this detection method for the first time to the stratified settling of sand-size sediment, on the basis of earlier, unpublished work by Appel (1953). Afterwards the same method was used by Schlee (1966), Brezina (1969), Channon (1971), Sanford/Swift (1971), Nelsen (1976).

In order to have an acceptable value of the error due to drift, the differential pressure method requires a relatively large sample size, which often leads to a conflict with the demand for low values of sediment concentration in the settling tube.

For a given sample volume the differential pressure method requires a maximum admissible drift that is significantly smaller than in the case of weighing, the ratio between the admissible drift values being equal to the area \( A \) of the settling tube cross-section. This may counterbalance the relatively complicated mechanical construction involved in the weighing method by means of an underwater balance.

Both the differential pressure method and the weighing method are applied presuming negligible dynamic effects. Brezina (1969) presents a diagram for the correction of particle impact in the case of weighing (however, without details on its derivation and its accuracy); for the differential pressure method the magnitude of dynamic effects has not been studied apparently.

In an appendix to this report the result is given of an attempt to estimate the dynamic effect for the weighing method.
Photo-extinction

Just as in the case of the differential pressure method, the measurement of the arrival of particles at the bottom of the settling tube by means of interruption of a light beam was used at first for particles in the silt and clay range. Recent studies concerning this method are given a.o. by Jordan et al. (1971), Allen (1972). As far as known to the authors only one paper deals with the application of this method to the analysis of sand-size sediment (Taira/Scholle, 1977).

In comparison with the other detection methods mentioned above, the optical method is very sensitive; it does not interfere with the settling particles and its delay time can be neglected. Its good sensitivity allows the analysis of very small samples, thereby reducing concentration effects in the settling tube. However, because of increasing sampling effects and the labour involved in sample splitting, this advantage will not always be utilized completely.

The optical method of detection requires a frequent change of the sedimentation fluid. According to Taira/Scholle (1977) the continuous analysis of more than 10 samples of mud-free sediment is possible before the sedimentation fluid has to be replaced; still this compares unfavourably with the other detection methods.

The photo-extinction method is the only one yielding information in terms of projected area (\(\propto d^2\)) of the particles, whereas the other methods yield information based on particle volume (\(\propto d^3\)).

Selection procedure

Figure 7 shows schematically the procedure that may be followed in order to arrive at appropriate dimensions of the settling tube proper and to find quantitative criteria for the selection of a detection method.

Starting points are
- the properties of the sediment particles and the sedimentation fluid, in particular the range of ideal fall velocities, the apparent density of the sediment and the size of the smallest particle to be analyzed,
- the range of sample volume,
- a criterion to limit concentration effects on the settling velocity to a prescribed level,
- the available height in the room where the settling tube is to be
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**SAMPLE VOLUME RANGE**

- Volume range: $V_{\text{min}}$ to $V_{\text{max}}$

**CONCENTRATION EFFECTS**

- Volume ratio: $c_1 = \frac{4 V_{\text{max}}}{\pi D^2 L}$

**AVAILABLE HEIGHT**

- Max. length of settling tube: $L$

**DISTURBANCES:**

- Mechanical,
- Electrical

**Schematic Design Procedure:**

- Max. drift: $(\rho_s - \rho_f) V_{\text{min}} w_{\text{min}} f_2$
- Max. delay time: $L \frac{f_1}{w_{\text{max}}}$
- Resolution

*Fig. 7.* Scheme of design procedure.
installed,
- the magnitude of mechanical and electrical disturbances.

The maximum length of the settling tube is given by the available net height. The diameter of the settling tube is derived by combination of the criterion for concentration effects with the settling tube length and the maximum sample volume. It is assumed that a high quality sample introduction system is applied, otherwise the criterion for concentration effects should be made more severe.

When the dimensions of the settling tube proper are known, the requirements to the detection system can be specified. Three aspects are taken into account:
- the delay time, which should be smaller than a certain fraction \( f_1 \) of the time of settling of the particle with the largest fall velocity;
- the drift, which should be smaller than a certain fraction \( f_2 \) of the minimum value of the apparent sample mass during the time of settling of the particle with the smallest fall velocity;
- the resolution: as the detection systems are differing in their sensitivity to mechanical and electrical disturbances, a comparison of the desired resolution (a certain fraction \( f_3 \) of the apparent mass of the smallest sample) with the magnitude of these disturbances may lead to a preference for (or a rejection of) one of the available detection methods.

It is noted that the delay time requirement is based on the assumption of an ideal settling process (i.e. \( w = \omega \)) along the whole length of the settling tube. In fact this assumption is not true. Apart from the concentration effect, which is accounted for in the choice of the volume ratio \( c_1 \), several other phenomena occurring at the upper and lower end of the settling tube have to be considered.

In the first place it takes time for a particle to adjust its velocity \( w_a \) from its initial value zero to its ideal value \( w \). The order of magnitude of the adjustment time is estimated by \( \omega/g \); for \( \omega = 300 \text{ mm s}^{-1} \) this yields an adjustment time of circa \( 3 \times 10^{-2} \) s. A correction of the ideal settling time based upon this velocity adjustment will probably not be accurate enough, because the introduction of a sample causes a disturbance of the sedimentation fluid. Hitherto this effect on \( w_a \), which will vary with the type of introduction method, is unknown.
Secondly, the application of detection by weight and by differential pressure implies the assumption of a static condition. As mentioned before, this is not realistic. From the appendix to this report it appears that in the weighing method the effect of particle impact on a pan may compensate — at least partly — the delay time of a critically damped weighing system. Because the magnitude of the sample introduction effect is unknown and the expression for the dynamic effect is not verified as yet, the assumption of an ideal settling process is maintained.

In a particular case the application of the procedure shown in Fig. 7, will not result in one and only one solution; it just points toward the close relation between various properties of the sediment, the settling tube and the detection method.

Obviously, the final choice of settling tube type also depends on other factors like suitability for routine analysis (type of work by operator, nature of signal), requirements on operating conditions (temperature, electricity), and costs.

Table 1 summarizes in a qualitative way the strong and weak points of the various settling tube types. Referring to this table it is noted that

- a settling tube of the volumetric type scores low in all respects except requirements on operating facilities and except costs;
- a settling tube of the differential pressure type scores relatively low with respect to either drift or concentration effects (sample volume); furthermore it requires special precautions to eliminate temperature effects on the detection system;
- settling tubes using weight detection or photo-extinction score almost equal with respect to instrumentation aspects; the latter is not influenced by mechanical disturbances, but seems less suitable for routine analysis as it requires frequent change of the sedimentation fluid.
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Table 1. Qualitative comparison between settling tube types.
DELFT UNIVERSITY SETTLING TUBE (DUST)

Thus far the design of a settling tube for sand-size sediment has been dealt with in a qualitative way only. In this chapter details are given of the development of a settling tube at Delft University by co-operation between the Departments of Civil Engineering and of Mechanical Engineering. This development has started with a specification of the requirements which the instrument should meet.

First of all the relevant properties of sediment and sedimentation fluid are given. Usually the sediment samples are derived from model or field investigations concerning sedimentological and morphological phenomena caused by the flow of water; samples from industrial processes are not taken into account. Therefore the particle density is practically equal to the density of quartz (2650 kg m\(^{-3}\)). The particle dimensions vary between 0.06 and 2 mm. Water is chosen as sedimentation fluid, as it directly yields the relevant settling velocity. Then the apparent density amounts to circa 1650 kg m\(^{-3}\), while the fall velocity varies between 3 and 300 mm s\(^{-1}\).

**Test model**

Taking into account the extra height that is needed for the sample introduction device and the detection system, the available height has led to the choice of 2 m for the effective settling tube length.

Assuming a maximum sample mass of 5 gram, the maximum sample volume equals approximately 1.9 ml. In order to have an error due to settling convection smaller than 5 %, the ratio between sample volume and tube volume, \(c_1\), should be smaller than \(10^{-4}\) (Kranenburg/Geldof, 1974, Fig. 5). This value has been derived for samples in which the ideal fall velocity \(w\) varies between \(w_{\text{max}}\) and zero. As will be shown later, however, this ratio is not a constant but varies with particle size.

Application of this criterion yields a settling tube diameter of 0.11 m. These dimensions of the settling tube are within the range of values reported in the literature.

Assuming a minimum sample mass of 0.5 gram, the minimum sample volume and the minimum apparent sample mass amount to 0.19 ml resp. 0.31 gram. Requiring a resolution of 1 % it follows that the minimum apparent mass that the settling tube should be able to detect, is approximately 3 mg. It also follows that the drift of the detection system has to be smaller than 3 mg.
during the settling time of the particle with the smallest fall velocity. When \( w_{\text{min}} = 3 \text{ mm s}^{-1} \) and \( L = 2 \text{ m} \), then the maximum admissible drift expressed as apparent mass per unit time, equals \( 4.7 \times 10^{-3} \text{ mg s}^{-1} \).

Finally the delay time of the detection system has to be shorter than \( 1\% \) of the time of settling of the particles with the largest fall velocity, viz. circa \( 7 \times 10^{-2} \text{ s} \).

Considering both these specifications and the suitability for routine analysis, the possibility of applying the volumetric method of detection is put aside.

Measurements using the differential pressure method have shown that the drift of this detection method prevents its application; moreover, these measurements indicate the occurrence of dynamic effects, especially when coarse-grained sediment is analysed (Geldof, 1978).

Furthermore, as it is doubtful that a weighing method using a pan suspended by wires has a delay time conforming to the required value, weighing by means of strain gauges or by an electrobalance at the top of the settling tube is discarded. In this connection it is noted that the delay time is depending on the natural frequency of the system, which is a function of a.o. the effective mass; in the case of a flat pan with a diameter of 0.12 m, the order of magnitude of the effective mass amounts 1 kg (see also Mavis, 1970). Therefore it has been decided to apply an underwater balance (at the time that this decision has been made the application of photometric extinction to the analysis of coarse-grained sediment was not known; however, in view of the need to change the sedimentation fluid frequently this detection method probably would have been considered as the next best).

Preliminary measurements on a test version of an underwater balance confirmed the viability of the detection method (Rietdijk, 1974; Slot, 1977).

Figure 8 shows a scheme of the measuring system adopted. The displacement of the weighing pan is proportional to the mass of sand on the pan; it is measured by two inductive transducers which form a part of a Wheatstone bridge. Therefore the amplified signal from this bridge is a measure of the mass of sand accumulated on the pan.

In order to obtain a weighing system with low drift, good linearity and a good response (critically damped: no overshoot), the system includes a feedback loop in which a part of the output signal is subtracted from the input by means of a coil and magnet. This feedback loop consists of a proportional part and a differentiating part (PD-circuit). The first part is intended to reduce the drift and to improve the linearity, while the second
Fig. 8. Measuring system of DUST.
part is used to obtain a critically damped system.

By application of an electrical test signal the magnet and coil combination can be used to adjust and to check the weighing system.

Moreover, the magnet and coil are used to tare the balance. When taring is no longer possible, the pan is cleaned by rotation of the whole underwater balance.

From the test measurements it also turned out that provisions had to be taken to reduce the influence of vibrations caused by pumps and by traffic. This reduction is accomplished by mounting the settling tube on a large concrete block (with a mass of approximately 1400 kg), supported by air springs and damped by a viscous fluid (glycerine). Obviously these provisions are superfluous in buildings in which no important mechanical disturbances are present.

Subsequent measurements with regard to concentration effects, using samples of sieved quartz sand, have shown (Geldof, 1978) that (Fig. 9)

- the error due to concentration effects indeed depends on the sample size as well as on the particle diameter (see also Gibbs, 1972),
- for particles with a diameter between 0.125 and 0.150 mm the concentration effect is not exceeding 5% if \( c_1 \), the ratio between sample volume and settling tube volume is smaller than 5 \( 10^{-6} \),
- for particles with a diameter between 0.25 and 0.30 mm the same applies if \( c_1 \) is smaller than 2 \( 10^{-5} \),
- for particles with a diameter between 0.71 and 0.85 mm the concentration effect is only small, it does not exceed 1% if \( c_1 \) is smaller than 8 \( 10^{-5} \),
- for particles with a diameter between 1.4 and 1.7 mm the concentration effect is practically absent when \( c_1 \) is smaller than 2.5 \( 10^{-4} \) (larger values of the ratio have not been investigated).

The range of ideal fall velocities occurring in these samples is rather limited, the ratio of minimum to maximum fall velocity varying between 0.75 and 0.81 depending on the sieve interval. Therefore the results of the measurements cannot be compared directly with the estimated concentration effect (smaller than 5% when \( c_1 \) is not exceeding \( 10^{-4} \)).

However, the estimating procedure can be modified in order to be applicable to the case of the measurements. It can be shown that the concentration effect for samples with \( w_{\min} > 0 \) equals the concentration effect for samples with the same value of \( w_{\min} \) but with \( w_{\max} = 0 \), when the volume ratio as found by the estimating procedure for the latter case, is multiplied by the factor \( (w_{\max} - w_{\min})/w_{\max} \) (C. Kranenburg, personal communication).
Hence, when considering a concentration effect of 5%, the experimental \( c_1 \) values have to be compared with 0.19 to 0.25 times the \( c_1 \) value of \( 10^{-4} \) found in the estimating procedure, yielding \( 2 \times 10^{-5} \).

Now the estimating procedure is rather tentative; it ignores the influence of particle size on the magnitude of the concentration effect. Therefore it is not surprising that it does not yield accurate results for most particle sizes. By coincidence the estimated \( c_1 \) value corresponds almost exactly with the measured value for particles of 0.25 to 0.30 mm. For the finer particles (0.125 - 0.150 mm) a concentration effect of 5% occurs when \( c_1 \) is 4 times smaller than its estimated value, while the estimated value is too small for particles with a diameter larger than 0.71 mm.
The result for the finer particles is one of the reasons to choose larger settling tube dimensions for the routine model.

Finally it is noticed that the results of these measurements are relating to the mean value of the median fall velocity for a series of observations with a given sample size. The coefficient of variation of the median fall velocity values never exceeded 2%; in many series it was even smaller than 1%. Thus the reproducibility of the settling process of sieved samples seems good as far as their median settling velocity is concerned. It must be subjoined, however, that the reproducibility of the second and higher moments of the settling velocity distribution probably will not be equally good. This aspect has not been investigated as yet.

**Routine model**

Although the same sample introduction method and the same detection method is applied, the routine model of DUST differs significantly from the test model in various respects.

The aforementioned provisions for reduction of vibrations diminish the available height by circa 0.5 m. Therefore the effective length of the settling tube of the routine model is given a value of 1.66 m. Because of the reduction in settling tube length and because of the large concentration effects on the fall velocity of fine particles, the settling tube diameter is augmented to 0.175 m. Hence the settling tube volume, which amounts $1.92 \times 10^{-2}$ m$^3$ in the test model, is increased to $3.99 \times 10^{-2}$ m$^3$ in the routine model.

This modification of the settling tube dimensions brings in its train that the underwater balance has to meet more severe requirements (Fig. 7). Because of the larger diameter of the balance pan (0.185 m) the added mass of water moving with the pan is also increased. At the same time the decreased settling tube length results in a shorter delay time requirement, viz. $5.5 \times 10^{-2}$ s. On the other hand, the shorter settling tube length allows a larger value of the drift criterion, viz. $5.7 \times 10^{-3}$ mg s$^{-1}$.

These specifications are indeed met by the underwater balance of the routine model of DUST (Fig. 10). The sample introduction device, which is of the venetian blind type, is shown in Fig. 11.

At the moment that this report is prepared, a series of measurements on the magnitude of concentration effects is started.
Fig. 10. DUST underwater balance.

Fig. 11. Sample introduction device.
CONCLUSIONS

1. The specifications of the detection method applied in a settling tube are closely related to the characteristics of the sediment, the sedimentation fluid and the settling tube dimensions.

2. An underwater balance as applied in DUST is sufficiently accurate for fall velocity analysis of both fine and coarse sand.

3. Measurements in the test model of DUST have confirmed that the error due to settling convection is depending on particle size. For particles smaller than 0.2 mm the maximum value of the ratio between sample volume and settling tube volume, as estimated by the procedure of Kranenburg/Geldof (1974) is too large.

4. The reproducibility of the median fall velocity of samples of sieved sand, analyzed in the test model, is better than 2%.

5. Given a certain error in the measurement of the time of arrival of the particles at the level of measurement and given the maximum fall velocity in the samples to be analyzed, it can be shown that an optimum value of the delay time of the weighing system exists. The magnitude of the dynamic effect of the settling particles on the weighing system needs further study.

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APPENDIX

**Effect of particle impact on the accuracy of the weighing system**

Assuming that the time of arrival of the particles is Poisson distributed with constant intensity, it can be shown (Slot, 1977) that the mean of the total delay time $\gamma_t$ of the output signal, compared to the ideal output signal (the output signal when $\gamma = 0$), is given by

$$\gamma_t = \gamma_o - \frac{w}{g}$$

in which $\gamma_o = \frac{2}{\omega_o}$ = delay time of the critically damped weighing system,

$\frac{w}{g} = \omega_o$ contribution of the impulse of the particles to the total delay time,

$w$ = fall velocity,

$g$ = acceleration of gravity,

$\omega_o$ = natural frequency of the weighing system.

Equation 1 shows that the impulse of the particles reduces the total delay time for increasing $w$ until $w = g \gamma_o$. For $w > g \gamma_o$ the total delay time becomes negative, i.e. the output signal will lead the ideal output signal. The error due to the delay time has to be small compared to the total settling time, i.e. it should not exceed a certain fraction $f_1$ of $L/w$, thus

$$|\gamma_o - \frac{w}{g}| \leq f_1 \frac{L}{w}$$

in which $L$ = settling tube length.

Equation 2 can be split in two parts,

for $w < g \gamma_o$: $$\gamma_o \leq \frac{w}{g} + f_1 \frac{L}{w} = \gamma_1$$

for $w > g \gamma_o$: $$\gamma_o \geq \frac{w}{g} - f_1 \frac{L}{w} = \gamma_2$$

From eqs. 3a and 3b it follows (see also Fig. 12) that the maximum fall velocity range for which $\gamma_2 < \gamma_o < \gamma_1$, occurs when

$$\gamma_o = 2 \sqrt{f_1 \frac{L}{g}}$$

i.e. a value of $\gamma_o$ which equals the minimum of curve $\gamma_1$ at $w = \sqrt{f_1 \frac{L}{g}}$.

The maximum value of $w$ is given by curve $\gamma_2$, viz.

$$\bar{w} = (\sqrt{2} + 1) \sqrt{f_1 \frac{L}{g}}$$
If $w_{\text{max}}$, the maximum fall velocity occurring in the samples to be analyzed, is smaller than $\sqrt{f_1 L/g}$, then $\gamma_o$ may be given a larger value than according to eq. 4, viz.

$$\gamma_o = \frac{w_{\text{max}}}{g} + f_1 \frac{L}{w_{\text{max}}}$$  \hspace{1cm} (6)
REFERENCES


Doeglas, D. J./Brezesinska Smithuysen, W. C., De interpretatie van de resultaten van korrelgrootte-analysen; Geol. en Mijnbouw, jrg. 3, 1941, no. 8, p. 273 - 285 and no. 12, p. 291 - 302.


Flemming, B. W., Construction and calibration of an automatically recording settling tube system for the hydraulic grain size analysis of sands; Univ. of Cape Town, Dept. of Geology, Techn. Report No. 8, 1976, p. 47 - 59.


Veen, J. van, Het bezinkingstoestel; Polytechnisch Weekblad, jrg. 31, no. 3, 1937, p. 131 - 133.

Wiegner, C., Uber eine neue Methode der Schlammanalyse; Die Landwirtschaftlichen Versuchs-Stationen, Band 91, 1918, p. 41 - 79.
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LIST OF SYMBOLS

A  area of cross-section of settling tube, m$^2$
$c_1$  ratio between sample volume and settling tube volume
d  particle diameter, mm or m
D  inner diameter of settling tube, mm or m
$f_1, f_2, f_3$  constants
g  acceleration of gravity, $9.81\ldots$ m s$^{-2}$
I  light intensity, cd
L  effective length of settling tube, mm or m
PD  proportional amplifier and differentiator
t  time, s
V  total volume of particles in sample, ml or m$^3$
$V_s$  total volume of particles in suspension above level of measurement, ml or m$^3$
w  ideal fall velocity, mm s$^{-1}$ or m s$^{-1}$
w$_a$  actual fall velocity, mm s$^{-1}$ or m s$^{-1}$
$\bar{w}$  maximum fall velocity for which $w_2 \leq w_0 \leq w_1$, mm s$^{-1}$ or m s$^{-1}$
W  weight, N
z  bed level, mm or m
$\max$  maximum value
$\min$  minimum value
$\gamma_0$  delay time of critically damped weighing system, s
$\gamma_t$  total delay time (effect of particle impact included), s
$\gamma_1, \gamma_2$  upper resp. lower boundary of $\gamma_0$, s
$\Delta$  $(\rho_s - \rho_f)/\rho_f$, relative apparent density of sediment
$\Delta p$  pressure difference, N m$^{-2}$
$\Theta$  temperature of sedimentation fluid, °C
$\pi$  $3,14\ldots$
$\rho_f$  density of sedimentation fluid, kg m$^{-3}$
$\rho_s$  density of sediment particles, kg m$^{-3}$
$\omega_0$  natural frequency, rad s$^{-1}$