Production Measurement Methods for Trailing Suction Hopper Dredgers

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PRODUCTION MEASUREMENT METHODS FOR TRAILING SUCTION HOPPER DREDGERS

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FOREWORD

This is a report of the project "Production measurement methods for trailing suction hopper dredgers" which was the final assignment of a course leading to a degree in Civil Engineering from the Delft University of Technology.

In this report several methods of measuring the production of trailing suction hopper dredgers are evaluated and recommendations for the improvement of the Tonnes Dry Solids System are included.

This project was commissioned by the Dredging Division of Rijkswaterstaat (Dutch Ministry of Transport and Public Works) in Hoek van Holland.

In this connection I should like to thank ing G. van der Lee and J van Tuyl of Rijkswaterstaat and ing C. Kramers, of IHC Systems, for their help and support in completing this project.

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- difference between polynomial and carène-diagram
- North sea climate observations
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- list of references
Because there may be some confusion about the definitions of specific density and of in-situ density, the definitions used in this report are given below.

**specific density:**

Dredged material consists of water and particles. The density of a dry particle in this mixture is called the specific density. The specific density of the particle is dictated by the chemical composition of the particle.

**in-situ density:**

The density of the material in the bottom profile is called the in-situ density. This density is dictated by:
- the percentage volume of particles in a specific volume of bottom material
- the specific density of the particles
- the volume percentage of the water in this specific volume and the density of this water.

A third definition used in this report is listed below:

The loading trim is the extra inclination of the surface of the load which is caused by the flowing behaviour of the incoming mixture.
1. INTRODUCTION

The establishment of production rates is of great importance in modern dredging practice.

When trailing suction hopper dredgers are employed, three methods of production measurement are commonly used. These are:

- in-situ measurement
- measurement in the pipeline
- measurement in the means of transport

The method chosen by the client should depend upon the local circumstances, the nature of the supervision and the accuracy required. This report is intended to provide a guide to the selection of the most appropriate method for particular conditions.

When the project started it was already clear that the Tonnes Dry Solids (TDS) System measured production-data more accurately than the other methods described, so most attention was paid to the TDS system, especially to the establishment of the accuracy of measurements of this system. This resulted in recommendations for further improvement of the system.

The accuracy is established by making a probabilistic calculation, after which the TDSS is assessed in comparison with the other measurement methods under consideration.

Chapter three gives the project description and objectives, while in chapters five, six and seven each of the previously mentioned methods of measuring is described and assessed with the criteria described in chapter four. In the sub-sections of Chapter Seven, several methods which may be used for measurement in the means of transport are considered.
2. SUMMARY

When trailing suction hopper dredgers are employed, three methods of production measurement are commonly used. These are:

- in-situ measurement
- measurement in the pipeline
- measurement in the means of transport

Before a choice can be made, the advantages and disadvantages of the methods of production measurement have to be assessed in relation to specific site conditions. In this report the advantages and disadvantages of several possible methods of measuring production when working with trailing suction hopper dredgers are evaluated.

To establish the accuracy of the Tonnes Dry Solids System - a modern measurement method which measures in the means of conveyance - a probabilistic accuracy calculation was made.

From this study the following conclusions can be drawn:

In-situ measurement

Measuring in-situ is a widely used method that is based on the measurement of bottom levels before and after dredging and known as in-survey and out-survey respectively. Formerly bottom levels were established by using a sounding pole or wire with a suitable weight attached to it, in conjunction with a reference level. The method was not only time consuming, but also had the disadvantage that measurements were carried out only at single points.

Currently the use of echosounding equipment is generally accepted for depth determination. While sailing along predetermined sounding-lines continuous depth-information can be collected, while fully automated data collection (tidal level, position) and the incorporation of this into sounding charts is also possible. In practice, an accuracy of 0.20 - 0.30 metres in depth determination is assumed for both the in survey and the out survey, therefore a reasonable degree of accuracy can be achieved only when amounts of material eroded or deposited during dredging or before the out survey are small in comparison to the thickness of the layer to be removed.

In-situ measurement is only suitable if the change in depth due to erosion or sedimentation is small in relation to the dredged volume. In areas with heavy erosion, heavy siltation, and/or shipping which uses maximum navigational depth (thus causing turbidity clouds), there are differences between the quantity of material actually dredged and the quantity for which payment should be due according to survey results. Such differences arise when dredging sand or gravel and are very much greater when dredging silt. Although the in-situ measurement method is not suitable for payment in such circumstances, soundings must still be used to monitor and control the progress of dredging works.
Measurement in the pipeline

Another way to establish dredged quantities is to measure the concentration and velocity of the mixture in the pipeline. This is done on the delivery-side of the dredge-pump, which is the only place presenting enough room to install both measuring instruments on trailing suction hopper dredgers. The density of the mixture is measured by means of a radioactive probe situated in a special casing and placed in the pipe, while the velocity of the mixture is measured by means of an electromagnetic velocity meter, installed in the pipe-line.

To measure in an overland pipeline an inverted U-tube may be installed and this provides more accurate measurements. In practice, it has been shown that in ideal conditions an accuracy of 2% - 3% can be obtained. However, owing to lack of space, it is impossible to install an inverted U-tube on board of trailing suction hopper dredgers, so other configurations of the density and velocity measuring equipment that are less accurate have to be used.

When measuring the production on board of the trailing dredger two problems occur:

1. how to measure the in-situ density of the dredged material in order to establish the density of the mixture in the pipe line
2. how to measure the overflow-losses.

When the overflow is used to optimize the loading of the dredger, the measurements do not provide an accurate indication of the amount of material which has been dredged. Because of the large dimensions of the overflow, the losses cannot be measured accurately and furthermore, it would not be safe to use a radioactive source of the strength required. Therefore, if the overflow system is used to optimize the load of the hopper, the measurement of density and velocity in the pipeline only gives relative information about quantity and quality of the material dredged and is totally unsuitable to establish hopper production.

If calibration is frequent and the vessel is loaded only up to the level of the overflow in the hopper the method may be used to measure dredged quantities for payment.

Measurement in means of conveyance

Three different methods of measuring in the means of conveyance are evaluated:

- The half-sphere method
- The hopper pressure measurement method
- The Tonnes Dry Solids System

It is obvious that payment should only be made for material dredged from the designated dredging area down to the target depth and within the tolerances of the dredging equipment.
The half sphere method

Over the last thirty years the 'half sphere' method has often been used to measure "payable quantities" of dredged material i.e. quantities on which payment will be based. This method is based upon measurement of the volume of dredged material in the hopper. When the suspended material has settled, soundings are made at a number of predetermined locations from a predetermined reference level. A semi-spherical lead, which has a specific weight such that it will stop sinking at a level where the density of the mixture is equal to or higher than 1200 kilogrammes per cubic metre, is used.

The volume of the settled part of the load can be determined from the hopper content table of the dredger in question. Samples are taken from the liquid layer that is above the settled part and, after consolidation by means of a centrifuge or consolidation cylinders, the amount of sediment, as a percentage of the volume of the total sample, is added to the quantity previously measured by the half sphere.
The method has several advantages:

- construction is simple
- it can be made operational quickly
- it is maintenance free
- it is inexpensive
- the measurements are rather accurate

This method also has disadvantages:

- there is no remuneration for increasing the density of the load to a density over 1200 kg/m³.
- what the measured volume actually represents is not known.
- the results are not immediately available on board because the samples have to consolidate, so optimization of the load is difficult to achieve.
- the results are affected by human influence

Overall, it may be concluded that the half sphere method measures volume accurately and independently of the dredger used, thus the production of dredgers may be compared. Therefore the method is satisfactory for production measurements, but when more sophisticated technology is available the use of a different method is preferable.

Hopper-pressure measurement method

When using the hopper-pressure measurement method, the number of tonnes dry solids can be established.

Measurement of tonnes dry solids has several advantages:

- the average density of the load is used and therefore the rate of consolidation in the hopper does not have any influence on the results.
there is no relation between the measurement of the production and the density of the in-situ material because the density of the surrounding water and the specific density of the dredged material is used to establish of tonnes dry solids there is no remuneration for water carried to the dumping area.

The system has to supply two variables to establish tonnes dry solids:
- the average density of the load
- the volume of the load.

Pressure sensors are used to measure the mean density of the load. A sensor is placed at the bottom of the hopper and a second sensor is used to measure atmospheric pressure. From the difference between hydrostatic pressure measured by the bottom sensor and the atmospheric pressure sensor, it is possible to calculate the average density of the load.

The level of the load in the hopper can be measured by means of an acoustic level sensor, hand-lead or a step-gauge. Another option is to use a third pressure sensor. This sensor is connected to a floating reference point on top of the load via a flexible tube filled with clean water. The measured pressure can be converted to give the height of the load. Of course to measure the height of the load the third sensor must be placed in a position lower than that of the floating reference point. The advantage of this configuration is that automated recording of production is possible.

The method measures the production to an accuracy greater than 14.5% of the total load expressed in tonnes dry solids (established in paragraph 7.2.2), though it is only suitable for liquid loads.

With non-liquid loads problems occur because if there is effective stress, bridging is possible and so only hydrostatic pressure will be measured. To cope with this problem a high pressure water jet system may be installed to fluidize the load. This system requires many adaptations, but, there is still no certainty about the absence of effective stress because it is not known whether the whole load is fluidized. Reliable data can only be obtained from liquid loads.

If there is any doubt about the presence of effective stress this method should not be used. For this reason the method is not used as basis for payment of dredged quantities.

The Tonnes Dry Solids System

The Tonnes Dry Solids System (TDSS) is a modern measuring method which measures in the means of conveyance.

The objectives for the development of the TDSS were:
- development of a fully automated production recording
system.
- development of a system which provides a fairer way of measuring the production.

The system is based on the measurement of the displacement of the vessel and volume-content of the hopper. The displacement is established by measuring the draft of the vessel, using two pressure sensors situated in the keel of the vessel.

The content of the hopper is established by using acoustic sensors to determine the level of the load from which, with the aid of the hopper volume calibration list, the volume is derived. The advantages of the TDSS are:

- exclusion of human influence
- the system is fully automated
- internal control of the functioning
- on-line presentation of production, so the contractor is able to improve the efficiency of the dredger
- accurate measurement of production expressed in tonnes dry solids, which is the most relevant parameter for the client.

The accuracy of the TDSS can be considered in terms of stochastic accuracy and of systematic accuracy.

The overall accuracy of the Tonnes Dry Solids System currently used has been established as being better than 8% - 10% of the total load expressed in tonnes dry solids. The accuracy has been established for three different trailing suction hopper dredgers and, from this, it has been concluded that the Tonnes Dry Solids System operates with ship-dependent measurements.

To improve the accuracy of the TDSS and to measure ship-independent data, the recommendations mentioned in chapter eight of the report may be used. When the existing TDSS has been adapted an accuracy better than approximately 5% may be possible.

The use of the TDSS gives rise to problems when dredging sand or sand rich material, but it is appropriate for use when dredging silt rich material.

A disadvantage of the TDS system is its dependence on sophisticated electronic instrumentation. If there is malfunctioning of measuring equipment the dredger must stop working, or an alternative backup system must be used. When the mobilization of spare parts takes much time, the downtime costs will be high. This may restrict the use of the system to areas where the maintenance and repair of such systems is no problem.
3. PROJECT DESCRIPTION AND OBJECTIVES

Project description:

- Since trailing suction hopper dredgers came into use there has been a significant demand for production-measurement. Over the years many attempts have been made to increase the accuracy of production measurements.

Since 1987 a new system, the Tonnes Dry Solids System, has been operated by Rijkswaterstaat in Hoek van Holland. The TDSS is a modern method of production measurement which is fully automated. It is based on the measurement of the displacement of the empty and loaded and vessel by means of hydrostatic pressure sensors and on measurement of the volume-content in the hopper-well by means of acoustic sensors.

The subjects of this graduation-project were:

- An analysis of the advantages, disadvantages and accuracy of different methods used to measure the production of trailing suction hopper dredgers.
- A probabilistic study of the accuracy of the Tonnes Dry Solids System.

Objectives:

- To evaluate production-measurement methods used before the Tonnes Dry Solids System was introduced.
- To study the accuracy of traditional methods of measurement.
- To establish a confidence level for the production of the TDSS.
- To analyze systematic errors detected in the TDSS which is used at present.
- To indicate variables which contribute significantly to the inaccuracy of the TDSS.
- To make recommendations for improvement of performance by either physical improvement or by changes in procedures.
- To develop an analytical preliminary investigation for the Tonnes Dry Solids System, as now in use, for a new dredging work.
- To draw up a program to be used for the development of procedures and programs to verify the accuracy of measurements made with the TDSS.
4. CRITERIA

4.1 Accuracy

Defining the accuracy of a measuring method gives rise to complications. Two accuracies can be distinguished: the absolute accuracy and the relative accuracy.

The absolute accuracy relates to the measuring of the load and is expressed in the same dimensions as the load. The relative accuracy also relates to the measuring of load but is expressed as a percentage of the total load.

The absolute accuracy may include stochastic variables and also variables which present systematic errors.

If systematic errors have been eradicated, greater accuracy may be obtained and, although the exact load is not measured, a payment unit can be established. If systematic errors are not ship-related, the measuring method can be used because different ships may be compared.

The accuracy of each method which is not subject to big variation caused by human influence will be examined. The maximum accuracy will be given for the different methods. If accuracy is entirely governed by human influence no accuracy can be given, so only the nature of the influence will be discussed.

4.2 Requisites

In dredging, in addition to the crew, the site administration with the site managers and superintendents and the head office with managers and technical department play a vital role and also contribute to the result of the dredging operation.

Today surveying, dredging and dredging monitoring involve the use of automation and sophisticated technology. Dredging monitoring and in particular some methods of quantity measurement, may demand sophisticated technology. When maintenance and the supply of spare parts is uncertain (e.g. in developing countries) it may be advisable to fall back on more traditional measuring techniques.

This report will consider the kind of environment for which a specific production measuring method is suitable and the requisites to achieve the best result.

4.3 Influence on dredging process

The results of a measuring method are influenced by natural phenomena (e.g. in an area of heavy siltation or erosion the in-situ measurement method cannot be used to establish the production of a dredger).

When choosing a measuring method these natural circumstances must be taken into account. A contractor selects and optimizes his working method on the basis of the measuring method prescribed in the contract. For example if a measurement method records a
load up to 1200 kg/m³ and the contractor has mobilized a dredger which is capable of dredging a mixture with a density greater than 1200 kg/m³, he may even reduce his level of production to keep the density of the load down to 1200 kg/m³. The extra effort to obtain a mixture with a density over 1200 kg/m³ cannot be measured and consequently will not be paid for. If relevant, the influence of the measuring method on the dredging process will be analyzed.

4.4 Suitability

In dredging, different bed-materials may be encountered such as silt, sand or mixed materials. These materials behave in different ways and thus it is possible that a method of measuring quantities which is suitable for silt loads will not be feasible when sand is present (e.g. hydrostatic pressure in the hopper can only be measured for liquid loads). Each method of measuring discussed in this report will be assessed on its suitability for use in particular circumstances.
5 IN-SITU MEASUREMENT

5.1 Description

A widely method used to measure dredged quantities is the establishment of change in the volume of material located at the dredging-site, based on careful measurement of bottom levels before and after dredging and known as the in-survey and the out-survey respectively. Known as the "in-situ" volume, this quantity is usually expressed in volumetric units.

Formerly depths were measured by means of a sounding pole or wire with a suitable weight. The method was not only time consuming but it also had the disadvantage that the depth was only recorded at the point where the sounding was made. Currently echosounders are generally accepted for depth determination. By sailing predetermined sounding-lines, continuous depth information can be collected, while fully automated data collection (tidal level, position) may be incorporated into sounding charts. Moreover a heave compensator may be installed to reduce the influence of wave-action.

The echosounder is based on the principle of the transmission of an acoustic signal which is reflected from the seabed. If the celerity of the signal is known, the depth can be established from the time involved in transmission of a signal to the seabed and the reception of its reflection.

As the celerity of the signal is a function of the density of the surrounding water environment, which alters with changes in temperature and/or salinity, the echosounder has to be calibrated for each special survey. Calibration can be carried out by adjusting the propagation-speed. This can be done by adjusting the frequency according to special density measurements, although the bar-check, which provides direct calibration, gives a better result. A steel plate or bar is lowered underneath the transducer at set depths, measured by a sounding line, and the frequency is calibrated against the depth. The bar-check in normally carried out in a stationary position.

A tide gauge, whether manually or automatically read, must be levelled in order to function as a proper bench mark, taking into account the specific difference between land and chart datum. If the gauge cannot be installed at a location where there is no interference from waves or swell, it should be fitted with a swell compensator. To obtain actual depth in the dredging area the data from soundings must be related to data from this tide gauge. The position of the tide gauge should be representative for the dredging site. In areas with a high tidal range or in rivers, several tide gauges may be needed to provide representative levels.

To ensure the accuracy of the chart, in addition to the depths there should also be a horizontal reference for the survey (figure 5.1). The horizontal location may be established electronically or visually, but the position of the transducer during sounding should be continuously monitored so that sounding-lines and sounding positions can be fixed in these
lines.
Automation demands electronic positioning which permits quick automated collection and elaboration of survey data. From surveys taken during dredging activities it is possible to monitor the progress of the works and from in and out surveys, taken before and after dredging, the result can be calculated in terms of the volume of material removed [25].

![Diagram of sounding checks](image)

**Figure 5.1 Basic sounding checks**

### 5.2 Accuracy

It is difficult to determine the accuracy of in-situ measurements. In practice, an accuracy of 0.20 - 0.30 m is accepted [3,4 and 25]. The overall accuracy is governed by the following phenomena:

- **tide**:
  
  * the accuracy in levelling the tide gauge. This depends upon the presence of specific points at a known distance from a reference level. If these are present an accuracy of 0.5 cm may be obtained.
  * the accuracy of readings from tide gauge. This depends upon whether the gauge is read visually or automatically and on the influence of wave action. Accuracy is estimated to be within 2 cm.
  * the location of the tide gauge in relation to the dredging site. The tide gauge must not be too far from the dredging site because variations in water depth related to tidal levels follow the progression of the tidal flow or time-difference in occurrence of the tidal curve, resulting in a difference between the water-level at the location of the tide gauge and the dredging location. The accuracy depends on the distance between the tide gauge and the dredging location, but an error of between 1 cm and 50 cm may be expected.
- calibration:
  * calibration of the echosounder by means of the bar-check. The error can be reduced only by frequent calibration.
  * frequency of the echosounder. Signals using different frequencies reflect at different densities of bottom material. Care should be taken in choosing the frequency, otherwise errors in depth-recordings ranging from 10 cm to several metres may be expected.

The same frequency should be used for the in-survey and the out-survey.

- environmental circumstances:
  * the movements of the survey vessel. Inaccuracies in depth measurements may occur owing to the effects of pitch, roll and squat. Variations of 5 - 30 cm may be possible (depending upon the dimensions of the vessel, the site conditions and the presence or absence of a heave compensator).
  * the speed of the survey vessel. The faster the vessel is sailing the bigger will be the difference in position between the point of reflection and the position when receiving the transmitted signal.
  * change in draft caused by different loading of the survey vessel (e.g. change in status of bunkers and trim tanks). The result depends upon the dimensions of the vessel, but differences up to several centimetres may be expected.
  * the distance between survey-lines and survey-plots. When the lines are widely spaced bumps or craters in the bottom may not be recorded. The error is estimated to vary between 2 cm and 1 meter.
  * width of the beam. The transmitted signal will reflect at the highest point within the beam of the signal. If a wide beam is used, craters will not be measured when there are rapidly changing bottom-levels. Errors are more likely to occur in areas consisting of massive material.

Further factors:

- "rounding off" and averaging in software and digitiser. The size of the errors will depend on the grid-size and the formulas used. On slopes and with rapidly changing bottom-levels, errors of 1 cm may be expected.

- offsets in antennas used by positioning systems.

Surveying in exposed conditions with waves and/or swell cannot always be avoided, although this has an impact on the accuracy of the in-situ measurement method (figure 5.2). The accuracy may be reduced by 0.5 m [3]. The time and place of measurement may have a great impact on the reliability of the survey on the dredging-site.
Owing to the use of the overflow, trailing suction hopper dredgers cause a turbidity cloud of fine sediment. As mentioned above, high frequency echo-sounding reflects at low densities and therefore instead of the bottom profile the depth of the turbidity cloud will be recorded, so surveying should not be carried out in the environs of dredgers immediately after dredging activities. The problems arise owing to the interference of shipping using the maximum water-depth and thus causing turbidity by propeller-action.

If the survey is carried out a few weeks after dredging, the bottom-configuration may have changed due to the occurrence of siltation or erosion.

The estimated quantity of material dredged is expressed in cubic meters.

This volume is obtained by multiplying the thickness of the layers dredged by the area which has been dredged. The accuracy of the estimate depends on the accuracy of both the horizontal survey and the depth measurements.

The accuracy for the establishment of dredged quantities can be expressed in cubic metres. These cubic metres can be calculated from the thickness of the layer (in metres) and the surface of the area to be dredged (in square metres). It is clear that the accuracy will depend on the thickness of the layer to be dredged.

The thickness of the layer (H) can be established via subtraction of the established depth from in-survey (H_{in}) from the established depth from out-survey (H_{out}).

The smallest best possible error in depth measurement is 0.1 metres but in practice an error of approximately 0.3 metres usually occurs [3,4 and 25].

When the following two assumptions are made:

- The probability density function of the error in depth measurement is symmetric.
- In 95% of depth measurements the error is less than 0.3 metres.

the standard deviation of the error in depth measurement can be established as:

\[ \sigma_{\Delta H_s} = \frac{0.3}{1.96} = 0.153 \text{ (metres)} \]  

(1)

\[ \sigma_{\Delta H_s} = \text{standard deviation of the error in depth measurement in metres.} \]

The standard deviation of the error in the establishment of the thickness of the layer in metres can be established as:

\[ \sigma_H = \sqrt{\sigma_{\Delta H_s}^2 + \sigma_{\Delta H_{arc}}^2} \]  

(2)
With the previous formula it may be assumed that in 95 % of the measurements of the thickness of the layer the error ($\Delta H$) will be less than $1.96 \times \sigma_H = 1.96 \times \sqrt{(0.153^2 + 0.153^2)} = 0.42$ metres.

The relative accuracy in measuring the thickness of the layer may now be taken as

$$\text{accuracy} = \frac{\Delta H}{H} \, (\%)$$  (3)

$\Delta H$ = error in measurement of thickness of layer in metres

H = thickness of layer in metres

When the in and out surveys both cover the same area, the accuracy in measurement of the dredged volume may be taken as:

$$\text{accuracy} = \Delta H \times A_p \, (M^3)$$  (4)

$A_p$ = surface of area to be dredged in square metres

In this way it is obvious that not only the accuracy of the lead or echosounder but also the dimensions of the area to be dredged are significant. Obviously the best results can be obtained in a small area with a rather thick layer to be removed and when surveying solid/sandy material. There should also be closely spaced survey-lines, a vessel equipped with a heave compensator and with an accurately levelled tide gauge near the dredging-site with moderate site-conditions.

The most important factor in the accuracy is $A_p/H$ (area in square metres/layer - thickness in metres). The biggest errors will be encountered in large areas where thin layers have been dredged giving a large factor $A_p/H$.

5.3 Requisites

In order to produce reliable survey data, a survey vessel equipped with an echosounder and an electronic position finding system should be available.

In exposed conditions the vessel should also be fitted with a heave compensator to reduce the influence from swell and waves and thus to obtain a reliable echo-reflection from the bottom configuration (figure 5.2).

As the productivity of dredgers has greatly increased in recent years and the "in-situ configuration" has become liable to rapid changes, frequent updating of survey-data of the dredging-site is necessary in order to execute the dredging works efficiently.

Automated data-collection and the conversion of data into charts and computerised displays have become essential to the achievement of an acceptable frequency in the updating of the dredging programme.
For echo-sounding equipment, the applied frequency, and thus the width of the transmitted beam and the penetration capacity, should be considered. Hydrographic sounding for navigational purposes is normally executed with a frequency of 210 kHz, meaning a narrow beam and a high sensitivity for reflection (density approximately 1025 kg/m³) [25]. A narrow beam gives the advantage of more accurate sounding in solid/sandy material, through a stronger reflected signal, especially on slopes (figure 5.3). A lower frequency (normally 30 kHz) has a wider beam and thus a greater coverage of the bottom-profile and a deeper penetration in silty areas (reflection at density approximately 1150 kg/m³), thus disregarding soft silt layers which do not hamper navigation. The nautical depth in Rotterdam is defined as the depth of the layer with a density of 1200 kg/m³ (figure 5.4) [8].
Publications such as The Royal Institution of Chartered Surveyors 'Guidelines for the Preparation of Hydrographic Surveys for Dredging' [27] and the British Ports Association's 'Guidance Notes for Hydrographic Surveying in Small Ports' may be used as a guidance [28].

![Diagram](image)

*figure 5.4 Nautical depth*

### 5.4 Influence on dredge process

The in-situ measurement method has implications for the dredging process. While the bulk of the material to be dredged can be removed by using the maximum capacity of the dredging equipment, when using trailing suction hopper dredgers a big loss of potential capacity occurs in cleaning up the dredging area, specifically in searching out "high spots". The smaller the agreed tolerance for payment of for over-depths on delivery, the greater will be the loss of productivity during the final phase of the project.

The contractor must balance his approach between over-dredging at full production, thus dredging, non-payable quantities within the contractually prescribed limitations and the loss of productivity which occurs when hunting for the high spots.

### 5.5 Suitability

Although the calculation of in-situ volume is widely used as a basis for payment for dredging, difficulties may arise in some cases.

Two types of problem may be distinguished:

- Changes occurring in the interval between in and out surveys. These changes may lead to over or under estimates of the work being done.
Changes are likely to become more significant when the mobility of the bed material is higher. Finer sediment will cause more problems than coarse sediment because fine material can easily come into suspension as a result of turbulence caused by either natural effects such as density currents, tidal currents or wave action, ship movements or by the dredging process itself. When there is a high degree of turbulence sand and gravel may enter into suspension/also be transported.

- Definition of the bottom level for contract purposes.
  Reflection of the acoustic signal depends on:

  a) the frequency of the acoustic signal.
  b) the density of the bottom material

High frequency echosounders reflect from low densities (approximately 1025 kg/m³) indicating the top of the layer. Low frequency echosounders penetrate more deeply into silty areas (reflection at density approximately 1150 kg/m³) so they do not record soft silt layers which do not hamper navigation. So the presence of fluid mud layers in which the state of material gradually changes from silt in suspension to consolidating sediments, may therefore present problems when measuring the results of maintenance dredging.

Another problem which occurs with all types of bed-material, is related to the accuracy of the lead or echosounder and the thickness of the layer of bed-material to be removed. The effect of the measuring error on the accuracy is greater in thin layers where the size of the error is a greater proportion of the total thickness of the layer. When an accuracy of 5% of the thickness of the layer to be removed is required, the thickness of the layer must be 20 times greater than the accuracy of measurement of the thickness of the layer (see paragraph 5.4 also).

Summarizing, it may be concluded that measuring in-situ can be used for all types of bed-material, except when there is heavy natural transport and that it is better to use the method to monitor the progress of the dredge work rather than for calculating.

5.6 Conclusion

The in-situ measurement method demands the use of qualified and experienced surveyors. The accuracy of the method is dependent upon specific site conditions but, as mentioned in paragraph 5.5, in 95% of the measurements of the thickness of the layer the accuracy will be better than approximately 0.42 metres. This is approximately 10% in the case of a 4 metre thick layer. This difference may be a very significant proportion of the contract and in maintenance dredging today may be probably of the same order as the planned profit margin. Thus the layer to be removed should not be too thin. The area to be dredged should not be too large, because surveying it would be very time consuming and the
bottom-level could change before the entire area had been surveyed.

The in-situ measurement method is suitable for capital dredging works because only the final result is of interest. However, much attention has to be paid to differences in dredged volume due to erosion or siltation to protect the contractor from great risks, otherwise his cost - and therefore his price - per cubic metre of material dredged will increase.

Several phenomena (e.g. stormy weather, waves and/or swell) may delay the out-survey, so the bottom-level may change between the end of dredging and the time of the survey. If the change in bottom-level due to erosion or siltation is small in comparison with the thickness of the layer to be removed, the in-situ measurement is suitable for measurement of payable dredged quantities.

In maintenance dredging, which in sandy areas implies the removal of relatively thin layers, problems may occur. Due to heavy erosion, siltation, ship-traffic using maximum navigational depth and turbidity clouds, differences between the quantity removed and the payable quantity arise. The in-situ measurement method is not suitable in such circumstances, although the method may still be used to monitor and control the progress of such dredging works.
6 PRODUCTION CALCULATION ON THE BASIS OF MEASUREMENT OF VELOCITY AND DENSITY OF THE DREDGED MIXTURE IN THE PIPE LINE.

6.1 Description

Another method which may be used to establish dredged quantities is to measure the density and velocity of the mixture on the delivery-side of the dredge pump. Owing to mixing caused by the dredge pump, the dredged mixture in the delivery-pipe is more homogeneous than that on the suction-side.

The density of the mixture is measured by means of a radioactive probe with a special casing, which is placed in the pipe (figure 6.1) [5].

![Figure 6.1 Radioactive density measurement](image)

The radiation transmitted by the source penetrates through the dredged mixture in the pipe and is recorded by the receiver. As the density of the mixture increases, the intensity of the radiation reaching the receiver is reduced. This reduction provides a measure of the concentration of the mixture. When the density of the in-situ material is known the concentration can be determined.

The velocity of the mixture is measured by means of an electro-magnetic velocity meter which is installed in the pipe-line (figure 6.2) [5]. Electro-magnetic coils are connected to a source of alternating current. The flow of current through the electro-magnetic coils causes an electro-magnetic field in a direction perpendicular to the longitudinal direction of the pipeline. When a liquid conductor passes through the pipe an electric voltage is induced. The direction of this electric voltage is perpendicular to the magnetic field and also perpendicular to the direction of movement of the liquid.

In order to measure the electric voltage, two stainless steel electrodes are installed in the pipe-wall. The induced voltage is relative to the intensity of the electro-magnetic field, to the inner diameter of the pipe and to the velocity of the liquid.
Because the intensity of the magnetic field and the inner diameter of the pipe are constant, the voltage depends solely on the value of the velocity of the liquid and so the velocity of the mixture in the pipe can be determined.

![Figure 6.2 Velocity measurement](image)

The production can be calculated from flow density and velocity and the pipe diameter.

For trailing suction hopper dredging this only applies before the overflow level has been reached, because overflow losses will not be taken into account. Measuring in the overflow in the same manner as in the pipe is impossible because of the occurrence of air or gas bubbles in the mixture and of the heterogeneous nature of the mixture. The pump performance, however, can still be measured and from this, optimization of the mixture can still be achieved.

When the load of trailer hopper dredgers is pumped directly to the discharge or reclamation area the method may be used to advantage. The same applies with regard to stationary suction dredgers when pumping to a reclamation area.

6.2 Accuracy

It is difficult to assess the accuracy of the velocity and density measurement method. The following method may be used to establish the production of the dredger [6]:

\[
\rho_p = \frac{\int \rho_x Q \, dt}{\int Q \, dt}
\]

(5)

\(\rho_p\) = average density of mixture in hopper in kg/m³
\(\rho_x\) = mean density of pumped mixture measured against time
\(Q\) = flow in m³/s of pumped mixture measured in time
\[ p = \frac{P_s - P_w}{P_{IS} - P_w} \]  

\( P_w \) = density of in-situ water in \( \text{kg/m}^3 \)

\( P_{IS} \) = density of in-situ material in \( \text{kg/m}^3 \)

\( p \) = volume-percentage of in-situ material \( \times \frac{100}{100} \)

Diameter of the pipe (in metres): \( d \)

The production of the hopper dredger (using one pipe) may be established as:

\[ \text{production} = p \times 0.25\pi d^2 \times V_m \text{ (m}^3\text{/s)} \]  

\( V_m \) = mean velocity of dredged material in the suction pipe in \( \text{m/sec} \)

Although errors may occur, with frequent calibration and ideal measuring conditions these may be taken as:

- error in water density 0.2%
- error in in-situ material density [25] 2.5%
- error in velocity measurement [7] 2%
- error in density measurement [7] 2%

However, in addition there are some conditions which induce greater error, including:

- the presence of gas in the mixture
- pipeline velocity falling below the critical value for sediment deposition
- use of the integration method over a period of time which multiplies the errors
- both systems are difficult to calibrate
- very rapid variations in density and velocity in the pipe
- the presence of debris
- wear en tear

It is impossible to establish the exact overall error in the measurement of the load of the hopper because the variables have to be integrated. Practical tests with the inverted U-tube have shown that an accuracy of approximately 2% - 3% can be obtained when dredging sandy material [29]. When measuring on board a trailing suction hopper dredger it is obvious that there is great uncertainty about the representative values of the recorded data. If there are overflow-losses it is impossible to measure absolute production. Because the overflow method is used to optimize the load of the hopper, from the time it comes into operation the measurement of density and velocity in the pipe-line gives only relative information about quantity and quality of the dredged material. The method is therefore totally unsuitable to establish
the production of a trailing suction hopper dredger.

6.3 Requisites

In addition to the instrumentation used to measure mixture velocities as described under 6.1, other appliances are available although they are less suitable [1]:

- differential head systems, in other words systems which measure hydrostatic pressure difference over a narrowing (e.g. nozzles, orifices), have the disadvantages of:
  
  * malfunction in case of pressure loss
  * decreasing accuracy through wear and tear
  * greater potential for blockage in the pipe-line
  * requiring a long straight section of the pipeline on both sides of the measurement device. There is no room for an optimum lay-out on board.
  * influence on readings from density-variations

- Ultrasonic flowmeters have the disadvantages that they cannot be used:

  * in heavily coated or lined pipes
  * if there is excessive pump-noise
  * in pulsating flows
  * in non-Newtonian liquids
  * owing to their presentation of non-averaged values over the cross-section of the pipe

Furthermore, they may be affected by variations in: mixture concentration, temperature, pipe thickness, grain size of sediment, debris and gas bubbles.

The electro-magnetic flow meter, used to measure liquids in pipelines, therefore remains the most suitable instrument for velocity measurement on board of trailing suction hopper dredgers. To eliminate the effects of sedimentation of grains, the sensors should preferably be mounted in a horizontal plane in a vertical part of the pipeline. The rubber or polyurethane inner lining of the instrument is liable to wear and tear caused by coarse abrasive material. Frequent calibration should be carried out to counteract the disadvantage of the inaccuracy of the instrument.

Radio-active devices are used to measure the density of the mixture in the pipeline. For pipe-diameters up to 700 mm Cs-137 (half-life time approximately 30 years) can be used as source while Co-60 (half-life time approximately 5 years) is used for larger pipe-diameters [2]. Geiger-Muller counter tubes, ionization chambers and scintillation counters are used as detectors. Scintillation counters have the advantage of a high accuracy and in combination with microprocessor amplifiers they are less prone to the effects of ageing. Greater sensitivity makes the use of
smaller sources possible. The data are processed in a computer on board the dredger.

The inverted U-tube is an accurate measuring system, but there is no room to install such a device on board trailing suction hopper dredgers. The principle is based on the use of pressure measurement to establish the density of the dredged material and electromagnetic velocity measurement to establish the velocity of the mixture in the pipe. To compensate for friction and fall velocity of the particles, measurement takes place in both upward pipe and downward sections of the pipe. A diagram of the U-tube is shown in figure 6.3.

![Diagram of the inverted U-tube](image)

**Figure 6.3. Principle outline of the inverted U-tube**

6.4 Influence on dredging process

Because the measurement is independent of the density of the mixture the method does not influence the dredging process. However, because the material escaping via the overflow cannot be measured, the overflow cannot be used to optimize the load of the dredger. For this reason the velocity and density measuring method has a considerable influence on the dredging process.

6.5 Suitability

The velocity and density method of measuring cannot be used to measure production for every type of sediment. If there is no degassing device on board, use of this method will produce inaccurate results when dredging material which contains gas (e.g. silt).

When dredging sand, and even more when dredging gravel, much attention must be paid to the calibration of the system because wear and tear affect the accuracy as the work progresses. If wear
and tear are excessive the velocity and density measurement method is totally unsuitable for the measurement of pay-units, although it may still be used for measurements relating to optimizing the production. A major problem is the measurement of material lost via the overflow. Because measurement in the overflow is not yet possible, the velocity and density measurement method cannot be used when the overflow is being operated.

To sum up: the method is suitable, provided that the instruments are calibrated frequently and dredging ceases when the level of the overflow is reached.

6.5 Conclusion

The velocity and density measurement method may be used to optimize the performance of the trailing suction hopper dredger during dredging. It is not suitable to measure the load of the hopper or to measure a pay-unit when the overflow system is being used to optimize the loading capacity of the dredger. The inverted U-tube provides accurate measurements in certain conditions but cannot be used on board of trailing suction hopper dredgers because of the lack of room to install this instrument. In some countries the use of radiometric devices is prohibited, thus preventing the use of this method. It is necessary to be aware of the legislation relating to the use of radiometric devices.

To sum up: the velocity and density measurement method should be used only to ensure optimum production in the dredging period of the cycle of a trailing suction hopper dredger for two reasons:

1 establishment of the in-situ density is very difficult
2 overflow losses are not to be measured.

With frequent calibration, and when dredging does not continue above the level of the overflow in the hopper, the method may be used to measure dredged quantities for payment. For stationary dredgers, with frequent calibration, the method it has been proved that the method can provide accurate production measurements in ideal conditions.
7 MEASUREMENT IN MEANS OF CONVEYANCE

7.1 HALF-SPHERE METHOD

7.1.1 Description

Over the last thirty years, 'half-sphere' or similar methods have been used to measure payable quantities of dredged material. This method is based on the fact that dredged material settles in the hopper. On completion of the loading cycle, soundings are taken in the hopper at a number of predetermined locations by lowering a semi-spherical lead onto the load from a predetermined reference level. The half-sphere (figure 7.1.1) has a specific weight and will stop sinking at a level where the density is equal to or higher than 1200 kilogrammes per cubic metre.

The distance from the reference level can be read and from the average result the contents in the hopper can be established with the aid of the hopper contents table.

The hopper contents table gives the hopper content in cubic metres as a function of the height, measured in centimetres.

For material which settles quickly, this is an appropriate method because there is only a layer of water on top of the load. However, when slowly settling materials such as fine sand particles or silt are being dredged, above the settled material there will be a layer of mixture with a density that is less than 1200 kg/m³ but greater than the density of the water.

In this case first the settled part of the load is measured, after which samples of 1 dm³ are taken from the mixture, at agreed points halfway between the settled surface and the upper surface (figure 7.1.2). At first it was assumed that to attain an approximation of the situ density, the sample should be given time to settle. The sample of 1 dm³ is shaken and poured into a measuring cylinder. After an appropriate predetermined period (e.g. one or more hours) the sample is examined. The level of the consolidated layer is expressed as a percentage of the total volume of the sample. The consolidation value after X hours is
assumed to be that of the liquid part of the hopper load. This method is called "the half-sphere and settling" method [3].

![Diagram of sampling points](Image)

**Figure 7.1.2 Measuring the load of the hopper**

To accelerate settlement a high revolution centrifuge (figure 7.1.3) may be used. The samples are centrifuged for ten minutes at a speed of 1500 rev/min, after which the amount of sediment is determined as a percentage of the volume of the total sample (1 dm³). This is called "the half-sphere and centrifuge" method [3]. To ensure a result close to the in-situ density of the material, the number of revolutions per minute and the duration of process have been previously determined [9]. This approach is easily understood, but any procedure could be used, provided it is well determined and followed accurately.

The silt content of the fluid load can be derived from the sediment percentage and added to the quantity previously measured by the half-sphere.

\[
\text{total volume} = \text{volume settled load} + \% \text{ sample settlement} \times \text{volume of mixture layer}
\]

![Centrifuge](Image)

**Figure 7.1.3 Centrifuge**
7.1.2 Accuracy of the half-sphere method

Because this method depends on hand sampling, there is a certain degree of subjectivity in the results, which affects the determination of its accuracy. It is not always possible to define effects on accuracy due to human influence. Disregarding human influence, the maximum absolute accuracy is still affected by:

- Errors due to variations in the mass and in the surface of the half-sphere. Calibration may correct these errors to a certain extent. Any small remaining error in the dimensions of the half-sphere will have an impact on the production measurement. After calibration neglect of remaining error is justified.

- Errors in measuring the distance from the bottom of the hopper to a reference level. Accuracy of the reference level is set as 0.01 metre.

- Errors in measuring the distance from the surface of the solid mass to the reference level. These may be caused by movements of the ship, limitations of the human eye, the tension in the measuring line and the influence of temperature on the measuring line. Altogether an accuracy of 0.05 metres is taken into account [25].

- Sampling errors when taking the sample from the fluid layer. First the distance from the reference level to the surface of the mixture must be recorded. Secondly the distance from the reference level to the surface of the solid mass must be recorded. The sample must be taken halfway between these two distances. The error in measuring both distances amounts 0.05 metres, the error in levelling the sample 0.05 metres. Altogether an accuracy of 0.10 metres has to be taken into account.

Absolute accuracy (in metres) of the measurements on board thus amounts:

- accuracy of recording reference level : 0.01
- accuracy of recording distance settled part : 0.05
- accuracy in recording distance for sample : 0.10

In the following example the accuracy, in relation to the above mentioned errors, will be established.

The relation between level of the load and the density of the load is schematized as in figure 7.1.4.

The volume of the hopper is taken as 6000 m³, and the surface of the hopper is taken as 600 m². According to figure 7.1.4. the level of the solid mass of the load reaches up to 6 metres, which implies a volume of 3600 m³. The accuracy in the measurement of the level of the solid mass
is set as 0.05 metres which implies an accuracy in volume of 0.05 * 600 = 30 m³.

The level of the fluid top layer in figure 7.1.4 is 4 metres. The accuracy in levelling the sample bottle is 0.10 metres. This implies that the average density of the mixture in the sample bottle is not 1100 kg/m³ but 1200/4 * 0.1 + 1100 = 1130 kg/m³. When the average density in the sample bottle is 1100 kg/m³, after consolidation the volume with density of 1200 kg/m³ is 50% of the total volume of the sample bottle.

![Figure 7.1.4. Schematized density profile.](image)

When the density is 1130 kg/m³ the volume with a density of 1200 kg/m³ will become:

\[ X \times 1200 + (1-X) \times 1000 = 1130 \]

\[ X = 0.65 \]

The volume of the fluid top layer is 6000 - 3600 = 2400 m³. The error in volume due to the error in levelling the sample bottle can now be taken as 0.15 * 2400 = 360 m³. The overall accuracy may now be established as

\[ \frac{(3600-30 + 0.65 \times 2400)-(3600 + 0.5 \times 2400)}{3600 + 0.5 \times 2400} \times 100\% = 6.9\% \]

of the total load of the dredger.

From this example it appears that the "half-sphere and sampling method" provides an accurate measurement of volume, but there are disadvantages, not included in the example, which bring about greater inaccuracies:

- the measurement of the distance with the half-sphere is done by hand. There is no procedure which prescribes the conditions for lowering the half-sphere. Therefore the half-sphere will not always sink into the silt in a same moderate way and differences of several centimetres may
occur. The effect of an error of several centimetres is difficult to determine. When the distance from the reference level to the surface of the settled part is greater the volume of the settled part will be less, so the sample will be taken at a greater distance from the reference level. The average density of the sample will be greater than the representative density of the liquid layer and therefore the percentage sample settlement will be higher, resulting in an increased volume.

- the content of the sample should be 1 litre of mixture. It is possible that the content could be more. After shaking, the sample will be emptied until the it becomes 1 litre. This is done by eye and errors may occur in measurement of the level of the solid mass in relation to the total sample.

- after consolidation the percentage of the volume of settled material is read. When using the half-sphere and settling method the percentage is read directly from the sampling bottle. When using the centrifuge, three values are read and the average of these will be taken as the percentage volume for settled material. Errors of 1% sample settlement occur.

- the sphere will not always float at a density of 1200 kg/m³. From research has been concluded that the half-sphere will stop sinking when a certain yield stress is reached and at this point the density is not always 1200 kg/m³ [10]. There is relation between yield stress and density, but this relation is specific to each type of silt (figure 7.1.5). When dredging, different types of silt can be encountered and because the flotation of the half-sphere is governed by yield stress, the rate of sinking of the half-sphere is not a measure of the density of 1200 kg/m³.

- the average density of the solid mass as "measured" by the half-sphere is not always 1200 kg/m³. The average density also varies in the vertical direction (figure 7.1.5). If the density of the solid mass is over 1200 kg/m³, the half-sphere will stop sinking. The average density of the solid mass is not known and therefore the extra material cannot be paid for. The vertical variation in density applies to all trailing suction hopper dredgers, but in spite of the results having no absolute meaning in relation to the quantities dredged in-situ, they are still suitable as a basis for payment because comparison is possible.

- sampling errors occur. Sampling halfway between the top and bottom of the fluid the mixture does not imply that at this point the mixture is at its average density. The difference in densities is not ship dependent so the results are suitable as a basis for payment.

- After settling or after centrifuging, the average density of the settled material should be 1200 kg/m³. Nevertheless
with a constant settling time and a constant time of centrifuging and with a constant speed, this will certainly not always be the case [30]. The settling and consolidation time of different types of silt differs and thus after X hours the density of the solid mass of different types of silt will differ. A forced consolidation with a centrifuge acts like an extra long settling time. The density reading will be more accurate and thus the use of a centrifuge will provide a better estimate of the volume of the settled part of the material in the hopper. In the late sixties and seventies extensive investigations were carried out in the Netherlands to correlate results of the settling method with the centrifuge method. The variation in results obtained by using this settling method is very great. The method is very sensitive to temperature, organic content and consolidation characteristics of the soil. Comparison between volume calculation according to the centrifuge method and volume based on settling ratio results in differences of 30 to 80 % [26]. It is obvious that lack of proper understanding of the method chosen method may have considerable bearing on the payments.

![Figure 7.1.5 Density in the hopper](image)

- because of the subjective role of the inspector on board, the measurements with the half-sphere and the taking of samples may differ.

Summing up: the half-sphere method measures the volume of the load simply and accurately but:

- the level at which the half-sphere stops sinking may not indicate a density of 1200 kg/m³
- the average density of a sample may not be representative for the average density of the fluid top layer
- after consolidation the density of the solid mass in the sample bottle may not be 1200 kg/m³.

Therefore what the measured volume really represents in terms of dredged material is not known.
7.1.3 Influence on dredging process

The half-sphere stops sinking when the density becomes more or less 1200 kilogramme per cubic metre. When the density of the dredged mixture in the lower part of the hopper is greater than 1200 kg/m$^3$, this extra production by the contractor will not be paid for. With degassing techniques, deep-loading facilities and underwater-pumps, the modern dredger is able to dredge mixtures with greater viscosity and of higher densities. The half-sphere and sampling method fails to determine the extra production, and as a result the contractor is inclined to optimize the load at lower densities than could be achieved, thus working inefficiently from the client's point of view.

7.1.4 Suitability

Sand loads:

When sand is dredged, the material will settle in the hopper very quickly, so the hopper load consists of settled sand particles with a layer of water above. The half-sphere gives an unambiguous indication of the level of the top of the mass of solids. In this way the method can be used to measure payable dredged quantities in areas with sandy bottom material.

Silt loads:

When silt is present in the bed-material, the density of the load will decrease. The mixture settles much more slowly and the density of the solid mass in the hopper is lower. During the seventies (construction of the Europoort area), trailing suction hopper dredgers were capable of dredging a mixture with a density of approximately 1200 tonnes/m$^3$, which corresponded with the concept of nautical depth. In the Rotterdam area, the nautical depth is defined as the depth at which the sediment has a density equal to or exceeding 1200 kg/m$^3$[8].

A half-sphere with an underwater mass of 1.5 kg and a diameter of 17 cm, which would float on a mixture with a density equal or more than 1200 kilogramme per cubic metre was designed [8]. In this way the volume of the settled part in the hopper could be measured and therefore the half-sphere method was also suitable for measuring loads consisting of greater or smaller proportions of silt.

When the half-sphere is used to measure the load, the results will have no absolute meaning in relation to the quantities dredged but, in indicating a relative volume, they are certainly suitable as a basis for payment.

On the assumption that in maintenance dredging the critical density of silt is 1200 kg/m$^3$ (critical in relation to the concept of nautical depth), both the "half-sphere and settling
method" and the "half-sphere and centrifuge method" are suitable for silt loads. When the average density of the settled part in the hopper well is over 1200 kg/m$^3$, the contractor is not paid for all the work done but, when this problem has been identified, a more fair price per cubic dredged material may be offered. The same applies to the density of the settled part in the sample bottles.

7.1.5 Conclusion

The advantages of the "half-sphere and centrifuge method" and more especially of the "half-sphere and settling method" are:

- construction is simple
- it can be made operational quickly
- it is maintenance free
- it is inexpensive

Obviously this method also has disadvantages:

- there is no payment for the improved production made possible by the use of modern sophisticated trailing suction hopper dredgers. The half-sphere stops sinking when a certain yield stress is reached and therefore what is actually representative of the measured volume is not known. Increasing the weight of the half-sphere leads to more changes in the density at which the half-sphere will float [10] (figure 7.1.6).
- the result depends on the settling time of the samples in the sample bottle when the "half-sphere and settling method" is used.
- the result depends on the time the centrifuge is running and the number of revolutions per minute of the centrifuge when the "half-sphere and centrifuge method" is used.
- the result is depends on the type of material being dredged.
- the inspector plays a subjective role in the measurement of the load, having to deal with a conflict of interest between the client and the crew of the hopper-dredger.
- the contractor is not always paid fairly for his efforts.
- the influence of the method on the dredging process. Because densities over 1200 kg/m$^3$ cannot be measured the contractor will try to keep the density of the solid mass down to 1200 kg/m$^3$, since the extra effort for increasing the average density of the load will not be paid for. This may result in inefficient dredging.
- The results are not directly known to the crew on board of the dredger. For this reason it is difficult to optimize the dredging process.

In general it can be concluded that the method measures volumes accurately and is not ship-dependent, but it does not provide absolute values. What it represents is not known. Modern dredgers can produce much more than the method is able to
measure because they have on-board computers to which more sophisticated measuring instruments can be connected. For small, older trailing suction hopper dredgers the "half-sphere and centrifuge method" can still be used for measuring a pay unit because comparison between different dredgers is possible.

The settling method shows more variation in the percentage of volume of the settled part and thus more deviation in the final result. More deviation implies a less accurate measuring method and therefore the "half-sphere and settling method" should not be used unless no other means are at hand.
Figure 7.1.6 Relation between yield stress and density
7.2 HOPPER PRESSURE MEASUREMENT METHOD

7.2.1 Description

The hopper pressure measurement method is not in general use, but the method has been developed from a research project. The objective of this research project was to develop an automated measuring method which would provide a fair basis for the determination of pay-units [6]. When using the hopper pressure measurement method, the tonnes dry solids dredged may be established. Tonnes dry solids may be seen as the weight of the particles in the dredged mixture.

In 1 m³ of dredged mixture the particles may be distributed as follows:

When the percentage of the total volume taken up by the particles is represented by the variable P, the weight of the particles can be established by multiplying P by the specific density of the particles ρₚ.

The remaining volume in the cubic metre of dredged material is taken up by water. The volume of the water is equal to 1-P and the weight of the water can be established by multiplying 1-P by the density of the water ρₚ wastewater.

The weight of the cubic metre dredged material can now be established as P*ρₚ + (1-P)*ρₚ wastewater. Because the volume is known, the density of the dredged mixture is known. Conversely, when the density and the volume of the dredged mixture in the hopper (ρₚ), the specific density of the dredged material and the density of the water are known, the weight of the dry particles can be established in the following way:

\[ \rhoₚ = P*\rhoₚ + (1-P)*\rhoₚ_{wastewater} \]

\[ P = \frac{\rhoₚ - \rhoₚ_{wastewater}}{\rhoₚ - \rhoₚ_{wastewater}} \]
from which the total weight of the dry particles in the hopper can be established as

\[ \text{total weight of dry particles} = P \cdot \rho_s \cdot V \]

In the research project the weight of the dry solids is called "tonnes dry solids".

From the load of a trailing suction hopper dredger the tonnes dry solids may be established by using the following formula:

\[ tds = \frac{P \cdot \rho_w - P \cdot \rho_s}{\rho_s - \rho_w} \cdot V \]  \hfill (8)

\( \rho_B \) = average density of the load in kg/m\(^3\)
\( \rho_W \) = density of the dredged water in kg/m\(^3\)
\( \rho_S \) = specific density of dredged material in kg/m\(^3\)
\( V \) = volume of the load in the hopper well in m\(^3\)

The system has to provide two variables to establish tonnes dry solids: the average density of the load and the volume of the load. For each individual trailing suction hopper dredger a hopper content table is available. The hopper content table presents the relation between the distance of the surface of the load inside the hopper from a reference level and the volume of the load. After this distance has been measured, the volume of the load can be derived from the hopper content table.

Load pressure instruments may be used to measure the mean density of the load. One sensor is placed at the bottom of the hopper and another sensor is used to measure atmospheric pressure. When the hydrostatic pressure difference between the bottom sensor and the sensor measuring atmospheric pressure are known, the average density of the load is known [6]:

\[ P_1 = h \cdot \rho_B \cdot g \]  \hfill (9)

\( P_1 \) = pressure difference between sensor 1 and atmospheric pressure in Pa
\( \rho_B \) = average density of the load in kg/m\(^3\)
\( h \) = average level of the load in m

This formula may be used only when the level of the load is known. The level may be measured by means of an acoustic level sensor, hand-lead or a step gauge. It is also possible (figure 7.2.1) to measure the pressure difference by using a third pressure sensor and a floating reference point to establish the level. The pressure sensor and the reference point are connected by a flexible tube filled with clean water. When measuring hydrostatic pressure, the level of the load can be established by using the following formula:
\[ h = \frac{P_2}{\rho_w g} \]  

**P₂** = pressure difference between sensor 3 and floating device in Pa  
\( \rho_w \) = density of water in kg/m³  
**h** = average level of the load in m

---

**Figure 7.2.1 Pressure measuring devices**

**F** = floating reference point for level measurement  
**R** = reference point for level measurement  
1 = pressure sensor 1 for measurement of hydrostatic pressure  
2 = pressure sensor 2 for measurement of atmospheric pressure  
3 = pressure sensor 3 for level measurement

When the level is known the volume of the load can be derived from the hopper content table. When all the variables in formula 8 are known the tonnes dry solids may be established.

---

### 7.2.2 Accuracy

The accuracy of the hopper pressure measurement method depends upon several parameters which are listed below:

- density of the load  
- level of the load  
- hopper content table  
- density of the water  
- specific density of the dredged material  
- effective stress in the load

Because the hopper pressure measuring method is fully automated, measurement of the density of the surrounding water and specific density of the dredged material is not possible. Both densities may be taken as constant in the formula for the establishment of tonnes dry solids, but if either or both of the densities is not accurately measured errors may occur. Although measurement of the exact load is not possible, the measurement of a pay unit is
still correct because the systematic error is not ship-dependent. A major problem occurs if there is effective stress in the load. If any settling material is present in the load, effective stress may occur. The output from the pressure sensor may deviate because the pressure measured deviates from the hydrostatic pressure. Control of existence of effective stress inside the hopper is almost impossible.

The variation in the density of the surrounding water and in specific density is not always the same in dredging areas. To set up a general accuracy calculation both densities must be estimated. With a fully liquid load the maximum accuracy may be established as follows:

- error in density of water 0.2%
- error in specific density of dredged material 1.5%
- error in pressure measurement 0.5%

The level of the load can be established by using several types of instrument. If several types of instrument are specified an accuracy of 0.5% across the calibrated span may be assumed. The error in volume depends upon the error in measuring the level and the surface of the hopper well. For trailing suction hopper dredgers, the surface of the hopper is rather constant over the entire height of the hopper and therefore the accuracy in determining volume as a percentage of the measured volume is equal to the accuracy in level measurement as a percentage of the measured level, thus 0.5%.

The error in mean specific density of the dredged material was assumed to be representative because no measurements were available.

The error in the measurement of the average density of dredged material depends on the error in pressure measurement and the error in measurement of level. The maximum error in measurement of the average density has been established in the following example.

\[
\rho_s = \frac{P}{h \times g} = \frac{107.91}{10 \times 9.81} = 1.1 \frac{kg}{m^3}
\]

When both the value from the pressure sensor and the value for the level of the load, are maximum values the maximum error is equal to 0.5% of the values. The maximum error in measurement of the average density may be established as

\[
\text{max error in density} = \frac{(107.91 \times 1.005)}{9.81 \times (10 \times 0.995)} - 1.1 = 1.111 \frac{kg}{m^3}
\]

and expressed as a percentage of the average density of the load the maximum error is:

\[
\text{max error in density} = \frac{(1.111 - 1.1)}{1.1} \times 100\% = 1.005\%
\]

Assuming a trailing suction hopper dredger with a hopper content
of 6000 m³ and an average density of the load equal to 1100 kg/m³, using formula 8, the overall maximum relative error in establishment of tonnes dry solids is:

\[
\text{Load} = \frac{1100 - 1000}{2650 - 1000} \times 2650 \times 6000/1000 = 963.6 \text{ TDS}
\]

\[
\Delta \text{TDS} = \frac{1100 \times 1.01 - (\frac{1000}{1.002})}{(\frac{2650}{1.015}) - (\frac{1000}{1.01})} \times \frac{2650 \times 6000 \times 1.005}{1000} - 963.6 = 139.35
\]

\[
\text{max relative accuracy} = \frac{\Delta \text{TDS}}{\text{LOAD}} \times 100 = \frac{139.35}{963.6} \times 100 = 14.5 \%
\]

Of course this accuracy calculation is only an indication for the specific example. This method for establishment of the maximum relative accuracy is chosen because

- it is a simple method
- there is no practical information about the system because the hopper pressure measurement method is never used as basis for measurement of payable dredged quantities.
- as will be explained in the conclusion, the method in unsuitable for measuring payable dredged quantities. Establishment of detailed (e.g probabilistic) accuracy will not change this conclusion, so therefore this simple method was chosen.

7.2.3 Requisites

Measuring instruments comprising two pressure sensors and a levelling device. To protect the sensors from pollution a water jet system must be installed. A pump with an output of at least 750 kPa and clean water is suitable for this purpose [6]. A computer must be available to process the data from the sensors, to establish tonnes dry solids and to store the calculated production data. Also necessary are floppy diskettes for the production data and a shore station to control the progress of the dredging project.

The measurement is correct when a non-place-dependent pressure sensor, suitable for liquids, is used. In this way, when tonnes dry solids are established, a fair pay unit is measured and the contractor may be correctly paid for all dredging-work being done.

7.2.4 Influence on dredge process

The hopper pressure measurement method is a step forward in the development of an ideal system. Payment on the basis of tonnes
Dry solids is fairer than any other basis, though only suitable for liquid loads. The dredge master will try not to obtain a mixture with any settling material as this may result in a lower pressure. If fluidization does not break down the effective stress completely, effective stress may cause bridging which decreases the measured pressure.

The vertical pressure in the hopper will be distributed over the level of the load as in figure 7.2.2.

![Figure 7.2.2. Vertical distribution of hopper pressure.](image)

The pressure measurements include hydrostatic pressure and effective stress. When effective stress is absent, only hydrostatic pressure will be measured. If effective stress is present the measured pressure will be greater. A higher pressure results in a higher average density reading for the load. This does not give a true indication of the density of the load. When sand particles are present in the mixture these particles will settle at the bottom of the hopper and the indication of the gauge will be impaired due to a bridging effect of the settled sand (figure 7.2.3), so the measurement is valueless.

![Figure 7.2.3. Effect of bridging.](image)

Fluidization of the load may break down the effective stress and thus possible bridging effects. Because it is doubtful whether fluidization will break down effective stress completely, the values measured are still unsuitable for measurement of payable dredged quantities.
7.2.5 Suitability

Measurements based on hydrostatic pressure are only suitable for liquid loads. In non-liquid loads problems occur because not only hydrostatic pressure, but also effective stress will be measured. To solve this problem a high pressure water jet system can be installed to fluidize the load, but such a system requires many adaptations and the costs are high, while there is still no certainty about the absence of effective stress. Because water is added to the load to fluidize it, the average density of the load will decrease, which will result in a decrease in payable dredged quantities. Data is only reliable when loads are without effective stress so because in trailing suction hopper dredging this state is seldom encountered, the method is unsuitable for the measurement of payable dredged quantities.

7.2.6 Conclusion

With a relative accuracy better than 14.5 % of the load and tonnes dry solids as pay unit, the hopper pressure method is an improvement on earlier ones and the accuracy may be increased when more pressure sensors are used in the hopper. A disadvantage is that only liquid loads without any effective stress (in other words without any settling material) are suitable for accurate and fair measurement. However it is almost impossible to obtain entirely liquid loads (without effective stress) when using trailing suction hopper dredgers. Fluidization of the load may break down the effective stress, but one cannot be certain that effective stress will be absent and therefore the hopper pressure measurement method is unsuitable for measurement of payable dredged quantities.
7.3 TONNES DRY SOLIDS SYSTEM

7.3.1 Introduction

In this chapter the Tonnes Dry Solids System will be discussed against the same criteria as were used in the previous chapters. Paragraph 7.3.3 is subdivided into two parts:

- establishment of the relative stochastic accuracy via a probabilistic accuracy analysis (paragraph 7.3.3.1 - 7.3.4.4)
- analysis of systematic errors (paragraph 7.3.5 - 7.3.5.5)

The stochastic accuracy and the systematic errors are separated because stochastic error may over or underestimate the load of the dredger. After several measurements, the mean value of the stochastic error will be equal to zero. Systematic errors occur with every measurement and will always lead to either overestimation or underestimation of the load. After several measurements the systematic errors will present a mean value which is not equal to zero.

The probabilistic accuracy analysis is used to establish a standard deviation of the measured production of the dredger. The results are relative standard deviations, because the density of the surrounding water is set as constant and the standard deviation of the specific density of the dredged material as 10 kg/m³. The dredging area is divided into several sub-areas because of variation of specific density due to variation in the composition of the dredged material, workability, dredgeability and differences in sailing distance. The standard deviation of the specific density is set as 10 kg/m³ to cover the variation per sub-area. This value is based on an assumption but, as presented in the appendix "relative accuracy of dredgers A, B and C", the influence of this variable is of minor importance (doubling the value of the standard deviation of the specific density will result in a maximum decrease in accuracy of 0.1%).

In order to evaluate how well the TDSS measures ship-independent production the standard deviation of the measured production has been established for three different trailing suction hopper dredgers.

To evaluate the final result of the complete accuracy analysis the systematic errors were also established for the same dredgers.

7.3.2 Description

The Tonnes Dry Solids System (TDSS) is a measuring method, developed by Rijkswaterstaat through extensive trials during the period 1985 - 1987. During the winter season 1988 - 1989, the first contract was negotiated and executed on the basis of remuneration in accordance with the TDSS. Since then the system has been fully operational.

The system is based on the measurement of displacement of the vessel and volume-content of the hopper.
The displacement is established by measuring the draft of the vessel, using two pressure sensors situated in the keel of the vessel. Given the draft of the empty vessel, the displacement can be derived from the carène diagram in which draft is related to the displacement, so the displacement of the empty ship displacement is known. The draft of the loaded vessel is also measured and so the displacement of the loaded vessel is known. By subtracting the displacement of the empty ship from that of the loaded ship and then multiplying the result by the density of the surrounding water, the weight of the load can be obtained.

The content of ballast-tanks changes or changes or additional ballast (i.e. spare parts) is introduced, the weights derived for the vessel when full and empty must be corrected. The content of the hopper is established by using acoustic sensors to determine the level of the load from which, via the hopper volume calibration list, the volume is derived (figure 7.3.1).

![Hopper Level Measure Instruments](image)

Figure 7.3.1 Measurement devices

By using the following formula, tonnes dry solids (explanation in paragraph 7.2.1.) may be derived from the measured results:

\[
TDS = \frac{(M/V) - \rho_w}{\rho_s - \rho_w} \cdot \rho_s \cdot V
\]

(11)

\(M\) = weight of the load in kg

\(V\) = volume of the load in m³

\(\rho_w\) = density of surrounding water in kg/m³

\(\rho_s\) = specific density of dredged material in kg/m³

The Tonnes Dry Solids System is fully automated; during the entire dredging cycle (figure 7.3.2) data are monitored and available.

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An example of the computer-screen is presented in figure 7.3.5.

There are several ways to check the measuring instruments [11]:

- trim-trim (figure 7.3.3).
  The surface of a static liquid is always horizontal. By measuring the surface in the hopper, using the acoustic sensors, and by measuring the surrounding water surface, using the pressure sensors, two independent inclination values may be derived. Subtraction of those values should give a zero-value if the sensors are measuring correctly. For a working dredger this is the most critical control. In practice many options have been tried in order to avoid using the trim-trim check and possible problems which it may cause. Much attention must be paid to the configuration of the trim-trim check. Currently the trim-trim check carried out during "dredging" takes five minutes. The hopper is filled with water until the check has been completed after which dredging will start. An other option is to interrupt the dredging process for five minutes in order to make the check. In nautical language the definition of a trimmed vessel is: "a vessel with equal draft fore and aft, resulting in an angle to the water-surface equal to zero". In the following chapters trim will be used to express the difference between draft fore and aft in relation to the surface of the surrounding water. The trim of the vessel is positive in case of draft aft exceeding the draft fore.

- fixed distance between level of pressure sensors and acoustic sensors (figure 7.3.4).
  The addition of the distance from the acoustic reference level to the filling-level of the hopper and the distance from the pressure sensor to the outboard water level, while the bottom doors are open, should be equal to the distance
between the pressure and acoustic sensors.

Figure 7.3.3 Trim-trim control

- water content of the hopper
  When the hopper is filled with water the indication of tonnes dry solids should be zero.

Figure 7.3.4 Level control

- bunker consumption.
  An additional control may be accomplished by periodical measurements of the "empty ship value" under restricted conditions. The intermediate trips should fit in the predefined regression line.
The status of the vessel (sailing empty, dredging, sailing loaded, dumping, shore delivery) is measured by means of 5 gate switches: suction pipe in dredging position, average draught < 6 metres (for medium to large size hoppers over 4000 m³ hopper-contents), bottom-doors closed, dredge pump running and shore delivery valve open. The status is determined by combining the signals (Table 1).

<table>
<thead>
<tr>
<th>status</th>
<th>suction pipe in dredging position</th>
<th>average draught &lt; 6m</th>
<th>bottom-doors closed</th>
<th>dredge-pump running</th>
<th>shore delivery valve open</th>
</tr>
</thead>
<tbody>
<tr>
<td>sailing empty</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>dredging</td>
<td>YES</td>
<td>-</td>
<td>YES</td>
<td>YES</td>
<td>-</td>
</tr>
<tr>
<td>sailing loaded</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>NO</td>
<td>-</td>
</tr>
<tr>
<td>dumping</td>
<td>NO</td>
<td>-</td>
<td>NO</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>shore delivery</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>YES</td>
<td>YES</td>
</tr>
</tbody>
</table>

Table 1. Determination of status
Datum 2 Mar 1983 Tijd 09:47:27 BEU DAT Nr 6009 File 1775
Waterverplaatsing leegschip op Stort 7932 ton
Waterverplaatsing leegschip maandag-vrijdag 64746 ton
Waterverplaatsing volschip eind zuigen 15776 ton
Watt 7932 ton Beuninh 6009 M3 Droge Stof 2694 ton
Volumegewicht 1.289 Ton/M3

Figure 7.3.5 Example of screen presentation
7.3.3 Probabilistic accuracy analysis

7.3.3.1 Description

The TDSS is accessible to probabilistic accuracy analysis because all variables have a stochastic distribution. The recorded weight of the load varies due to variations in the accuracy of pressure sensor, temperature influence, influence of wave and/or swell on the pressure sensor and the accuracy of the carène diagram. Variation in the recorded volume of the load may occur due to the inaccuracy of the acoustic sensors. Variation in water density may occur due to the presence of fresh water in tidal rivers and saline seawater. When dredging in several locations, variation in specific density of the dredged material may occur. For all variables, a symmetrical density distribution is taken into account. The variables temperature influence, influence of wave and/or swell, accuracy of the carène diagram, variation of density of surrounding water and variation in specific density of dredged material may cause a specific density distribution, but to be able to establish a mean value and a standard deviation in a simple way, a symmetrical density distribution is assumed.

The results of a study into the stochastic variation of the variables, as used in the TDS system, are listed below:

- An error may occur in the carène diagram for several reasons. Paying proper attention to the correct interpretation of the carène diagram may diminish errors or even exclude them.

- The pressure measurement sensors may have an error. The maximum error due to non-linearity prescribed in the contract for Rijkswaterstaat, is set as 0.5% of the span, exclusive of errors due to repeatability and hysteresis. The span is the physical value with matching output signal of 10 volts minus the physical value with matching output signal of 2 volts. An error due to the influence of temperature may also have a maximum of 0.5% of the span. For all pressure sensors used the error in repeatability of the output values may be taken as 0.05% of the span. The TDS presents several values every five seconds as values averaged over 125 signals, so the error of repeatability diminishes and may even be taken as zero, leaving an error due to temperature influence and linearity. The error due to non-linearity occurs in all measuring and is therefore to be regarded as a systematic error. The error due to temperature influence remains. This error is a stochastic error because the temperature of the surrounding water varies in time and so the variation of the pressure sensors may be set as:
  In this way 99.5% of all correct measurements have a temperature influence of less than 0.5% of the span. The relation between the value 99.5% and the value 2.81 is
\[ \text{Var}_{\text{pressure measurement}} = \frac{(0.5\% \text{ of span})^2}{2.81} \] (12)

presented in the appendix "symmetrical density distribution". In the specification of the measurement instruments a maximum value for the accuracy is presented and therefore all measurements will have an accuracy less or equal to 0.5\% of the calibrated span. When a value of 100\% is used for a symmetrical density distribution the standard deviation will become zero. Therefore the value 99.5\% which approximates the 100\% value very well is used and this value is often found in literature on the subject.

- For the acoustic sensor the criteria which apply in the contract are the same as for the pressure sensors. The same procedure may be followed to establish the variation, resulting in a variation of acoustic level measurement of:

\[ \text{Var}_{\text{acoustic measurement}} = \frac{(0.5\% \text{ of span})^2}{2.81} \] (13)

Furthermore, a systematic error due to non-linearity has to be taken into account. The value 2.81 is extracted from a table of a standard symmetrical density distribution (appendix symmetrical density distribution).

7.3.3.2 Probabilistic calculation

For establishment of failure-chances, three levels have been classified [12]:

- level III contains the exact probabilistic approach. Use is made of probability density functions (p.d.f's) for all variables taken into account.
- level II incorporates a number of approximation methods. The problem is linearized near a specific point.
- level I contains design methods which use safety-factors which create a distance between characteristic "load" and "resistance" values.

In recent years the popularity of probabilistic calculation has greatly increased, especially for "level II" calculations, because of its practical applicability. A second advantage is that it includes insight into the contribution of each variable to the resulting failure-band.

Because of these advantages the "level II" method is used to establish the failure-band for the Tonnes Dry Solids System.

Probabilistic calculation:

First a reliability function Z has to be made. To calculate tonnes dry solids the following formula 11 is used.
\[ TDS = (\frac{M}{V} - p_W) \cdot p_s \cdot V \]

The weight of the load is determined by measuring the weight of the vessel when empty and when loaded, using the carène diagram. The currently operated Tonnes Dry Solids System uses a polynomial function which approximates the carène diagram for a fully trimmed vessel (angle of vessel with the surface of the surrounding water is equal to zero). The polynomial function introduces errors, therefore the intention is to replace the polynomial function by an exact matrix of the carène diagram. This matrix is used to establish the accuracy of the Tonnes Dry Solids System. Linearization of the matrix over a very short part of the draft-range (approximately 0.20 metres) for the empty and loaded vessel is allowed because the matrix shows a linear relation over such a short band. The water-displacement of the load may therefore be established as:

\[ W = A \cdot D_{\text{loaded}} + B_u \cdot C + D_{\text{empty}} \cdot D_u \] (14)

\( D_{\text{Loaded}} \) = draft of loaded ship in metres

\( D_{\text{empty}} \) = draft of empty ship in metres

B and D are symmetrical density distributions with mean values \( B_u \) and \( D_u \), established to linearize the carène matrix, and the standard deviations \( B_0 \) and \( D_0 \) which represent the accuracy of the carène diagram. The dimension of B and D is \([\text{m}^3]\), the dimension of A and C is \([\text{m}^3/\text{m}]\). The relation between draft, displacement, A, Bu and Bo is presented in figure 7.3.6.

![Figure 7.3.6. Relation between draft, displacement, A, Bu, Bo](image)

Now only the variables draft of the loaded and empty ship are variables for the measurement of the load. \( D_{\text{Loaded}} \) and \( D_{\text{empty}} \) are depend not only upon the accuracy of the draft measurement instrument but also on the influence of wave action and ship motion.
Influence of wave action:

For wave action the following assumptions are made:

- the steepness of the waves, $S$, is assumed to be constant meaning:

$$S = \text{wave height/wave length} = \frac{H_s}{L} = \text{constant}$$

For the wave height in deep water:

$$L_0 = \left(\frac{g}{(2\pi)}\right) \cdot (Tp)^2$$

$$= 1.56 \cdot (Tp)^2$$

$$\Rightarrow Tp = \sqrt{\left(\frac{L}{1.56}\right)}$$

$Tp$ = wave-peak period (in seconds)

Therefore the peak period becomes:

$$Tp = \left[\frac{1}{\sqrt{(S \cdot 1.56)}}\right] \cdot \sqrt{H_s}$$

With wave steepness $S=0.035$ and a known wave height, the peak period may be established as:

$$Tp = 4.28 \cdot \sqrt{H_s}$$

If a ship is sailing at a speed $V_s$ and there are incoming waves from all possible directions, the following formula applies:

$$T_1 = Tp - \frac{2\pi}{g} \cdot V_s \cdot \sin(\alpha)$$  \hspace{1cm} (15)

$\alpha$ = angle between wave propagation direction and vessel propagation direction in degrees.

$T_1$ = resulting wave period in seconds.

$g$ = earth gravity acceleration in m/s$^2$.

In shallow water the wavelength becomes:

$$L_1 = L_0 \cdot \tanh(kh) = \frac{9.81 \cdot T_1^2}{2\pi} \cdot \tanh(kh)$$  \hspace{1cm} (16)

$L_1$ = resulting wavelength in metres.

$tanh(kh)$ may be read from a table which shows a relation between $h/L_0$ and $tanh(kh)$ with $h$ = water-depth.

To establish the influence of waves on the pressure distribution underneath the keel of the vessel, the assumption is made that in the case of a wavelength smaller than the length of the ship (angle $\alpha$ more than zero: the diagonal length of the ship must be calculated) the influence of the wave on the pressure-sensor may be neglected. Otherwise the wave has an influence equal to the following formula [13]:

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\[
\Delta p = A_w \times 9.81 \times p_w \times \frac{\cosh(h+z) \times k}{\cosh(kh)}
\]

\(\Delta p\) = maximum pressure difference during wave-passage in N/m²

\(A_w\) = amplitude (half of wave height) in metres

\(z\) = depth of pressure-sensor to the water-surface in metres

\(p_w\) = density of surrounding water in kg/m³

The pressure measured by the pressure sensor will now have the following distribution in time

\[p(t) = z \times p_w \times 9.81 + \Delta p \times \sin\left(\frac{2 \times \pi \times t}{T_1}\right)\]

For \(z\) = draft loaded and empty ship and a given wave height, the influence of the wave \(\Delta p\) on the pressure sensor may be established. The Tonnes Dry Solids System averages the signals over a specific time and thus the amplitude of the resulting pressure-difference will decrease. When the wave period is equal to the averaging time of the TDSS the resulting pressure variation will be zero. If the wave period is not equal to the averaging time, the final decrease in the amplitude is related to the proportion of the averaging time and the wave period and can be established as follows:

\[A_{wres} = \int_{T_{avr}} \Delta p \times \sin\left(\frac{2 \times \pi \times t}{T_1}\right) \delta t\]

\(A_{wres}\) = resulting amplitude in metres

\(T_{avr}\) = averaging time of the TDSS in sec

The resulting formulas are suitable for numerical calculation with the aid of a computer and for this purpose the computer-program D_PRESS.EXE has been developed to calculate the resulting influence.

The computer-program rotates the vessel over 360 degrees and establishes the variation in pressure due to wave influence for any angle between the vessel’s sailing direction and the propagation direction of the waves. To establish a standard deviation for wave influence, the resulting probabilistic density functions will be numerically integrated into one probabilistic density function. The computer-program D_PRESS.EXE presents the variation in draft due to the wave influence Var_Dw.

The results from the computer-program apply for one pressure-sensor. The TDS system uses the average value of two pressure-sensors for the establishment of the draft, so the following formulas must be used to establish the variation of the draft measurement:

63
\[ Var_{Da} = Var_{Df} = \left( \frac{0.005 \cdot \text{span}}{2.81} \right)^2 + Var_{Dw} \]  

(20)

\[ Var_{Dapp} = Var_{Da} \cdot (1 + \frac{L_a}{L_{av}})^2 \cdot Var_{Df} \cdot \left( \frac{L_a}{L_{av}} \right)^2 \]  

(21)

\[ Var_{Dfpp} = Var_{Df} \cdot (1 + \frac{L_f}{L_{av}})^2 \cdot Var_{Da} \cdot \left( \frac{L_f}{L_{av}} \right)^2 \]  

(22)

\[ Var_{avD} = 0.25 \cdot Var_{Dapp} + 0.25 \cdot Var_{Dfpp} \]  

(23)

- \( Var_{Dapp} \) = variation of draft at a.p.p. in metres
- \( Var_{Dfpp} \) = variation of draft at f.p.p. in metres
- \( Var_{Da} \) = variation of aft draft measurement in metres.
- \( Var_{Df} \) = variation of fore draft measurement in metres.
- \( L_{av} \) = distance between pressure sensors in metres.
- \( L_a \) = distance from aft pressure sensor to a.p.p in metres.
- \( L_f \) = distance from fore pressure sensor to f.p.p in metres.
- \( Var_{avD} \) = variation of average draft of the vessel in m.

**Establishment of weight of the dredger:**

The weight of the loaded ship will be established as:

\[ (A \cdot D_{av} \cdot \text{(loaded ship)} \cdot Bu) \cdot 1013, \text{ with } D_{av} \text{ as average draft and } 1013 \text{ the density of the surrounding water in kg/m}^3. \]

In this way two assumptions are made:

- First the average density of the surrounding water is taken as 1013 kg/m\(^3\). Investigation [14] leads to the conclusion that near Hoek van Holland (at Km 1029) the average density of the surrounding water at a depth of 10 metres is 1013 kg/m\(^3\). The density of the surrounding water has no influence on the result because the weight of the hopper is constant.

The second assumption is that pressure sensors are used to measure the draft. This is certainly not true because the sensors measure hydrostatic pressure. The draft may be obtained from the pressure as

\[ \frac{Draft}{\left( \frac{Pressure \ (Pa)}{g \ (m/s^2) \cdot \rho_w \ (kg/m^3)} \right)} \]  

(24)

The draft can be used with the carène diagram and thus the displacement of the loaded ship is known. To establish the weight of the loaded ship, the displacement is multiplied by the density of the surrounding water. The density of the
water may vary due to changes in temperature and salinity and therefore the draft of the loaded ship changes but not the weight of the loaded ship. When assuming an average loaded draft of the ship and average density of the surrounding water at the given depth, the weight of the loaded ship is established as constant. This assumption will thus not influence the result of the probabilistic accuracy calculation. For the empty ship the same assumption can be made.

The measurement of the empty ship nearly always takes place at the northern dump-site, where the average density of the surrounding water is 1020 kg/m³. The weight of the empty ship may be established as:

\[
\text{weight empty ship} = (C \cdot D_{\text{avr}}(\text{empty ship}) \cdot Du) \cdot 1020
\]

The reliability function \( Z \) may now be translated into:

\[
Z = \frac{((A \cdot D_{\text{avr,loaded}} \cdot Bu) \cdot 1013 - (C \cdot D_{\text{avr,empty}} \cdot Du) \cdot 1020) - \rho_g \cdot V}{\rho_s - \rho_w} \cdot \rho_s - \text{TDS}
\]

**Establishment of variation in volume of the load:**

The distance from the acoustic sensors to the surface of the load at the front and back of the hopper respectively may be established as follows:

\[
N_{\text{bhv}} = N_s \cdot \frac{(N_s - N_f)}{Bl_{av}} \cdot Bl_s
\]

\[
N_{\text{fhv}} = N_f \cdot \frac{(N_s - N_f)}{Bl_{av}} \cdot Bl_f
\]

\[
A_{av} = \frac{(N_{\text{bhv}} + N_{\text{fhv}})}{2}
\]

When four sensors are used (two sensors fore and two sensors aft), the sensors fore and aft must present an averaged value. The variation of the averaged signals can be established as 0.5*variation of one aft acoustic sensor for aft acoustic measurement and the variation of fore acoustic measurement as 0.5*variation of one fore acoustic sensor.

The variation of the measurement of volume when using four acoustic sensors, may be established as follows:
\[ \text{Var}_{\text{Hbw}} = \text{Var}_{\text{Na}} \times (1 + \frac{\text{BL}_{f}}{\text{BL}_{av}})^2 \times \frac{\text{Var}_{\text{Nf}} \times (\frac{\text{BL}_{f}}{\text{BL}_{av}})^2}{\text{BL}_{av}} \] (28)

\[ \text{Var}_{\text{Hfw}} = \text{Var}_{\text{Nf}} \times (1 + \frac{\text{BL}_{f}}{\text{BL}_{av}})^2 \times \frac{\text{Var}_{\text{Nf}} \times (\frac{\text{BL}_{f}}{\text{BL}_{av}})^2}{\text{BL}_{av}} \] (29)

\[ \text{Var}_{v} = (0.25 \times \text{Var}_{\text{Hbw}} + 0.25 \times \text{Var}_{\text{Hfw}}) \times \text{Opp}^2 \] (30)

\( \text{Var}_{v} \) = variation of volume of hopper-load in m³
\( \text{Opp} \) = surface of hopper in square metres
\( \text{Na} \) = aft acoustic measurement in metres
\( \text{Nf} \) = fore acoustic measurement in metres
\( \text{Nphw} \) = acoustic level at back of hopper in metres
\( \text{Nfhw} \) = acoustic level at front of hopper in metres
\( \text{BL}_{av} \) = distance between acoustic sensors in metres
\( \text{BL}_{f} \) = distance from b.h.w. to aft acoustic sensor in m
\( \text{b.h.w.} \) = back of hopper.
\( \text{f.h.w.} \) = front of hopper.

"level II" probabilistic accuracy calculation:

With the previously mentioned variables the "level II" probabilistic accuracy calculation may be established as:

<table>
<thead>
<tr>
<th>( X_i )</th>
<th>Mean value</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>draft loaded</td>
<td>( \text{D}_{avr}(\text{loaded}) = \text{input} )</td>
<td>( \text{Var}_{avd}(\text{loaded}) = \text{input} )</td>
</tr>
<tr>
<td>draft empty</td>
<td>( \text{D}_{avr}(\text{empty}) = \text{input} )</td>
<td>( \text{Var}_{avd}(\text{empty}) = \text{input} )</td>
</tr>
<tr>
<td>A</td>
<td>( A = \text{input} )</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>( B_u = \text{input} )</td>
<td>( B_o = \text{input} )</td>
</tr>
<tr>
<td>C</td>
<td>( C = \text{input} )</td>
<td>-</td>
</tr>
<tr>
<td>D</td>
<td>( D_u = \text{input} )</td>
<td>( D_o = \text{input} )</td>
</tr>
<tr>
<td>V</td>
<td>( V = \text{input} )</td>
<td>( \text{Var}_{v} = \text{input} )</td>
</tr>
<tr>
<td>( \rho_{N} )</td>
<td>( \rho_{N} = \text{input} )</td>
<td>( \text{Var}_{\rho N} = \text{input} )</td>
</tr>
<tr>
<td>( \rho_{S} )</td>
<td>( \rho_{S} = \text{input} )</td>
<td>( \text{Var}_{\rho S} = \text{input} )</td>
</tr>
</tbody>
</table>

Table 2. Input list
<table>
<thead>
<tr>
<th>$X_i$</th>
<th>$\frac{\partial z}{\partial X_i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{\text{loaded}}$</td>
<td>$\frac{A \cdot p_s}{p_s - p_w}$</td>
</tr>
<tr>
<td>$D_{\text{empty}}$</td>
<td>$\frac{-C \cdot p_s}{p_s - p_w}$</td>
</tr>
<tr>
<td>$B$</td>
<td>$\frac{1013 \cdot p_s}{p_s - p_w}$</td>
</tr>
<tr>
<td>$D$</td>
<td>$\frac{-1020 \cdot p_s}{p_s - p_w}$</td>
</tr>
<tr>
<td>$V$</td>
<td>$\frac{-p_w \cdot p_s}{p_s - p_w}$</td>
</tr>
<tr>
<td>$p_w$</td>
<td>$\frac{V \cdot (p_s - p_w) + (A \cdot D_{\text{loaded}} + Bu) \cdot 1013 - (C \cdot D_{\text{empty}} + Du) \cdot 1020 - p_w \cdot V}{(p_s - p_w)^2}$</td>
</tr>
<tr>
<td>$p_s$</td>
<td>$\frac{-p_w \cdot ((A \cdot D_{\text{loaded}} + Bu) \cdot 1013 - (C \cdot D_{\text{empty}} + Du) \cdot 1020) + p_s^2 \cdot V}{(p_s - p_w)^2}$</td>
</tr>
</tbody>
</table>

Table 3. Partial differentials
After multiplication of the partial differentials by the square root of the variation, the sum of the results is equal to the variation in the tonnes dry solids.

\[ \text{Var}_{\text{ms}} = \sum_{i=1}^{N} (\sqrt{\text{Var}_{i}} \frac{\partial z}{\partial x_i})^2 \]  

(31)

After multiplication of the square root of the variation in tonnes dry solids by 1.96, the maximum absolute error of 95% of the tonnes dry solids-measurements is known.

The Tonnes Dry Solids System used by Rijkswaterstaat does not measure the tonnes dry solids but provides a pay-unit, because the density of the surrounding water and the specific density of the dredged material are not actually measured but taken as 1020 kg/m³ and 2600 kg/m³ respectively.

To establish the relative accuracy, the variation of \( \rho_W \) and \( \rho_S \) must be known.

For a basis of comparison it is not necessary to measure the real values of the densities of water and dredged material because they differ throughout the seasons and/or from area to area. In the Hoek van Holland area several dredgers are operating at different periods and in different dredging areas. In the various locations differences in mean density of water and mean specific density of dredged material (due to differences in composition of the dredged material) may occur, making a reliable comparison impossible.

The contractor will try to predict his production and, on the basis of this prediction, he offers a price per ton dry solids. The density of the water influences the quantity of tonnes dry solids, but not the efficiency of the dredger and therefore the variation of the density of the water must be used in the probabilistic accuracy calculation.

The specific density of the dredged material also influences the quantity of tonnes dry solids, but differences in density imply differences in material. Different materials, together with differences in workability, dredgeability and differences in sailing distance, will lead to differences in production and efficiency of the dredger so the contractor will offer a different price per ton dry solids. The difference in tonnes dry solids, due to differences in specific density of the dredged material may be incorporated in the price per ton dry solids.

Comparison of production of tonnes dry solids in different dredging areas is not possible because differences in specific density of dredged material may occur but the contractor is only interested in comparison of profits. This comparison take place on the basis of price per ton dry solids and production and, because the difference in specific density are incorporated in the price, comparison is allowed when the specific density is set as constant.

In the Hoek van Holland area dredging has taken place for several years and the contractor may be able to predict production and efficiency of the dredger in the different dredging areas so prices per ton dry solids vary for different dredging areas. Now only differences in mean specific density of the dredged material per dredging area have to be
considered. The specific density of the dredged material is set as 2600 kilogramme per cubic metre but comparison is still allowed because of the difference in prices. If the standard deviation is estimated as 10 kg/m³, the mean specific density for one dredging area varies between 2570 and 2630 kg/m³, which is assumed to approximates reality. As mentioned in paragraph 7.3.1, the influence of the variation in the mean specific density of the dredged material on the probabilistic accuracy is only of minor importance and therefore no in-situ specific density measurements have been executed to confirm the estimated variation.

Throughout the Hoek van Holland dredging area the average density of the surrounding water is 1020 kg/m³, because the lower water layer has a density of 1020 kg/m³ owing to the influence of the salt water wedge. Measurements [14] show an average density of 1016.4 kg/m³ at a depth of 14-16 metres and therefore it may be assumed that at a depth of 24 metres the density will be 1020 kg/m³. Variation in the density of the water occurs owing to difference in temperature. A temperature variation of 10 degrees causes a 2kg/m³ variation in density and the standard deviation will be very small. The influence in the probabilistic accuracy calculation, due to the variation in density of the water, will be very small and therefore this phenomenon may be justifiably neglected.

In the following paragraph three trailing suction hopper dredgers operating with the Tonnes Dry Solids System, will be compared for loads with a mixture density of 1330 kg/m³, which is approximately the average density for all trailing suction hopper dredgers operating with the Tonnes Dry Solids System in the Hoek van Holland area.

The relative probabilistic accuracy encompasses accuracy of measurement instruments and wave influence. The calculation and the data used is presented in the appendix.

7.3.4 Analysis of relative stochastic accuracy.

A preliminary analysis of the data resulted in the impression that the accuracy of the TDS system varies with ship-dependent characteristics.

To prove this supposition, the relative stochastic accuracy for three different trailing suction hopper dredgers has been established.

The calculation is presented in the appendix "relative stochastic accuracy". The results are presented in the following three paragraphs.

7.3.4.1 Relative stochastic accuracy of dredger A.

The trailing suction hopper dredger A was built in 1981 and has operated with the Tonnes Dry Solids System for several years.

The results of the probabilistic calculation are:
quantity of tonnes dry solids = 3100.39 tonnes
density of mixture in hopper = 1330 kg/m³
maximum error in 95% of measurements = 107.5 tonnes
maximum error in 95% of measurements = 3.47 %

7.3.4.2 Relative stochastic accuracy of dredger B

The trailing suction hopper dredger B was built in 1984 and has operated with the Tonnes Dry Solids System for two years.

The results of the probabilistic calculation are:

quantity of tonnes dry solids = 4201.59 tonnes
density of mixture in hopper = 1330 kg/m³
maximum error in 95% of measurements = 184.5 tonnes
maximum error in 95% of measurements = 4.39 %

7.3.4.3 Relative stochastic accuracy of dredger C

The trailing suction hopper dredger C was built in 1969 and has operated with the Tonnes Dry Solids System for several years.

The results from the probabilistic calculation are:

quantity of tonnes dry solids = 3067.19 tonnes
density of mixture in hopper = 1330 kg/m³
maximum error in 95% of measurements = 147.2 tonnes
maximum error in 95% of measurements = 4.80 %

7.3.4.4 Evaluation of relative stochastic accuracy

The following table was derived from the results given in the previous paragraph:

<table>
<thead>
<tr>
<th></th>
<th>dredger A</th>
<th>dredger B</th>
<th>dredger C</th>
</tr>
</thead>
<tbody>
<tr>
<td>quantity tds (tonnes)</td>
<td>3100.39</td>
<td>4201.59</td>
<td>3067.19</td>
</tr>
<tr>
<td>density of mixture (kg/m³)</td>
<td>1330</td>
<td>1330</td>
<td>1330</td>
</tr>
<tr>
<td>maximum error in 95% of measurements (tonnes)</td>
<td>107.5</td>
<td>184.5</td>
<td>147.2</td>
</tr>
<tr>
<td>maximum error in 95% of measurements (% of production)</td>
<td>3.47</td>
<td>4.39</td>
<td>4.80</td>
</tr>
</tbody>
</table>

Table 4. Relative stochastic accuracy.
The distances between the measurement instruments of dredgers A and C are of the same order in relation to the length of the dredger. The distances between the measurement instruments of dredger B are larger in relation to the length of this dredger. This has a minor influence on the accuracy of the TDS system (0.05-0.1 % of the production).

Dredger A has the largest block-coefficient and dredger C has the smallest block-coefficient. It is clear that the relative accuracy is strongly related to this block-coefficient. Modern trailing suction hopper dredgers have a large block-coefficients which increases the accuracy of the Tonnes Dry Solids System.

7.3.5 Analysis of systematic errors in system in current use.

7.3.5.1 Systematic errors in system in current use.

The carène diagram presents the relation between draft and displacement of a vessel. The diagram is derived from the construction drawings of the vessel. For several levels (different drafts to a reference basis) the volume of the part below this level is established by means of mathematical formulas. The volume is only established for the part within the outer edge of the ribs and thus without the shell and appendages (like rudders and propellers) of the vessel. The reference level is not, therefore, the underside of the vessel but the outer edge of ribs, the difference between these two levels being equal to the thickness of the shell.

The volume of the shell and appendages is established separately and may be added to the previously mentioned volume. If there are changes in the shell and/or appendages, the volume of these parts must be re-established, and recalculated, thus avoiding the need to re-establish of the total volume [15]. Errors may occur due to inaccuracies in the carène diagram and in the interpretation of that diagram. The possible errors are:

- The volume of the shell and appendages of the vessel are incorrectly calculated. It may be that a deviation of approximately 0.5% from the established volume inside the outer edge of the ribs is accepted as the volume of the shell and appendages. An error of approximately 5 to 20 m³ may occur (Tables 5 and 6) but the volume of the shell and appendages has been established for all trailing suction hopper dredgers operating in the Hoek van Holland area and therefore no errors occur due to this phenomenon.
<table>
<thead>
<tr>
<th>draft (m)</th>
<th>volume (m³)</th>
<th>volume of shell +app (m³)</th>
<th>volume total (m³)</th>
<th>volume + 0,5% (m³)</th>
<th>difference (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>4610</td>
<td>36</td>
<td>4646</td>
<td>4633</td>
<td>-13</td>
</tr>
<tr>
<td>4.0</td>
<td>6360</td>
<td>39</td>
<td>6399</td>
<td>6392</td>
<td>-7</td>
</tr>
<tr>
<td>5.0</td>
<td>8150</td>
<td>42</td>
<td>8192</td>
<td>8191</td>
<td>-1</td>
</tr>
<tr>
<td>6.0</td>
<td>10000</td>
<td>47</td>
<td>10047</td>
<td>10050</td>
<td>+3</td>
</tr>
<tr>
<td>7.0</td>
<td>11890</td>
<td>50</td>
<td>11940</td>
<td>11949</td>
<td>+9</td>
</tr>
<tr>
<td>8.0</td>
<td>13850</td>
<td>53</td>
<td>13903</td>
<td>13919</td>
<td>+16</td>
</tr>
</tbody>
</table>

Table 5. Difference of volume for dredger A.

<table>
<thead>
<tr>
<th>draft (m)</th>
<th>volume (m³)</th>
<th>volume of shell +app (m³)</th>
<th>volume total (m³)</th>
<th>volume + 0,5% (m³)</th>
<th>difference (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>7290</td>
<td>76</td>
<td>7366</td>
<td>7326</td>
<td>-40</td>
</tr>
<tr>
<td>5.0</td>
<td>9320</td>
<td>91</td>
<td>9411</td>
<td>9367</td>
<td>-44</td>
</tr>
<tr>
<td>6.0</td>
<td>11415</td>
<td>99</td>
<td>11514</td>
<td>11472</td>
<td>-42</td>
</tr>
<tr>
<td>7.0</td>
<td>13565</td>
<td>103</td>
<td>13668</td>
<td>13633</td>
<td>-35</td>
</tr>
<tr>
<td>8.0</td>
<td>15755</td>
<td>107</td>
<td>15861</td>
<td>15834</td>
<td>-27</td>
</tr>
<tr>
<td>9.0</td>
<td>17990</td>
<td>111</td>
<td>18101</td>
<td>18080</td>
<td>-21</td>
</tr>
</tbody>
</table>

Table 6. Difference of volume for dredger D.

- An error may occur due to incorrect interpretation of the reference basis. Unless specifically mentioned the reference basis is always the outer edge of the ribs. If when using such an carène diagram, the outer shell of the hull is chosen as the basis, an error of 0.02 to 0.05 m occurs, resulting in displacement error of 5 to 20 m³.

- Incorrect interpretation of the dimensions of the carène diagram may result in an error in the displacement calculation of the vessel. The carène diagram presents the relation between draft and displacement of a vessel. The idea may prevail that the carène diagram presents the relation between draft and weight of the vessel. The weight of the vessel is established by multiplying the displacement by the density of the surrounding water. Because the density of the water may differ the displacement of the vessel differs and thus the draft of the vessel but not the weight. Therefore it is not possible to establish a unique fresh and salt water carène diagram. Sometimes a relation between draft and weight in salt and fresh water is supplied but these relations must never be used unless it is absolutely certain that the density of
the surrounding water is equal to the density of the water used in these relations. If the density of the surrounding water differs from that used in the relations between draft and weight, an systematic error of up to 2.5% of the weight of vessel may occur.

- Up to now a polynomial is still used to approximate the carène diagram. It intended that the polynomial should be replaced by a matrix consisting of the data from the carène diagram so the polynomial is not used in the probabilistic calculation. However, when the polynomial is used systematic errors may occur. For an equally trimmed vessel (angle with the surface of the surrounding water equal to zero), the polynomial approximates to the carène diagram rather well, with an error of 5 to 20 m³ displacement. For trim in empty state of 1 to 2 metres and for trim in loaded state of -1.0 metre, differences in displacement caused by the load, amount to between 40 and 100 m³ depending upon the trailing suction hopper dredger being used (appendix difference between polynomial and carène-diagram). Replacement of the polynomial by the matrix is certainly justified.

- To establish draft via pressure measurement, conversion using formula 24 is necessary. The Tonnes Dry Solids System currently used by Rijkswaterstaat, uses a value of 10 instead of the exact value 9.81 for the earth gravity acceleration and a density of the surrounding water of 1000 kg/m³. In this way the measured pressure will be converted into a draft which would occur in fresh water. The displacement is derived from the carène diagram and multiplication of the displacement by 1000 (density of surrounding water) gives the weight of the vessel. When dredging in the open sea the density of the surrounding water will be approximately 1020 kg/m³. To establish the draft of the vessel the measured pressure must be converted by using formula 24. In using g=10 m/s² and \( p_W = 1000 \) kg/m³ instead of g=9.81 m/s² and \( p_W = 1020 \) kg/m³ a systematic error of 0.062% in draft measurement will be made which may be neglected. To establish the weight of the vessel the displacement will be derived from the carène diagram and multiplied by the density of the surrounding water. In using \( p_W = 1000 \) kg/m³ instead of 1020 kg/m³ an error of 2% will be made in establishing the empty and loaded weight. The load of the dredger will be less and an error of approximately 100 - 150 tonnes dry solids will be made, depending upon the dredger being used. When the value for the earth gravity acceleration g=10 m/s² is replaced by g=9.81 m/s² and the fresh water draft at the middle of the hopper is converted to a salt water draft, the error will decrease to 30 tonnes dry solids. Care should be taken when the value is replaced because other variables may depend upon the value being used for the earth gravity acceleration.
- When dredging in rivers, the density of the surrounding water is less than in the open sea due to stratification of water layers of different densities. Figure 7.3.7 shows a vertical distribution of the water density near Hoek van Holland.

From this figure it may be concluded that the density is less than 1020 kg/m³ in the upper layers but more or less equal to 1020 kg/m³ near the bottom. Because the density of the water used by the Tonnes Dry Solids System, is set as 1020 kg/m³ incorrect conversion of pressure to draft may occur if the density of the water varies. If the density of the surrounding water is 1010 kg/m³ the converted draft will be less than the actual draft, resulting in less displacement. To calculate the weight of the vessel the displacement has to be multiplied by the density of the water. Because the actual density is less than the density used by the TDS system the calculated weight will greater. The overall systematic error is dependent upon the shape of the vessel.

![Figure 7.3.7: Vertical distribution of water density](image)

- Errors may occur due to the location of the pressure and acoustic sensors. The pressure sensors should both be installed on the centre line of the vessel. If this is not possible the sensors may be placed as near to it as possible, after which an authorized superintendent of Rijkswaterstaat examines the locations and, if satisfied, states his acceptance. There is no procedure for checking the location of the pressure sensors and because of this errors may be made due to athwart inclination of the vessel. A line drawn between both sensors should cross the middle of the vessel at the centre line (figure 7.3.8), if it does not do so, the average draft will shift in case of athwart inclination, resulting in a deviation from water displacement.
Figure 7.3.8. Position of pressure sensors

The same applies for the acoustic sensors. When a line drawn between both acoustic sensors does not cross the middle of the hopper at the centre line the calculated average volume will be incorrect. When measuring the empty vessel, the mean draft should be established at the middle of the hopper, to indicate the difference between the level inside and outside the hopper. If a line between the pressure sensors and a line between the acoustic sensors does not cross the centre line in the middle of the vessel and the middle of the hopper respectively, in cases of athwart inclination there will be a systematic difference between the level recorded inside and outside the hopper.

Pressure measurement may be disturbed due to pressure variations underneath the vessel previously described in [16]. In this report the following facts are presented:

While the vessel has no velocity the vertical lift force will be delivered by a constant hydrostatic pressure along the bottom of the vessel (figure 7.3.9).

Figure 7.3.9. Pressure distribution of non-moving vessel

If the vessel is moving the pressure distribution changes and a wave pattern will occur as shown in figure 7.3.10.
Figure 7.3.10. Wave pattern along the vessel

So it may be possible that the converted draft does not correspond with the actual draft of the vessel. A likely pressure distribution is presented in figure 7.3.11.

Figure 7.3.11. Possible pressure distribution

When the pressure sensors are placed in position 1 the measured pressure will be lower and therefore the converted draft will be less than the actual draft. When placed in position 2 the measured pressure will be higher and thus the converted draft will be more than the actual draft of the vessel. Because the pressure distribution is speed, trim and draft dependent, it is difficult to establish an optimum position for the pressure sensors. A longitudinal section of a vessel may look like that shown in figure 7.3.12.

Figure 7.3.12. Surface of cross-section over length of vessel

Under sailing conditions a gradient in displacement will occur which is dependent upon increase of surface, leading to a gradient in water-velocity. This gradient determines the maximum and minimum values of the pressure underneath the keel. If draft increases the forward gradient may also

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increase, resulting in increased pressure variations at the front.
At the stern of the vessel the water velocity is slackened, resulting in an increase of hydrostatic pressure and turbulence. Measurement of correct hydrostatic pressure is not possible at this location.
In case of a negative trim the draft at f.p.p. will be greater than the average draft and increase of the gradient may occur.

From report [16] must be noticed that the pressure distribution mentioned occurs at a sailing speed of approximately 14 miles per hour. When dredging, the operating speed of the vessel is approximately 2.5 miles per hour. Influence of the pressure distribution is assumed to be noticeable at a sailing speed over seven miles per hour, so no influence may be expected. When dumping, the sailing speed is approximately six miles per hour. No influence may be expected here either, but the circumstances are more critical. Attention should be paid to positioning the pressure sensors in areas where the least possible influence may be expected.
In the middle of the vessel the pressure distribution is almost equal to the hydrostatic pressure so this position is the most reliable one for measurement of hydrostatic pressure.

Incorrect draft measurement will occur due to bending of the vessel. If pressure sensors are positioned at a.p.p. and f.p.p. the bending will not be measured but this bending does lead to extra displacement. Because this extra displacement is not measured the weight of the load is underestimated (figure 7.3.13).

![Diagram](image)

**Figure 7.3.13.** Displacement not measured due to bending

If a pressure sensor is located at the middle of the vessel the bending will be measured but if this draft is used as mean draft the displacement, and thus the weight, of the vessel, is overestimated (figure 7.3.14).
The pressure sensors should be placed in a position where extra displacement is compensated by the unmeasured displacement. To approximate the shape of the bend in the vessel the following formula may be used:

$$y = \frac{4\times f}{LL^2} \times (-x + 0.5 \times LL)^2 + f$$

(32)

- $f$ = maximum bend in metres
- $y$ = bending in metres


Because of the previously mentioned phenomenon of pressure fluctuation, in some cases it may be impossible to use these positions so other solutions to this problem should be found. For dredgers A, B and C the influence has been established as a percentage of the maximum sagging (Results presented in the appendix). The results are not given in the evaluation of the systematic errors because the maximum sagging is not known.

- When dredging with an almost fully loaded hopper, the surface of the mixture will have an extra trim in relation to the trim of the dredger. If the pumps are switched off the material contributing to this extra trim will disappear via the overflow and because of this phenomenon and of ship motions, dredged material is lost. The lost material consists of dredged material and foam which may be present due to turbulence. To establish the amount of material lost the TDSS computer-program has been modified, resulting in data-files which contain physical values of the acoustic metres, three minutes before and after a change of status. If the surface of the hopper is known the difference of volume between the dredging and dumping states may be established. The size of this error is stochastically distributed but because this error always lead to overestimation of the dumped load it is still a systematic error.
- As mentioned before, systematic errors occur due to errors in linearity of pressure and acoustic sensors. The contract drawn up by Rijkswaterstaat demands a linearity better than 0.5% of the span. The maximum deviation of the drafts for each output signal may therefore be 0.5% of the span. Because the error due to linearity may differ for different dredgers (due to differences in the calibrated span) and because the error differs even between different equal sensors. When the sensors are positioned and calibrated an error due to non-linearity is present but cannot be established because the dredger cannot be taken out of production. Because of the costs involved only the maximum error due to non-linearity is established. Because the error differs for different equal sensors it was not even possible to conclude whether the error leads to over or underestimation of the load.

In the following three paragraphs the systematic errors for three dredgers are established. The systematic errors due to errors in the carène diagram are not mentioned, because these errors may be avoided by careful application. The error due to bending may be established as in [17]. Because no dredger was available with pressure sensors in the critical positions this error has not been established. For the same reason it was not possible to measure the pressure distribution underneath the keel of the dredger to establish that error. The resulting, systematic errors that have been investigated:

- error due to the use of polynomial without trim correction.
- error in draft measurement due to variation in density of surrounding water.
- error due to athwart-ship position of pressure sensors.
- loss of material via overflow due to the set-up in the hopper after changing from "dredging" to "sailing loaded".
- error due to non-linearity of measurement instruments.

The data used and the exact calculations are presented in the appendix "systematic errors of dredgers A,B and C". In the following paragraphs only the results of the items which influence the accuracy are mentioned.

7.3.5.2 Systematic errors of dredger A

- Error due to the use of polynomial without trim influence. The difference is established at an empty draft of 4.75 metres with a trim of 1.97 metres and a loaded draft of 7.85 metres with a trim of -0.69 metres.

The use of a polynomial without trim influence causes a difference between "actual" tonnes dry solids and measured tonnes dry solids equal to 99.0 tonnes, meaning 99.0/3214.3*100 = 3.08 % is incorrectly taken into account.

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- error due to weight measurement in "fresh" water.

Near Hoek van Holland (km 1029) many samples have been taken to establish the density of the water [14]. At a depth of 9 metres (approximately the draft of the loaded vessel) the average density of the water at km 1029 is 1013 kg/m$^3$, with a standard deviation of 3.6 kg/m$^3$. In 95% of measurements the density of the surrounding water will be over 1006 kg/m$^3$. The error may now be established by comparison of the measured production with a density of the surrounding water of 1020 kg/m$^3$ and 1006 kg/m$^3$ respectively.

Difference in calculation is 59.3 tonnes resulting in a quantity of approximately 59.3/3140.5*100=1.89%. In 95% of the measurements a quantity less than 1.89% is incorrectly taken into account.

- loss of material due to set-up in the hopper

The mean value for the loss of material via the overflow due to the loading trim in the hopper is 75.9 m$^3$ with a standard deviation equal to 54.8 m$^3$.

- error due to non-linearity of measurement instruments.

The maximum influence of non-linearity of the measurement instruments may be established as 1.67% of the production of the dredger.

7.3.5.3 Systematic errors of dredger B

- Error due to the use of polynomial without trim influence. The difference is established at an empty draft of 6.27 metres with a trim of 1.79 metres and a loaded draft of 9.35 metres with a trim equal to zero.

The use of a polynomial without trim causes a difference between "actual" tonnes dry solids and measured tonnes dry solids equal to 82.3 tonnes. Every dredge-cycle a quantity of approximately 82.3/4224.7*100 = 1.95% is incorrectly taken into account.

- error due to weight-measurement in fresh water.

As mentioned, near Hoek van Holland (km 1029), many samples have been taken to establish the density of the water. At a depth of 9 metres (approximately the draft of the loaded vessel) the average density of the water at km 1029 is 1013 kg/m$^3$ with a standard deviation of 3.6 kg/m$^3$. In 95% of measurements the density of the surrounding water will be over 1006 kg/m$^3$. The error may now be established by comparison of the measured production with a density of the surrounding water of 1020 kg/m$^3$ and 1006 kg/m$^3$ respectively.
The difference in calculation is -60.3 tonnes resulting in a quantity of approximately $60.3/4246.0 \times 100 = 1.42\%$. In 95\% of the measurements a quantity less than 1.42\% is not taken into account.

- loss of material due to loading trim in the hopper.

The mean value for the loss of material via the overflow due to the loading trim in the hopper is 79.5 $m^3$, with a standard deviation equal to 41.2 $m^3$.

- error due to non-linearity of measurement instruments.

The maximum influence of non-linearity of the measurement instruments may be established as 3.40 \% of the production of the dredger.

7.3.5.4 Systematic errors of dredger C

- Error due to the use of polynomial without trim influence. The difference is established at a empty draft of 6.53 metres with a trim of 1.20 metres and a loaded draft of 8.86 metres with a trim of 0.03 metres.

The use of a polynomial without trim causes a difference between "actual" tonnes dry solids and measured tonnes dry solids equal to 122.5 tonnes. Every dredge-cycle a quantity of approximately $122.5/3120.3 \times 100 = 3.93 \%$ is incorrectly taken into account.

- error due to weight-measurement in fresh water.

As mentioned, near Hoek van Holland (km 1029) many samples have been taken to establish the density of the water. At a depth of 9 metres (approximately the draft of the loaded vessel), the average density of the water at km 1029 is 1013 kg/m$^3$ with a standard deviation of 3.6 kg/m$^3$. In 95\% of measurements the density of the surrounding water will be over 1006 kg/m$^3$. The error may now be established by comparison of the measured production with a density of the surrounding water of 1020 kg/m$^3$ and 1006 kg/m$^3$ respectively.

Difference in calculation is 42.1 tonnes resulting in a quantity of approximately $42.1/3023.9 \times 100 = 1.39\%$. In 95\% of the measurements a quantity less than 1.39\% will be incorrectly taken into account.

- loss of material due to loading trim in the hopper.

The mean value for the loss of material via the overflow due to the loading trim in the hopper is 170.9 $m^3$ with a standard deviation equal to 75.9 $m^3$. 

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- error due to non-linearity of measurement instruments.

The maximum influence of non-linearity of the measurement instruments may be established as 4.24% of the production of the dredger.

7.3.5.5 Evaluation of systematic errors

The systematic errors have a ship dependent influence on the total accuracy and therefore may not be neglected.

The higher losses of dredger C in comparison with the other dredgers mentioned are remarkable. The reason for this may be the type and position of the overflow. Dredgers A and B have a circular tube in the centre line of the hopper. In case of roll the level in the centre of the hopper is practically constant and no extra overflow losses occur. Dredger C has an overflow in the side of the hopper. During rolling material will float out via the overflow and for this reason the amount of overflow losses may be greater.

<table>
<thead>
<tr>
<th>error</th>
<th>dredger A</th>
<th>dredger B</th>
<th>dredger C</th>
</tr>
</thead>
<tbody>
<tr>
<td>polynomial without trim influence (% of production)</td>
<td>3.08</td>
<td>1.95</td>
<td>3.93</td>
</tr>
<tr>
<td>difference in density of surrounding water (% of production)</td>
<td>1.89</td>
<td>1.42</td>
<td>1.39</td>
</tr>
<tr>
<td>mean loss of material (m³)</td>
<td>75.9</td>
<td>79.5</td>
<td>170.9</td>
</tr>
<tr>
<td>standard deviation of loss of material due to the loading trim in the hopper (m³)</td>
<td>54.8</td>
<td>41.2</td>
<td>75.9</td>
</tr>
<tr>
<td>non-linearity of measurement instruments (% of production)</td>
<td>1.67</td>
<td>3.40</td>
<td>4.24</td>
</tr>
</tbody>
</table>

Table 7. Systematic errors

7.3.6 Overall accuracy of dredger A, B and C

The overall accuracy of dredgers A, B and C is presented in the following table:
<table>
<thead>
<tr>
<th></th>
<th>dredger A</th>
<th>dredger B</th>
<th>dredger C</th>
</tr>
</thead>
<tbody>
<tr>
<td>relative stochastic accuracy</td>
<td>3.47</td>
<td>4.39</td>
<td>4.80</td>
</tr>
<tr>
<td>systematic error</td>
<td>3.08</td>
<td>1.95</td>
<td>3.93</td>
</tr>
<tr>
<td>systematic error</td>
<td>1.89</td>
<td>1.42</td>
<td>1.39</td>
</tr>
<tr>
<td>systematic error</td>
<td>1.67</td>
<td>3.40</td>
<td>4.24</td>
</tr>
<tr>
<td>total (% of production)</td>
<td>10.11%</td>
<td>11.16%</td>
<td>14.36%</td>
</tr>
</tbody>
</table>

Table 8. Overall accuracy

7.3.7 Summary of accuracy calculation

From the previous paragraphs it can be concluded that the Tonnes Dry Solids System is not ship-independent. The reason for this may be sought in the different configurations of the TDSS on the different dredgers and the different block coefficients of the different dredgers.
This will not cause problems when the stochastic part is concerned because the average result over many measurement will be the same for different dredgers.
The systematic errors are also ship-dependent and, because systematic errors do not average over many measurements, these errors cause problems when different dredgers are being compared. This problem could be solved by offering different prices per ton dry solids per dredger but this would lead to an unclear measurement method.
It would be better to adapt the TDSS to minimize or even to exclude the systematic errors.
It is obvious that the use of a polynomial to approximate the displacement of the vessel causes a rather large error in the measurement of the production. Replacement of the polynomial by a matrix, containing the displacement in relation to the mean draft and the trim of the vessel, is highly recommended.
The conversion of measured pressure to weight used also causes a rather large error in measurement of production.
Dredger A shows the smallest maximum error due to non-linearity because the error in weight measurement for the loaded vessel and empty vessel respectively are almost equal to each other owing to the large block-coefficient. The resulting error is only dictated by the error in volume and therefore the error due to non-linearity is less then for both other dredgers.
Because only the maximum error is established and therefore no positive effects due to compensation are taken into account, care should be taken in interpretation of this error.
7.3.8 Requisites

To operate with the Tonnes Dry Solids System, at least two pressure sensors and two or more acoustic sensors are required. The output signal of the sensors has to be manipulated to obtain signals suited for the computer. A signal must be produced from which the status of the dredger can be known. The measured data are stored on computer-diskettes and sent to a shore station where the data may be used to evaluate the operation of the system and as a back-up for problems which occur. The method uses sophisticated technology and therefore those required to operate it, whether in the service of the client or of the contractor, must be well educated and trained to interpret the data measured, to maintain the instruments and to monitor the progress of the dredging work.

7.3.9 Influence on dredge process

The Tonnes Dry solids System offers the contractor the possibility to increase the efficiency of his dredger because he will be paid for the work actually done. The system does not influence the dredging production process, the measurement of the empty and loaded vessel takes only a few minutes and during these minutes the dredging process is interrupted anyway. Because in the absence of a back-up system the dredger may be out of production in case of malfunctioning of the TDS system, a provision to continue dredging on the basis e.g. of the half sphere method, may be incorporated in the contract.

7.3.10 Suitability

To obtain reliable mean data from the acoustic sensors the liquid must have a plane surface. In case of sandy material the particles settle almost immediately. To distribute the mixture over the hopper several discharge chutes are present. When dredging sandy material the overflow may be positioned lower than when dredging silty material because the volume weight of the sand mixture is greater. As soon as the mixture reaches the top of the overflow the water runs off. The dredge master may now distribute the mixture via the most remote chute from the overflow. Because of the quick settlement of the material the surface of the load near the discharge chute may be higher than the level of the overflow.

When averaging the recorded heights from the acoustic sensors it may well be possible that the related volume extracted from the hopper contents table does not match the actual volume of hopper-load. Due to this phenomenon the currently used Tonnes Dry Solids System is only applicable for mixtures consisting of silty material and for settled loads which are completely covered by a liquid layer.
7.3.11 Conclusion

On the basis of the previous paragraphs, it may be concluded that, for the Hoek van Holland area, in 95% of the measurements the overall relative accuracy of dredgers A, B and C may be less than:

<table>
<thead>
<tr>
<th></th>
<th>dredger A</th>
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<th>dredger C</th>
</tr>
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<tr>
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<td>3.47</td>
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</tr>
<tr>
<td>systematic error</td>
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<td>3.40</td>
<td>4.24</td>
</tr>
<tr>
<td>total (% of produc-</td>
<td>10.11%</td>
<td>11.16%</td>
<td>14.36%</td>
</tr>
<tr>
<td>tion)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

without influence from bending, loss of material during "sailing loaded" and ship-movements.
Strictly speaking, one should not add up the errors but the sum presents a good impression about the ship-dependent accuracy and of the improvement after elimination of a systematic error.
If the polynomial is replaced by a matrix to establish the displacement of the vessel the relative accuracy increases to 7.03% for dredger A, 9.21% for dredger B and 10.43% for dredger C.
After replacement of the polynomial by the exact carène matrix, the accuracy is much more comparable.
The measurements of dredger C are still less accurate than those of the other dredgers. The reason may be that dredger C has a lower block-coefficient.
From the above mentioned total accuracy, it may be concluded that the error due to non-linearity has a large influence on the result. As mentioned in paragraph 7.3.5.1, only the maximum error is established, without taking into account liquidation effects, so care should be taken when interpreting this error. For an objective conclusion the error due to non-linearity should be erased. Now the relative accuracy for dredger A becomes 5.36%, for dredger B 5.81% and for dredger C 6.19%.
It must be kept in mind that reduction of the error due to non-linearity should be given high priority because the large influence on the accuracy in case of occurrence of the maximum error.
The establishment of bending was not possible because of the costs involved (a dredger would be out of production for several hours). It is recommended, nevertheless, to make such a survey before starting work with any new dredger on site. Ship-movements have a random character and it will be very difficult to filter the results, but it may be stated that the periodic time and amplitude of the movements are ship-dependent.
When dredging sandy material it may be possible that the solid mass of the load will extend above the surface of the water in the hopper so it is not possible to measure the volume of material unless a fluid top layer is present over the solids mass, which may lead to less efficient production of the trailer suction hopper dredger.

It may be concluded that the currently used system measures the production in a fair, reliable manner with a more or less acceptable relative accuracy which is not ship-independent. The system should be adapted to operate with ship-independent relative accuracy, thus providing overall comparable basis which will be generally acceptable.

The system should also be adapted to operate with increased accuracy.

Finally it may be concluded that in case of dredging sandy material the Tonnes Dry Solids System may cause problems in measurement of payable dredged quantities although the system is well suited for dredging silty material. In areas of heavy siltation or erosion the TDS system provides a basis for fair, accurate measurement of payable dredged quantities.
8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The conclusions from the previous chapters are repeated briefly below:

- In-situ measurement method.
  This measurement method demands qualified and experienced surveyors. The best possible accuracy is 0.1 metres, but in practice an accuracy of approximately 0.20 - 0.30 metres is obtained for both in survey and out survey. The accuracy of the measurement of the thickness of the layer removed may therefore be established as 0.40 metres. In-situ measurement is only suitable if the change in depth due to erosion or sedimentation is small in relation to the dredged volume. In areas with heavy erosion, heavy siltation, and/or shipping which uses maximum navigational depth (thus causing turbidity clouds), there are differences between the quantity of material actually dredged and the quantity for which payment should be due according to survey results. Such differences arise when dredging sand or gravel and are very much greater when dredging silt. Although the in-situ measurement method is not suitable for payment in such circumstances, sounding is still necessary to monitor and control the progress of dredging works.

- Measurement of velocity and density in the pipeline.
  For trailing suction hopper dredgers this method may be used to optimize the suction process during dredging. Several phenomena may exert a big influence on the measuring process so frequent calibration is necessary to avoid the introduction of major errors. It is not possible to measure the amount of material escaping via the overflow, and therefore the method is not suitable for production measurement on trailing suction hopper dredgers. For stationary dredgers working in ideal conditions the method has proved to provide an accurate measurement of production.

- Half sphere method.
  The half sphere method is a simple method which is maintenance free and inexpensive. Unfortunately the method has the following disadvantages:

* what the measured volume actually represents is not known.
* no payment for improved production
* the result is dependent upon the rate of consolidation
* the result is dependent upon the type of material dredged
* influence of the method on the dredging process
* the subjective role of the inspector.
It may be concluded that the method is only acceptable for production measurement when no other methods which use more sophisticated technology are available.

- **Hopper pressure measurement method.**
  With a relative accuracy better than 14.5% of the load and tonnes dry solids as pay unit, the hopper pressure method is an improvement on the above method, but for accurate and fair measurement it is restricted to liquid loads without any effective stress. Since it is almost impossible to obtain loads which are entirely liquid (without effective stress) the method has never been used to measure payable dredged quantities though a research project was based on it.

- **Tonnes Dry Solids System.**
  In areas of heavy siltation or erosion the TDS system is a basis for fair, accurate measurement of payable dredged quantities.
  The Tonnes Dry Solids System may cause problems when used to measure payable dredged quantities of sandy material but is suitable when dredging silty material.
  The system in current use measures the production to an accuracy of approximately 8 - 10%, depending upon the dredger being used.
  The TDS system should be adapted to operate more accurately and be ship-independent. The recommendations in the following paragraph may be used to achieve this objective.

It may be concluded that the in-situ measurement produces reliable data but in cases with heavy erosion or siltation in relation to the volume to be removed the method should only be used to monitor and control the progress of the dredging work. When heavy erosion or siltation occurs, especially in maintenance dredging, measurement in the means of conveyance produces fair and accurate production data.

The settling method shows more deviation in the recording of the volume percentage of the settled part and thus more deviation in the final result. More deviation implies a less accurate measuring method and therefore the "half sphere and settling method" should not be used unless no other option is available.

For larger hopper dredgers more accurate and sophisticated methods are available and should be used. Computerized systems require reliable measurements. If the measurements fail, the load of the suction hopper dredger may not be paid for, so the maintenance of electronic equipment must be given a high priority to ensure reliable measurements. If maintenance facilities are poor, one is inclined to fall back on the sample measurement with half sphere and sampling of fluids.

It is obvious that when measuring in the means of conveyance the client must ascertain that dredging takes place only in the designated dredging area. Dredging outside this area should not be paid for. Similarly over-dredging should be avoided.
8.2 Recommendations

To improve the accuracy of measurements for the Tonnes Dry Solids System, adaptations are recommended to improve the general acceptance of the system.

The following recommendations apply:

- The use of a matrix containing the displacement of the vessel in relation to average draft and trim will increase the accuracy of TDS measurements by approximately 2% to 4%.

- For accurate measurement of the weight of the dredger the density of the surrounding water should be used. Because the Tonnes Dry Solids System is a fully automated system, continuous measurement of the density of the surrounding water should be performed. When continuous measurement is not possible and a little deviation in density of the surrounding water occurs, a mean value may be used. If possible, site specific mean values for the density of the surrounding water should be used. The dredge-dump codes, which apply to the different areas, could be linked to the density of the surrounding water and then the systematic error would change into a stochastic error. The productivity of different dredgers could be more accurately compared.

- In practice, problems in fulfilling the trim-trim check occur so the five-minute trim-trim check should be replaced. For measurement of the loaded vessel it is only important that measuring equipment operates correctly during the measurement of the loaded vessel. At present the measurement of the loaded vessel takes place over a period of 25 seconds before and 25 seconds after the change from the state "dredging" to the state "sailing loaded". The trim-trim check should also be made during this period of 50 seconds and the trim-trim must be less than the required margin for a period of e.g. 10 seconds together, after which the measurement of the loaded vessel takes place immediately. In this way the instruments are checked during the moment of measurement of the loaded vessel so that there can be absolute certainty of their correct operation. A second advantage is that manipulation of the trim-trim check during the state "dredging" is not possible. Furthermore the crew of the dredger does not have to worry about making the trim-trim check during the state "dredging" and they can focus on full optimization of the load.

For trailing suction hopper dredgers with a closed hopper this configuration may cause problems because it may be possible that the load does not have a plane surface (figure 8.1).
This problem may be remedied by placing the acoustic sensors in tubes a few metres above the hopper. The trim-trim margin is ship-dependent. A computer program TRIMTRIM.EXE has been developed to establish ship-dependent trim-trim margins. Detailed information on this is presented in the manual [31]. A positive effect for the client will be the reduction of "the wedge" of mixture on top of the load referred to as loading trim. At the end of the state "dredging" the wedge is measured as load but during the state "sailing loaded" the wedge will disappear via the overflow. In case of a trim-trim check at the end of the state of "dredging" the dredge master is obliged to load the hopper more carefully in order to reduce the height of the wedge (maximum height in relation to the currently used trim-trim margin approximately is 20 cm). The loss of material will be reduced and less material that is not transported to the dumping area, will be measured as load.

- The value of 10, used for the earth gravity acceleration, should be replaced by 9.81 for the Hoek van Holland area. This value has been scientifically established and thus conversion of pressure into draft will be more accurate. To measure the weight of the hopper the pressure should be converted to draft via:

\[
\text{depth(metres)} = \frac{\text{pressure(Kpa)}}{g \times \text{density of water}}
\]

The average draft (together with the trim of the vessel) must be included in the carène-diagram to obtain the displacement of the vessel. To establish the weight, the displacement should be multiplied by the density of the surrounding water.

- The contractor is responsible for the signals delivered by the measuring instruments to the TDS computer. These signals are converted by the dredge-computer and supplied to the TDS computer. At present there is no control over the representative value of the output signals of the dredge-computer. It may be possible that the values
presented do not match the actual production of the
dredger. A monitoring program should be developed to check
the conversion by the dredge-computer.

- The accuracy of the measuring instruments depends on their
range. The error due to non-linearity is systematic because
averaging of the output signals does not influence this
error. The output signals should match, as closely as
possible, the values 2 volts and 10 volts when the vessel
is measured empty and loaded in such a way that the range
is as small as possible. The error will decrease and thus
the accuracy of TDS measurements will increase.

- The Monday-calibration is used to check the accuracy of
measuring instruments and to set a starting-value for the
Monday-Friday line. This calibration is very important
because it will be the starting value for the Monday-Friday
line and the matching "100 tonnes" margin line.
If, during the course of the week, an empty ship value is
recorded that is over 100 tonnes less than the value
according the Monday-Friday line, the empty ship value for
that particular trip is corrected to the value of the
Monday-Friday line. If the starting point established
during the calibration is not accurate, the correction of
the empty-ship values is affected throughout the week.
If the density of the surrounding water is measured with
the aid of a salinity sensor, the density could be applied
for the TDS system and a more accurate value might be
established.

- The position of the pressure sensors should be very
carefully chosen. If the sensors are not placed in the
centre line, athwart inclination of the vessel may cause an
error in draft measurement. The effect may be positive or
negative and may introduce an opportunity for manipulation.

- At present the TDS system uses two input-signals for two
pressure sensors and two input-signals for two acoustic
sensors. With four acoustic and/or pressure sensors the
average of the signals fore and aft should be presented to
the TDS computer as one signal fore and one signal aft. If
the TDS computer is extended to include four input-signals,
the signals from the measuring instruments can be read
separately and it is not necessary to monitor the mean
value of the signals because the TDS computer itself
carries out the averaging.
In this way it is even possible to present a window on the
TDS screen to show the physical values of all measuring
instruments. If there is a malfunction of the system the
window may be used to detect the instrument responsible.

- The averaging period should be variable. With an adapted
TDSS program it would also be possible to investigate
whether a different averaging period might increase the
accuracy of measurements.
- The required accuracy of the measuring instruments should be better defined. In the definition of the required accuracy there is no provision for the accuracy in repeatability. It may even be possible to tighten up the requirements because all modern instruments are much more accurate. In this way the contractor will be forced to choose the most accurate measuring equipment so it will be possible to make a more accurate comparison between the production of different dredgers. Care should be taken in setting the ship dependent margins. Because the margins are related to the accuracy of the measuring equipment the margins could become smaller, but they should also be related to the site specific conditions and therefore should not be reduced.

- The loss of material via the overflow due to the loading trim in the hopper during the state of "sailing loaded" could be monitored. In this way an average value for the amount of the volume lost via the overflow may be established. If there is leakage via the bottom doors, the quantity lost will be systematically more, but because the quantity is known under normal circumstances leakage may be detected.

- Due to the influence of bending and pressure distribution underneath the keel of the vessel, systematic errors occur. Solutions for these problems should be sought in different configurations for the Tonnes Dry Solids System. When a third pressure sensor is positioned in the middle of the vessel the influence of pressure variation will diminish. The trim of the dredger may be measured by the other pressure sensors. An inclinometer could also be used. With the inclinometer the movements of the dredger could be measured unless movements were too heavy, thus making accurate measurement of the weight of empty and loaded vessel impossible.

It is also possible to reduce the effect of bending with the aid of the third pressure sensor. When the draft is measured at the middle of the vessel and at the perpendiculars, in calm water, the bending may be established for the empty and loaded vessel. The displacement of the vessel may then be corrected for the extra displacement due to the bending of the vessel. If the shape of the sagged keel is schematised as in the computer-programma BENDING.EXE, the average draft, with the corresponding real displacement, will be equal to the measured draft minus 1/3 of the maximum bending.

- For some trailing suction hopper dredgers foam is a problem. The acoustic sensors reflect from the top of the foam and errors occur in measurement of the surface of the mixture. The layer of foam may be over 20 centimetres thick and problems may occur in making the trim-trim check. Step-gauges may not have this problem because they only respond to the surface of the mixture in the hopper. Step-gauges have the disadvantage that only a
limited range of the hopper can be measured. If step-gauges are placed close to acoustic sensors on top of the hopper, the acoustic sensors can be used to measure the distance to the surface of the mixture. When the surface of the mixture reaches the step-gauge, this gauge takes over the function of the acoustic sensor and the foam no longer exerts any influence. A step-gauge measures with a specific interval (e.g. 5 centimetres). If foam has a height of 20 centimetres, a step-gauge may be used to advantage. Investigation of this type of configuration is recommended.

To measure the weight of the dredger before the first cycle, the difference between the water-level in the hopper and the water-level outside must be less than 0.1 metres. For accurate measurement of the empty weight of the dredger the difference must be less than 0.2 metres. Small trailing suction hopper dredgers may more easily meet this requirement than larger ones. For this purpose the margin should be ship-dependent. The margin will depend upon the accuracy of the measuring equipment, the establishment of the draft of the dredger at the middle of the hopper and dynamic movements of the dredger. The dynamic movements are unpredictable and so it is not relevant to establish a ship-dependent margin. Ship-dependent margins would not increase the accuracy of the TDS measurements, which provides another reason not to establish ship-dependent margins. It may be possible to set a margin, monitor the empty ship values and, after several weeks, adapt the margin in such a way that all accurate measurements are covered.

The Monday-Friday line presents the theoretical weight of the empty dredger at the start and finish of the weekly operations. The weight of the dredger decreases due to fuel and water consumption. After each measurement of the empty dredger a check is made to find out whether the empty weight is less than the weight according to the Monday-Friday line minus 100 tonnes. If so it is assumed that the measuring equipment did not operate correctly and the weight of the dredger is adapted according the Monday-Friday line. For small trailing suction hopper dredgers the 100 tonnes margin is a less strict requirement than it is for larger dredgers. The accuracy of measurement of empty weight depends on the accuracy of measuring equipment (dependent upon the span), dynamic movements of the dredger and the shape of the dredger. The dynamic movements are unpredictable, and again it is not relevant to establish a ship-dependent margin. Averaging over a longer period could be beneficial because dynamic movements may be filtered. The averaging period must be a multiple of 5 seconds, otherwise the influence of wave-action could increase. The wave period in the Hoek van Holland area is approximately 5 seconds in normal circumstances [appendix North sea climate observations] and for this reason the period should be a multiple of 5. Preferably the regression line should not be established at the end of the week. The accuracy of
the regression-line would be influenced by rest-load which is not dumped (especially with sand-loads). It is possible to detect excessive deviation in empty-ship values and bunker consumption in a computer-program which shows the Monday-Friday line together with the empty-ship values on demand. If sand-loads are rejected, the regression line should match the Monday-Friday line and can be used to monitor the bunker-consumption of the dredger.

8.3 General measurement campaign and application programs

8.3.1 Description of measurement campaign

Before starting a new dredging work, in order to operate the TDSS it is necessary to carry out an extensive measurement campaign. First the total dredging-area must be known. In this area the contractor and the client will investigate the nature of the bottom material to be able to predict the production of the dredger. If the bottom material is uniform (with a constant specific density,) the production over the entire dredging area will be constant, apart from sailing distances and workability. If there are variations in the bottom material (and thus variations in mean specific density), sailing distances and workability the dredging-area should be divided into smaller sub-areas. The variation in bottom material, sailing distances and workability may lead to different productions, expressed in different prices per sub-area.

To establish a mean value for the density of water used in the TDS formula, the density of the water should be measured as close to the bottom as possible. To measure comparable weights of a loaded dredger, a mean value for the density of the surrounding water at loaded draft has to be established. In case of differences in water-density the dredging area may also be separated in sub-areas. The size of the sub-area depends upon the accuracy of weight-measurement required. These sub-areas should preferably be the same as the sub-areas defined for differences in specific density, otherwise the system would become too complex. The same applies to the dump-area. Densities may be designated to dump and/or dredge codes applying for the sub-area.

A dredging-program must be drawn up in such a way that during one dredging-cycle, dredging is performed in one specific sub-area, because otherwise different prices apply to parts of the load, resulting in payment problems.

The earth gravity acceleration must be introduced to ensure correct establishment of draft via hydrostatic pressure measurement.

In order to avoid over-dredging bathymetric surveys should be performed regularly to update of the dredging-program. It is also possible to install a draghead-depth indicating system to control the maximum depth of the dragheads and thus to prevent possible over-dredging.

A positioning system must be installed on board of the dredger to establish whether the dredged load is obtained from the designated dredge area. Dredging outside this area should be
disregarded. After establishment of the system-parameters, the ship-dependent parameters must be determined. The position of the instruments used to measure average draft, trim and distance from acoustic sensors to the surface of the load must be determined. The distance of measurement instruments from the perpendiculars, should be checked for consistency and for influence due to athwart inclination, after which a trim-trim margin may be established with the aid of the computer-program TRIMTRIM.EXE. The hopper-level table and the carène-diagram should be checked on representative value.

Furthermore, a margin has to be established for calibration of the TDS system. The addition of the distance from the acoustic reference-level to the filling-level of the hopper and the distance from the pressure sensors to the outboard water level (while the bottom doors are open), should match the distance between the pressure and acoustic sensors. Because of inaccuracy of the measuring instruments the sum of the measured distances may not match the fixed distance between the measuring instruments. The maximum deviation should be delimited. This maximum deviation is called "the calibration margin". The margin can be established by using a margin which has been established from experience during other dredging works. If there is no experience, possible margins have to be predicted and these may be adjusted after tests in practice. The same applies for the margin for the difference between the levels inside and outside the dredger during measurements of empty weight.

An additional control may be accomplished by periodical measurement of the "empty ship values" under restricted conditions (i.e. with the vessel moored, before and after bunkering). The intermediate trips should fit pro-rata into the regression line. Again the maximum deviation should be delimited. This maximum deviation is called "the Monday-Friday margin". The margin can be established by using a margin which has been established from experience during other dredging works. If there is no experience, possible margins have to be predicted and after practical tests may be adjusted. Establishment of the exact margins is not possible because of influence of dynamic movements of the vessel and influence of waves and/or swell. Furthermore, exact margins do not contribute to a better accuracy of the TDS system and therefore margins established from experience during other dredging works may be used.

After the calibration, the dredger may be filled with water to check the accuracy and linearity of the measurement instruments. If the system operates correctly dredging can start. In the case of maintenance dredging, the production of the dredger may vary in time (figure 8.2). By lowering the dragheads through the soft top-layer, a mixture with a higher density may be obtained during the first stage of the dredging work. During the first stage of the dredging work it may be beneficial to lower the dragheads through the soft top-layer but over a longer period the production will stabilize at a mean value. Draghead-indication systems, in combination with regular bathymetric surveys, may be used to limit the variation in production.
8.3.2 Application programs

8.3.2.1 Computer-program Mon-Fri.exe

The computer-program Mon-Fri.exe has two objectives:

- Establishment of a regression-line through the empty weight values of the dredger for the Monday and Friday calibration. With the regression-line an indication of the bunker-consumption may be obtained. If the bunker consumption deviates during the course of a week an intermediate empty weight value should be established.

- Detection of excessive deviation of empty weight values. A correlation-coefficient may be established that expresses the variation of the empty weight values in relation to the Monday-Friday line. Care should be taken when dredging sandy material. Dumping of sandy material takes quite a while and because of the efficiency of the dredger not all of the load may be dumped, which results in excessively high weights of the empty dredger. For sandy loads the empty weight values should be ignored from the Monday-Friday line to obtain a reliable indication about the deviation.

The program uses the time of establishment of the empty weight value of the dredger. It might be possible to introduce this program into the TDS system and present the Monday-Friday line on the TDS screen by means of a window whenever any doubt arises about the accuracy of measurements.
8.3.2.2 Testing of input signals

At present it is not possible to monitor the measurement instruments in relation to the TDSS computer. Losses in cables and electronic instruments may result in errors. Inaccuracy may also occur due to transformation of the output-signals of the measurements of 2 - 10 volts to 4 - 20 ampere. For this transformation also, no control procedure is available as yet. With the aid of a computer and a multimeter it might be possible to check the entire system. Before starting the first dredging cycle, the following procedure may be carried out:

- As the output signal of the measurement instruments is known, the signal at the end of the cable can be measured by a multimeter. If no difference is established the cable is correct. The output signal of the transformation-device can also be measured. As the output signal of the TDS-measurement instrument is known, the output signal of the transformation-device is known because of its linear relation. If the measured output-signal deviates, transformation has not take place correctly. If transformation has been correct, the signal used by the TDSS computer may be read from the TDSS screen. Again, this value should match the output-signal of the TDS-measuring instruments. If the signals match the entire system operates correctly.

If the TDS system operates correctly, dredging can take place. The transformation-device should have double input and output devices with which it becomes possible to check the device at any moment. A computer, which measures input and output signals from the transformation-device, can be installed and the transformation method can be established without delay to the dredging process. If the transform method is still correct, dredging may continue, otherwise repair is needed in order to arrive at accurate, fair measurement of pay-units.

8.3.2.3 Test of hopper table

With the aid of a computer-program it is possible to check the relation between volume and distance from a reference level to a level in the hopper. This relation can be presented on the computer-screen. If there is any doubt it should be possible to segregate a part of the relation to check whether the relation is correct.

8.3.2.4 Test of carène matrix

With the aid of a computer, it is possible to check the relation between displacement, trim and draft of the vessel. For each trim, the relation between draft and displacement can be presented. If there is any doubt it should be possible to segregate a part of the relation to check whether the relation
is correct. For each trim, this procedure may be followed and if the relation is correct the matrix may be used.
9 COMMENTARY

In this chapter a commentary will be given on the operation of the Tonnes Dry Solids System in practice.

The TDSS is a fair, accurate production measurement method. It uses sophisticated technology and therefore those required to operate it, whether in the service of the client or of the contractor must be well educated and trained to interpret the data measured and to maintain the instruments. Even if the instruments are frequently maintained by qualified staff, the TDS system may fail. This may result in problems of production measurement. The production measurements are divided into three categories:

a. correct production measurements
b. wrong measurements which may be corrected so that they can be used as a basis for payment
c. wrong measurements for which no payment will be made

When operating the TDSS the following problems may occur:

- 1. the TDS system does not operate
- 2. deviation of hopper content
- 3. malfunctioning measuring instrument(s)
- 4. leakage of bottom valves
- 5. printer failure
- 6. wrong dredge/dump code
- 7. status determination failure

The contractor is responsible for the correct operation of the hardware of the TDS system, the client supplies the software. The software has been tested and therefore problems should not be expected.

If one or more of the above mentioned problems occurs, the dredger will be out of production and, because the contractor is responsible for the hardware of the TDSS, there will be no income for the contractor.

To ensure his profit, the contractor will include the risk of malfunctioning of the system in the price per ton dry solids offered.

Because different contractors may interpret the risk in different ways, different prices per ton dry solids will be offered. Selection of the contractor for a project becomes difficult because the basis of his price structure is not clear.

To reduce the risk, and therefore clarify the structure of the prices tendered per ton dry solids, a contract may be implemented which specifies the following procedures:

1. When the TDS system does not operate, malfunction of the hardware of the TDSS computer will probably be the cause. When the TDS system fails payment on basis of TDSS measurements is stopped immediately. The contractor is offered an opportunity to repair the system within a specific time interval. After consultation with the client, dredging may continue on
the basis of the half sphere method or a cost covering hourly rate. When the system is not repaired within the specified time interval, payment will not continue.

2. The hopper content, as measured by the TDS system, may deviate from visible inspection. The difference may occur due to inaccuracy of the measurement instruments, heave pitch and roll of the dredger and dirt on the instruments. The motions of the dredger are stochastically distributed and therefore the hopper content should not be corrected. Foam will always increase the volume of the load but careful loading of the dredger at the end of the state of "dredging" may diminish this problem.

3. If the measurements do not comply with the internal control procedures (trim-trim difference less than set limit and water level inside-outside less than set limit), measuring instruments are not functioning. For payment the same procedure may be followed as in 1. When the contractor has installed a backup system, the TDSS can switch over to this backup system. After the TDS system has switched over, calibration is necessary before dredging can continue.

4. Leakage of bottom valves during the state of "sailing loaded" can be detected. After many measurements an impression of the loss of material in relation to the site specific conditions may be obtained. This impression may be translated into a stochastic distribution of the loss of material, expressed in a mean loss and a standard deviation of the loss from which a margin for the leakage can be derived. After the stochastic distribution is set, detection of leakage is possible. When the average value of the loss of material measured is systematically more than the mean value of the stochastic distribution of the loss, the bottom valves are probably leaking. The contractor must repair the dredger immediately. When dredging continues, the leakage may be detected and the amount of payable dredged quantities decreased by an amount equal to the leakage. In this way dredging can continue until the weekend, during which the dredger can be repaired.

5. To fulfill the conditions of the contract, the contractor is obliged to present a print-out of all production measurements. When the TDSS printer fails, the printer must be replaced as soon as possible and, because the contractor is not fulfilling the conditions of the contract, the production will not be paid. The measurements fall into category b and the measured data, stored on floppy disks, can be printed out at a shore basis computer after which payment is possible.
6. Because different prices per ton dry solids apply, the dredge/dump code must be correct.

Using the wrong dredge/dump code is a human error. The measured data can be reprinted at a shore base, with the correct dredge/dump code. The crews of the trailing suction hopper dredgers, as well as the inspectors, should be well instructed to avoid the use of wrong dredge/dump codes.

When a positioning system is used, the different dredge and dump areas could be shown on a computer screen. In the dredge and dump areas the code could also be shown on the computer screen as memory support.

7. Status determination failure may be handled in the same way as measurement instruments failure.

The contractor is offered an opportunity to repair the system within a specified time interval. For payment the same procedure may be followed as in 1.

If the contractor has installed a backup status determination system, the client's permission to use the system is required.

Of course the cost-covering hourly rate should be limited in such a way that the income is less than or equal to the income derived from the dredger in when in full production, otherwise the contractor is not stimulated to optimize his production.

The above mentioned procedures are well suited to protect the contractor from risk due to failure of the system. For the client the advantage of the procedures may be that, in some cases, dredging is continued and there is some control over the costs for repair of the Tonnes Dry Solids System.

To use these procedures it is obvious that a technological surrounding is required, otherwise mobilisation of new equipment takes up too much time and dredging is still interrupted.

The measuring instruments do not provide an exact measure of the load of the trailing suction hopper dredger but to an accuracy within certain the limits the measurements are ship independent.

When all variables are stochastically distributed, an average value will be reached after a number of measurements. Therefore the system should be adapted to eliminate ship-dependent systematic errors so that the same average value will be reached after a number of measurements for different dredgers which have equal loads. In this way the contractor is correctly paid for the work being done.
RELATIVE ACCURACY OF DREDGERS A, B AND C
Comparison of accuracy.

Relative stochastic accuracy of dredger A.

The trailing suction hopper dredger A was built in 1981 and has operated the Tonnes Dry Solids System for several years. The dimensions of the ship are:

- length (between a.p.p. and f.p.p.) = 106.00 m
- width = 19.60 m
- hopper capacity approximately = 6300 m³
- hopper length = 52.00 m
- hopper width = 12.60 m
- distance hopper reference level to base = 12.60 m
- distance from aft pressure sensor to a.p.p. = 35.20 m
- distance from fore pressure sensor to f.p.p. = 25.45 m
- distance between pressure sensors = 45.35 m
- distance a.p.p. to aft back of hopper = 28.70 m
- distance b.h.w. to aft acoustic sensor = 15.75 m
- distance between acoustic sensors = 20.70 m
- distance fore acoustic sensor to f.h.w. = 15.75 m
- distance f.p.p. to front of hopper = 25.10 m

To calculate the relative accuracy, plots have been made of the TDSS screen to obtain an indication of the measure of the draft of the ship in loaded and empty states and the volume of mixture in the hopper.
The data used to establish the probabilistic relative accuracy are listed below:

- draft aft loaded = 7.85 m
- draft fore loaded = 8.06 m
- draft aft empty = 5.09 m
- draft fore empty = 4.24 m
- span of pressure sensors = 10.20 m
- span of acoustic sensors = 12.00 m

The draft at a.p.p. and f.p.p. may be calculated as:

- draft at a.p.p. loaded = 7.68 m
- draft at f.p.p. loaded = 8.18 m
- draft at a.p.p. empty = 5.74 m
- draft at f.p.p. empty = 3.77 m

The following displacements are derived from the carène diagram:

- displacement at loaded draft = 13713.0 m³
- displacement at loaded draft -0.10 m = 13572.5 m³
- displacement at loaded draft +0.10 m = 13853.5 m³
- displacement at empty draft = 5698.0 m³
- displacement at empty draft -0.10 m = 5573.0 m³
- displacement at empty draft +0.10 m = 5823.0 m³
With the aid of the computer-program Eureka the factors $A, B_u, C$ and $D_u$ are determined.

- factor $A$ = 1405
- factor $B_u$ = 2571.35
- factor $C$ = 1250
- factor $D_u$ = -245.75

Because only the relative accuracy is concerned, the density of the surrounding water is taken as 1020 kg/m$^3$ without variation and the specific density of the dredged material as 2600 kg/m$^3$, with a variation equal to 10 kg/m$^3$.

The variation in the average loaded and empty drafts is established by using formula 20,21,22 and 23 and the computer program D_PRESS.EXE.

The following data are used in the computer-program:

- length of vessel = 112 m
- width of vessel = 19.6 m
- wave height = 1.0 m
- speed of vessel = 2.5 m/h
- channel depth = 24 m
- minimum draft = 4.75 m
- maximum draft = 7.93 m
- averaging time in empty state = 5 sec
- averaging time in loaded state = 50 sec

The wave height is set as 1.0 metre because this is the most common wave height is the Hoek van Holland area. During 1968 to 1988 in 70% of the measurements the wave height was less than 1.0 metre [24].

Resulting variation in draft:

- standard deviation of average draft loaded = 0.0164 m
- standard deviation of average draft empty = 0.0168 m

To derive a mean density of the mixture of 1330 kg/m$^3$, the volume of the mixture in the hopper is taken as 6080 m$^3$.

The distance of the average level of the acoustic sensors from the surface of the mixture may be derived from the hopper contents table.

The average distance is 1.50 metres. The angle of trim is equal to the angle of trim measured with the pressure sensors and thus the distance from the fore and aft acoustic sensors to the surface of the mixture in the hopper may be established by using formulas 28 to 29.

With formula 30 the variation in volume may be established as 104.37 m$^6$. 
The data thus established are used in the computer program TDSPLUS.EXE which produces the following data:

Data from probabilistic accuracy calculation for trailer suction hopper dredger A:

measured draft aft empty..............: 5.09 m
measured draft fore empty............: 4.24 m
measured draft aft loaded............: 7.85 m
measured draft fore loaded...........: 8.06 m
standard deviation of draft empty....: 0.0168 m
standard deviation of draft loaded...: 0.0164 m
factor A............................: 1405
factor Bu............................: 2571.35
factor C............................: 1250
factor Du............................: -245.75
variable Bo.........................: 5.06
variable Do.........................: 2.25
density of water.....................: 1020 kg/m³
specific density of material........: 2600 kg/m³
standard deviation of specific density: 10 kg/m³
volume of mixture in hopper.........: 6080 m³
variation in volume.................: 104.37 m³
influence of draft empty.............: 39.73 %
influence of draft loaded............: 47.83 %
influence of factor Bo...............: 0.47 %
influence of factor Do...............: 0.21 %
influence of volume................: 9.78 %
influence of specific density........: 1.97 %

quantity of "tonnes dry solids"......: 3100.39 tonnes
density of mixture in hopper.........: 1330 kg/m³
maximum error in 95% of measurements.: 107.5 tonnes
maximum error in 95% of measurements.: 3.47 %

For mixtures with a mean density of 1330 kg/m³ the relative error of 95% of the measurements is less than 107.5 tonnes. For all probabilistic relative accuracy calculations the density of the mixtures in the trailing suction hopper dredgers is taken as 1330 kg/m³ and therefore the errors, expressed as a percentage of the total load, may be used as basis for comparison.
Relative stochastic accuracy of dredger B

The trailing suction hopper dredger B was built in 1984 and has operated the Tonnes Dry Solids System for two years. The dimensions of the ship are:

- length (between a.p.p. and f.p.p.) = 125.00 m
- width = 23.00 m
- hopper capacity approximately = ± 8200 m³
- hopper length = 46.20 m
- hopper width = 12.60 m
- distance hopper reference level to base = 15.22 m
- distance from aft pressure sensor to a.p.p. = 17.85 m
- distance from fore pressure sensor to f.p.p. = 14.05 m
- distance between pressure sensors = 93.10 m
- distance a.p.p. to aft back of hopper = 40.60 m
- distance b.h.w. to aft acoustic sensor = 07.50 m
- distance between acoustic sensors = 33.60 m
- distance fore acoustic sensor to f.h.w. = 05.10 m
- distance f.p.p. to front of hopper = 38.20 m

To calculate the relative accuracy, plots have been made of the TDSS screen to obtain an indication of the draft of the ship in loaded and empty states and the volume of mixture in the hopper. The data used to establish the probabilistic relative accuracy are listed below:

- draft aft loaded = 9.35
- draft fore loaded = 9.35 m
- draft aft empty = 6.91 m
- draft fore empty = 5.58 m
- span of pressure sensors = 12.00 m
- span of acoustic sensors = 14.19 m

The draft at a.p.p. and f.p.p. may be calculated as:

- draft at a.p.p. loaded = 9.35 m
- draft at f.p.p. loaded = 9.35 m
- draft at a.p.p. empty = 7.17 m
- draft at f.p.p. empty = 5.38 m

The following displacements are derived from the carène diagram:

- displacement at loaded draft = 20661.0 m³
- displacement at loaded draft -0.10 m = 20405.0 m³
- displacement at loaded draft +0.10 m = 20917.0 m³
- displacement at empty draft = 9774.0 m³
- displacement at empty draft -0.10 m = 9596.0 m³
- displacement at empty draft +0.10 m = 9952.0 m³
With the aid of the computer-program Eureka the factors A, Bu, C and Du are determined.

- factor A = 2560
- factor Bu = -3275
- factor C = 1780
- factor Du = -1395.5

Because only the relative accuracy is concerned, the density of the surrounding water is taken as 1020 kg/m³ without variation and the specific density of the dredged material as 2600 kg/m³ without variation.
The variation of the loaded and empty average drafts is established by using formula 20,21,22 and 23 and the computer program D_PRESS.EXE.

The following data are used in the computer program:

- length of vessel = 140 m
- width of vessel = 23.0 m
- wave height = 1.0 m
- speed of vessel = 2.5 m/h
- channel depth = 24 m
- minimum draft = 6.27 m
- maximum draft = 9.35 m
- averaging time in empty state = 5 sec
- averaging time in loaded state = 50 sec

The wave height is again taken as 1.0 metre.
The resulting variation of the draft:

- standard deviation of average draft loaded = 0.01788 m
- standard deviation of average draft empty = 0.01803 m

To derive a mean density of the mixture of 1330 kg/m³, the volume of the mixture in the hopper is taken as 8242 m³.
The distance of the average level of the acoustic sensors from the surface of the mixture may be derived from the hopper contents table.
The average distance is 1.15 metres. The angle of the trim is equal to the angle of the trim measured with the pressure sensors and thus the distance from the fore and aft acoustic sensor to the surface of the mixture in the hopper may be established using formulas 28 and 29.
With formula 30 the variation in volume may be established as 94.61 m².
The data thus established are used in the computer-program TDSPLUS.EXE which produces the following data:

Data from probabilistic accuracy calculation for trailer suction hopper dredger B:

measured draft aft empty : 6.91 m
measured draft fore empty : 5.58 m
measured draft aft loaded : 9.35 m
measured draft fore loaded : 9.35 m
standard deviation of draft empty : 0.01803 m
standard deviation of draft loaded : 0.01788 m
factor A : 2560
factor Bu : -3275
factor C : 1780
factor Du : -1395.5
variable Bo : 6.25
variable Do : 3.06
volume of mixture in hopper : 8242 m³
variation in volume : 94.61 m³
density of water : 1020 kg/m³
specific density of material : 2600 kg/m³
standard deviation of specific density : 10 kg/m³
influence of draft empty : 31.47 %
influence of draft loaded : 64.00 %
influence of factor Bo : 0.20 %
influence of factor Do : 0.10 %
influence of volume : 3.01 %
influence of specific density : 1.23 %

quantity of "tonnes dry solids" : 4201.59 tonnes
density of mixture in hopper : 1330 kg/m³
maximum error in 95% of measurements : 184.5 tonnes
maximum error in 95% of measurements : 4.39 %
Relative stochastic accuracy of dredger C

The trailing suction hopper dredger C was built in 1969 and has operated the Tonnes Dry Solids System for several years. The dimensions of the ship are:

- length (between a.p.p. and f.p.p.) = 119.80 m
- width = 19.60 m
- hopper capacity = 6085 m³
- hopper length = 49.72 m
- hopper width = 12.60 m
- distance hopper reference level to base = 15.05 m
- distance from aft pressure sensor to a.p.p. = 33.87 m
- distance from fore pressure sensor to f.p.p. = 27.30 m
- distance between pressure sensors = 58.63 m
- distance a.p.p. to aft back of hopper = 35.03 m
- distance b.h.w. to aft acoustic sensor = 20.66 m
- distance between acoustic sensors = 22.68 m
- distance fore acoustic sensor to f.h.w. = 6.38 m
- distance f.p.p. to front of hopper = 35.05 m

To calculate the relative accuracy plots have been made of the TDSS screen to obtain an indication of the draft of the ship in loaded and empty states and the volume of mixture in the hopper. The data used to establish the probabilistic relative accuracy are listed below:

- draft aft loaded = 8.87 m
- draft fore loaded = 8.86 m
- draft aft empty = 6.79 m
- draft fore empty = 6.20 m
- span of pressure sensors = 12.75 m
- span of acoustic sensors = 10.50 m

The draft at a.p.p. and f.p.p. may be calculated as:

- draft at a.p.p. loaded = 8.88 m
- draft at f.p.p. loaded = 8.85 m
- draft at a.p.p. empty = 7.13 m
- draft at f.p.p. empty = 5.93 m

The following displacements are derived from the carène diagram:

- displacement at loaded draft = 16115.8 m³
- displacement at loaded draft -0.10 m = 15913.4 m³
- displacement at loaded draft +0.10 m = 16318.2 m³
- displacement at empty draft = 8171.8 m³
- displacement at empty draft -0.10 m = 8042.0 m³
- displacement at empty draft +0.10 m = 5301.6 m³
With the aid of the computer-program Eureka the factors A, Bu, C and Du are determined.

- factor A = 2024
- factor Bu = -1827
- factor C = 1298.4
- factor Du = -306.75

Because only the relative accuracy is concerned, the density of the surrounding water is taken as 1020 kg/m³ without variation and the specific density of the dredged material as 2600 kg/m³ with a variation equal to 10 kg/m³.

The variation of the loaded and empty average draft is established by using formula 20, 21, 22 and 23 and the computer program D_PRESS.EXE.

The following data are used in the computer-program:

- length of vessel = 127 m
- width of vessel = 19.5 m
- wave height = 1.0 m
- speed of vessel = 2.5 m/h
- channel depth = 24 m
- minimum draft = 6.53 m
- maximum draft = 8.86 m
- averaging time in empty state = 5 sec
- averaging time in loaded state = 50 sec

The wave height is taken as 1.0 metre for this is the most common wave height in the Hoek van Holland area. During 1968 to 1988 in 70 % of the measurements the wave height was less than 1.0 metre [24].

Resulting variation of draft:

- standard deviation of average draft loaded = 0.01830 m
- standard deviation of average draft empty = 0.01850 m

To derive a mean density of the mixture of 1330 kg/m³, the volume of the mixture in the hopper is taken as 6006 m³.

The distance of the average level of the acoustic sensors from the surface of the mixture may be derived from the hopper contents table.

The angle of trim is equal to the angle of trim measured with the pressure sensors and thus the distance from the fore and aft acoustic sensors to the surface of the mixture in the hopper may be established using formulas 28 and 29.

With formula 30 the variation in volume may be established as 101.86 m⁶.
The data thus established are used in the computer-program TDSPLUS.EXE which revives the following data:

Data from probabilistic accuracy calculation for trailer suction hopper dredger C:

- measured draft aft empty: 6.79 m
- measured draft fore empty: 6.20 m
- measured draft aft loaded: 8.87 m
- measured draft fore loaded: 8.86 m
- standard deviation of draft empty: 0.01850 m
- standard deviation of draft loaded: 0.01830 m
- factor A: 2024
- factor Bu: -1827
- factor C: 1298.4
- factor Du: -306.75
- variable Bo: 5.06
- variable Do: 2.25
- density of water: 1020 kg/m³
- specific density of material: 2600 kg/m³
- standard deviation of specific density: 10 kg/m³
- volume of mixture in hopper: 6006 m³
- variation in volume: 101.86 m³
- influence of draft empty: 27.69 %
- influence of draft: 65.84 %
- influence of factor Bo: 0.25 %
- influence of factor Do: 0.11 %
- influence of volume: 5.08 %
- influence of specific density: 1.03 %

- quantity of "tonnes dry solids": 3067.19 tonnes
- density of mixture in hopper: 1330 kg/m³
- maximum error in 95% of measurements: 147.2 tonnes
- maximum error in 95% of measurements: 4.80 %

The relative error of 95 % of the measurements is less than 147.2 tonnes for mixtures with a mean density of 1330 kg/m³. For all probabilistic relative accuracy calculation the density of the mixtures of the trailing suction hopper dredgers is set as 1330 kg/m³ and therefore the errors expressed as a percentage of the total load may be used as basis of comparison.
SYSTEMATIC ERRORS OF DREDGER A, B AND C
Systematic errors of dredger A

- Error due to use of polynomial without trim.
The difference between the carène-matrix and the polynomial is established at an empty draft of 4.75 metres with a trim of 1.97 metres and a loaded draft of 7.85 metres with a trim of -0.69 metres.

Data used in measurement with polynomial:

- displacement of empty vessel (closed) = 7741 m³
- volume of water in empty hopper = 2092 m³
- density of surrounding water = 1020 kg/m³
- specific density of dredged material = 2600 kg/m³
- displacement of loaded vessel = 13605 m³
- volume of mixture in loaded hopper = 6100 m³

The displacement of the load of the hopper dredger may now be established as 13605-7741+2092 = 7956. With formula 11 the quantity of tonnes dry solids may now be established as 3115.3 tonnes.

Data used in measurement with the carène diagram:

- displacement of empty vessel (open) = 5698 m³
- density of surrounding water = 1020 kg/m³
- specific density of dredged material = 2600 kg/m³
- displacement of loaded vessel = 13713 m³
- volume of mixture in loaded hopper = 6100 m³

The displacement caused by the load of the dredger may now be established as 13713-5698 = 8015 m³. With formula 11 the quantity of tonnes dry solids may now be established as 3214.3 tonnes.

The use of a polynomial without trim causes a difference between the tonnes dry solids in the hopper and "measured tonnes dry solids" equal to 99.0 tonnes, meaning that 99.0/3214.3*100=3.08% is incorrectly taken into account.

- error due to measuring the weight in fresh water.

Near Hoek van Holland (km 1029) many samples have been taken in order to establish the density of the water [14]. At a depth of 9 metres (approximately the draft of the loaded vessel), the average density of the water at km 1029 is 1013 kg/m³, with a standard deviation of 3.6 kg/m³. In 95% of the measurements the density of the surrounding water is be over 1006 kg/m³. The error may now be established using the following data:

- trim empty and loaded = 0 degrees
- specific density of dredged material = 2600 kg/m³
- measured average pressure = 80 KPa
- earth gravity acceleration = 9.81 m/s²
- weight of empty vessel = 5812 tonnes
- volume of mixture in hopper = 6200 m³
If the density of the surrounding water is taken as 1006 kg/m³, the draft may be established as 8.11 metres using formula 24. By using the carène diagram the weight of the loaded hopper may be established as 14044 tonnes. With formula 11 the quantity of tonnes dry solids may be established as 3140.5 tonnes.

If the density of the surrounding water is taken as 1020 kg/m³, the draft may be established as 8.00 metres, the weight of the vessel as 14080 tonnes and the quantity of tonnes dry solids as 3199.8 tonnes. The difference in calculation results is 59.3 tonnes resulting in a quantity of approximately 59.3/3140.5*100=1.89%. In 95% of the measurements a quantity less than 1.89% is incorrectly taken into account.

- Dredger A uses four pressure sensors to establish the average draft of the vessel. All sensors are at a distance of 0.5 metres from the centre line and no influence of athwart inclination may therefore be expected.

- loss of material due to loading trim in the hopper.

The loss of material via the overflow due to the loading trim in the hopper is established with the aid of the adapted TDSS computer-program. The result is an average loss with a standard deviation. A figure can be made to show the relation between the quantity of mixture lost and the chance that the loss will be less than that quantity. The figure for dredger A is given below.
- error due to non-linearity of measurement instruments.

Draft with a matching output-signal of 2 volts is 0.012 metres.
Draft with a matching output-signal of 10 volts is 10.209 metres.
The span is 10.197 metres and the maximum deviation of linearity of the pressure sensors 0.5/100*10.197=0.05 metres.
The draft of the empty vessel is approximately 4.75 metres, with a resulting influence of non-linearity equal to 0.50% 0.05 metres. Using the carène diagram the error can be translated into an error of displacement of approximately 62.5 m³.
The draft of the loaded vessel is approximately 7.93 metres. The error due to non-linearity at this draft is also 0.50% of the span, resulting in an error of 0.05 metres.
Translating the draft to displacement results in an error of 70.25 m³.

The span of the acoustic meters is 12.0 metres. When the hopper is fully loaded the distance from the acoustic metres to the surface of the mixture is approximately 2.20 metres. The error due to non-linearity is taken as 0.50% resulting in a maximum error of 0.50 / 100 *12.0 = 0.06 metres = 29.9 m³. The overall result:

if the error in linearity of acoustic and pressure sensors deviates in the same direction, the error may be established as:

\[3100.39 - ((13713 + 70.25) * 1.013 - (5698 + 62.5) * 1.02) / (6080 - 29.9) - 1.02 / 1.58 * 2.6 * (6080 - 29.9) = 51.9 \text{ tonnes dry solids, resulting in an error of } 51.9 / 3100 * 100 = 1.67\%.

- Error due to bending.

With program BENDING.EXE, the position for taking exact measurement is established. The position is 22.40 metres from the perpendiculars, indicating a extra draft equal to 2/3 of the maximum bend.
The pressure sensors are not positioned optimally, which influences the calculation. With the distance from the pressure sensor to the perpendiculars and the formula, used to establish the bend, the difference in draft, as a percentage of the maximum bend, can be established as:

\[D_\alpha = \frac{-4 * f}{106^2} * (-35.2 + 0.5 * 106)^2 + f = 0.887 * f\]

\[D_\nu = \frac{-4 * f}{106^2} * (-25.46 + 0.5 * 106)^2 + f = 0.73 * f\]

The difference in the results of the mean draft calculations can now be established as:
\[ D_g = \frac{27.54}{45.34} \times 0.887f + \frac{17.8}{45.34} \times 0.73f = 0.8255f \]

from which the influence can be established as:

\[ \Delta \text{bend} = (0.8255 - 0.6666)f = 0.158f \text{ excess draft measured.} \]
Systematic errors of dredger B

- Error due to the use of polynomial without trim. The difference between the carène-matrix and the polynomial is established at an empty draft of 6.27 metres, with a trim of 1.79 metres and a loaded draft of 9.35 metres with a trim equal to zero.

Data used in measurement with polynomial:

- displacement of empty vessel (closed) = 12987 m³
- volume of water in empty hopper = 3170 m³
- density of surrounding water = 1020 kg/m³
- specific density of dredged material = 2600 kg/m³
- displacement of loaded vessel = 20659 m³
- volume of mixture in loaded hopper = 8276 m³

The displacement of the load of the hopper dredger may now be established as 20659-12987+3170= 10842. With formula 11 the quantity of tonnes dry solids may now be established as 4307.0 tonnes.

Data used in measurement with a carène diagram:

- displacement of empty vessel (open) = 9774 m³
- density of surrounding water = 1020 kg/m³
- specific density of dredged material = 2600 kg/m³
- displacement of loaded vessel = 20661 m³
- volume of mixture in loaded hopper = 8200 m³

The displacement caused by the load of the dredger may now be established as 20661-9774= 10793 m³. With formula 11 the quantity of tonnes dry solids may now be established as 4224.7 tonnes.

The use of a polynomial without trim causes a difference between tonnes dry solids and "measured tonnes dry solids" equal to 82.3 tonnes. Every dredging cycle a quantity of approximately 82.3/4224.7*100=1.95% is incorrectly taken into account.

- error due to measuring the weight in fresh water.

Near Hoek van Holland (km 1029) many samples have been taken in order to establish the density of the water [14]. At a depth of 9 metres (approximately the draft of the loaded vessel), the average density of the water at km 1029 is 1013 kg/m³, with a standard deviation of 3.6 kg/m³. In 95% of measurements the density of the surrounding water will be over 1006 kg/m³. The error may now be established by using the following data:

- trim empty and loaded = 0 degrees
- specific density of dredged material = 2.60 t/m³
- measured average pressure = 93 KPa
- earth gravity acceleration = 9.81 m/s²
weight of empty vessel = 9970 tonnes
volume of mixture in hopper = 8250 m³

If the density of the surrounding water is taken as 1.006 tonnes/m³, the draft may be established as 9.42 metres using formula 24. From the carène diagram the weight of the loaded hopper may be established as 20965 tonnes. With formula 11 the quantity of tonnes dry solids may be established as 4246.0 tonnes.

If the density of the surrounding water is taken as 1020 kg/m³, the draft may be established as 9.29 metres, the weight of the vessel as 20928 tonnes and the quantity of tonnes dry solids as 4185.7 tonnes.

The difference in calculation results is -60.3 tonnes resulting in a quantity of approximately 60.3/4246.0*100=1.42%. In 95% of the measurements a quantity less than 1.42% is not taken into account.

- Dredger B uses two pressure sensors which are both placed on the centre line of vessel. No influence due to athwart inclination may be expected.

- loss of material due to loading trim in the hopper.

The loss of material via the overflow due to the loading trim in the hopper is established with the aid of the adapted TDSS computer-program. The result is an average loss with a standard deviation. A figure can be made to show the relation between the quantity of mixture lost and the chance that the loss will be less than that quantity. The figure for dredger B is printed below.
- error due to non-linearity of measurement instruments.

Draft with a matching output-signal of 2 volts is 0.04 metres.
Draft with a matching output-signal of 10 volts is 12.04 metres.
The span is 12 metres and the maximum deviation in linearity of the pressure sensors 0.5/100*12=0.06 metres.

The draft of the empty vessel is approximately 6 metres, with a maximum error of 0.06 metres. By using the carène diagram the error can be translated into an error of displacement of approximately 104 m³.
The draft of the loaded vessel is approximately 9 metres. The error due to non-linearity at this draft is taken as 0.5% of the span, resulting in an error of 0.06 metres.
Translating the draft to displacement results in an error of 153.6 m³.

The span of the acoustic meters is 14.19 metres. When the hopper is fully loaded the distance from the acoustic meters to the surface of the mixture is approximately 1.15 metres. The error due to linearity is taken as 0.50% resulting in a maximum error of 0.50/100 *14.19 = 0.004 metres = 35.5 m³. The overall result:

If the error in linearity of acoustic and pressure sensors deviates in the same direction, the error may be established as:

$$4201.59 - ( ((20661 + 153.6) \times 1.013 - (9774 + 104) \times 1.02) / (8241 - 35.5) - 1.02) / 1.58 \times 2.6 \times (8241 - 35.5) = 142.7 \text{ tonnes dry solids resulting in an error of } 142.7/4201\times100 = 3.40\%.$$  

- Error due to bending.

With program BENDING.EXE the position for taking exact measurement is established. The position is 26.42 metres from the perpendiculars, indicating a extra draft equal to 2/3 of the maximum bend.
The pressure sensors are not positioned optimally which influences the calculation. With the distance from the pressure sensor to the perpendiculars and the formula used to establish the bend, the difference in draft, as a percentage of the maximum bend, can be established as:

$$D_s = \frac{-4 \times f}{125^2} \times (17.85 + 0.5 \times 125)^2 + f = 0.4896 \times f$$

$$D_v = \frac{-4 \times f}{125^2} \times (14.05 + 0.5 \times 125)^2 + f = 0.3991 \times f$$

The difference between the results of the mean draft calculations can now be established as:
\[ D_g = \frac{48.45}{93.10} \times 0.4866f + \frac{44.65}{93.10} \times 0.3991f = 0.4462f \]

from which the influence can be established as:

\[ \Delta \text{bend} = (0.6666 - 0.4462)f = 0.22f \] is excess draft measured.
Systematic errors of dredger C

- Error due to use of polynomial without trim. The difference between the carène-matrix and the polynomial is established at an empty draft of 6.53 metres with a trim of 1.20 metres and a loaded draft of 8.86 metres with a trim of 0.03 metres.

Data used in measurement with polynomial:

- displacement of empty vessel (closed) = 11435 m³
- volume of water in hopper empty = 3331 m³
- density of surrounding water = 1020 kg/m³
- specific density of dredged material = 2600 kg/m³
- displacement of loaded vessel = 16121 m³
- volume of mixture in loaded hopper = 6085 m³

The displacement of the load of the hopper dredger may now be established as 16121-11435+3331 = 8017. With formula 11 the quantity of tonnes dry solids may now be established as 3242.8 tonnes.

Data used in measurement with carène diagram:

- displacement of empty vessel (open) = 8172 m³
- density of surrounding water = 1020 kg/m³
- specific density of dredged material = 2600 kg/m³
- displacement of loaded vessel = 16116 m³
- volume of mixture in loaded hopper = 6085 m³

The displacement caused by the load of the dredger may now be established as 16116-8172 = 7944 m³. With formula 11 the quantity of tonnes dry solids may now be established as 3120.3 tonnes.

The use of a polynomial without trim causes a difference between tonnes dry solids and "measured tonnes dry solids" equal to 122.5 tonnes. Every dredge-cycle a quantity of approximately 122.5/3120.3*100=3.93% is incorrectly taken into account.

- error due to measuring the weight in fresh water.

Near Hoek van Holland (km 1029) many samples have been taken to establish the density of the water [14]. At a depth of 9 metres (approximately the draft of the loaded vessel), the average density of the water at km 1029 is 1013 kg/m³, with a standard deviation of 3.6 kg/m³. In 95% of measurements the density of the surrounding water will be over 1006 kg/m³. The error may now be established by using the following data:

- trim empty and loaded = 0 degrees
- specific density of dredged material = 2600 kg/m³
- measured average pressure = 88 kPa
- earth gravity acceleration = 9.81 m/s²
- weight of empty vessel = 8335 tonnes
- volume of mixture in hopper = 6000 m³
If the density of the surrounding water is taken as 1006 kg/m³, the draft may be established as 8.92 metres using formula 24. By using the carène diagram the weight of the loaded hopper may be established as 16318 tonnes. With formula 11 the quantity of tonnes dry solids can be established as 3066.0 tonnes.

If the density of the surrounding water is taken as 1020 kg/m³, the draft may be established as 8.79 metres, the weight of the vessel as 16293 tonnes and the quantity of tonnes dry solids as 3023.9 tonnes. The difference in calculation results is 42.1 tonnes resulting in a quantity of approximately 42.1/3023.9*100=1.39%. In 95% of the measurements the a quantity less than 1.39% will be incorrectly taken into account.

- Dredger C uses four pressure sensors to establish the average draft of the vessel. All sensors are at a distance of 0.5 metres from the centre line and influence of athwart inclination may thus not be expected.

- loss of material due to loading trim in the hopper.

The loss of material via the overflow due to the loading trim in the hopper is established with the aid of the adapted TDSS computer-program. The result is an average loss with a standard deviation. A figure can be made to show the relation between the quantity of mixture lost and the chance that the loss will be less than that quantity. The figure for dredger C is printed below.
It is remarkable that the losses are higher than those of the other dredgers mentioned. The reason may be the type and position of the overflow. Dredgers A and B have a circular tube in the centre line of the hopper. During rolling the level in the centre of the hopper is practically constant and no extra overflow losses occur. Dredger C has a overflow in the side of the hopper. During rolling material will float out via the overflow and for this reason there may be greater overflow losses.

- error due to non-linearity of measurement instruments.

Draft with a matching output-signal of 2 volts is 0.005 metres
Draft with a matching output-signal of 10 volts is 12.751 metres.
The span is 12.746 metres and the maximum deviation of linearity of the pressure sensors 0.5/100*12.746=0.064 metres.
The draft of the empty vessel is approximately 6.53 metres, with resulting influence of non-linearity equal to 0.5% = 0.064 metres. By using the carène diagram the error can be translated into an error of displacement of approximately 83.1 m³.
The draft of the loaded vessel is approximately 8.86 metres. The error due to non-linearity at this draft is taken as 0.50% of the span, resulting in an error of 0.064 metres.
Translating the draft to displacement results in an error of 129.5 m³.

The span of the acoustic meters is 10.50 metres. When the hopper is fully loaded the distance from the acoustic metres to the surface of the mixture is approximately 4.50 metres. The error due to non-linearity is taken as 0.50% resulting in a maximum error of 0.50/100 * 10.50 = 0.0525 metres = 31.9 m³. The overall result:

if the error in linearity of acoustic and pressure sensors deviates in the same direction, the error may be established as:

\[
3067.19 - (((16116+129.5)\times1.013-(8172+83.1)\times1.02)/(6006-31.9)-1.02) /1.58*2.6*(6006-31.9) = 130.0 \text{ tonnes dry solids resulting in an error of } 130.0/3067.2*100 = 4.24%).
\]

- Error due to bending

With program BENDING.EXE the position for exact measurement is established. The position is 25.32 metres from the perpendiculars, indicating a extra draft equal to 2/3 of the maximum bend.
The pressure sensors are not positioned optimally which influences the calculation. With the distance from the pressure sensor to the perpendiculars and the formula, used to establish the bend, the difference in draft, as a percentage of the maximum bend, can be established as:
\[ D_a = \frac{-4f}{119.8^2} \times (-33.87+0.5 \times 119.8)^2 + f = 0.8112f \]

\[ D_v = \frac{-4f}{119.8^2} \times (-27.30+0.5 \times 119.8)^2 + f = 0.7038f \]

The difference in the results of the mean draft calculations can now be established as:

\[ D_g = \frac{32.60}{58.63} \times 0.8112f + \frac{26.03}{58.63} \times 0.7038f = 0.7635f \]

from which the influence can be established as:

\[ \Delta \text{bend} = (0.7635-0.6666)f = 0.097f \] as excess draft measured.
DIFFERENCES BETWEEN POLYNOMIAL AND CARÈNE DIAGRAMS
difference between carene diagram and polynomial for dredger C with trim= -1

- displacement (m³) (Ouizendtalen)
- depth (m)

- carene diagram
- polynomial

difference between carene diagram and polynomial for dredger C with trim=-1

- difference of displacement (m³)
- depth (m)
difference between carene diagram and polynomial for dredge C with trim=0

depth (m)

3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

displacement (m³) (Buizendalien)

square: carene diagram + polynomial

difference between carene diagram and polynomial for dredge C with trim=0

difference of displacement (m³)

3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10

-25 -20 -15 -10 -5 0 5 10 15
difference between carene diagram and polynomial for dredger C with trim=1

- Square: carene diagram
- Plus: polynomial

difference between carene diagram and polynomial for dredger C with trim=1

- X: carene diagram
- Square: polynomial
difference between carene diagram and polynomial for dredger C with trim=2

depth (m)

- carene diagram

polynomial for dredger C with trim=2

difference of displacement (m3)

-20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160

2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8
difference between carene diagram and polynomial for dredger E with trim=0

- Displacement (m³) vs. Depth (m)
- Carene Diagram (□) and Polynomial (+)

difference between carene diagram and polynomial for dredger E with trim=0

- Difference of Displacement (m³) vs. Depth (m)
- Data points show variations around the polynomial line.
difference between carene diagram and polynomial for dredger E with trim=1

depth (m)

displacement (m$^3$) (Duitzendstollen)

- carene diagram
- polynomial

difference between carene diagram and polynomial for dredger E with trim=1

difference of displacement (m$^3$)

2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9
difference between carene diagram and polynomial for dredger E with trim=2

depth (m)

displacement (m³)

- carene diagram
- polynomial

difference between carene diagram and polynomial for dredger E with trim=2

difference of displacement (m³)

[Graphs showing data with depth on the x-axis and displacement or difference of displacement on the y-axis.]
NORTH SEA CLIMATE OBSERVATIONS
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SPECIFICATIONS OF MEASURING INSTRUMENTS
MILLTRONICS

NON-CONTACTING

ULTRASONIC TRANSUDCERS
Milltronics non-contacting ultrasonic technology provides industry with safe efficient process measurement. Our systems monitor levels from a few centimetres (inches) to 61 metres (200 feet), on materials ranging from corrosive liquids to dry bulk solids, and master bin conditions which include turbulence, dust, steam, bin obstructions, as well as general environmental noise.

The systems consist of two components, a rugged, high efficiency transducer and the electronic transceiver. In operation, a Milltronics transducer emits continuous sonic pulses and captures the echoes which are reflected from the target material. The microprocessor based transceiver converts the signals electronically into distance, level or even volume, and presents the data as digital or analog signals.

Milltronics transducers are designed specifically to provide high level signal returns without pre-amplification or in-field signal enhancement. This factor, combined with a unique echo processing capability is the foundation of our system reliability.

Milltronics echo processing assures precise analysis of the entire range of echoes, and highest accuracy in selection of the true echo. In our approach, a true image of all bin echoes, a digitized sonic profile, is stored and continuously updated in the system’s memory. This process employs patented, field-proven software techniques including the patented ALF process, curve shaping, statistical analysis, as well as digital filters to remove electrical interference and narrow echoes.

The advantage of this method is that it allows abrupt changes in bin echo patterns to be detected and analyzed instantly and accurately. As a result, the data displayed is continuously current and reliable.

Short to Medium Range ST Series Transducers

The ST series Ultrason transducers offer maximum operating efficiency for ranges to 30 metres (100 feet). These maintenance-free units can be faced with protective coatings for both wet, corrosive applications and dry, dusty applications with high attenuation. In these dry applications, the radiating surface is self-cleaning. For corrosive applications, use of the flanged unit for standpipe mounting exposes only the protected face to the environment.

Long service is assured. Today, applications twenty-five years old still operate with original transducers.

Features:
- maintenance-free operation
- temperatures as high as 150°C (300°F)
- submersible models
- faces and flanges for acids, corrosives and sanitary applications
- minimum ranges from as low as 300mm (12 in)
- approvals for hazardous areas
- totally enclosed, self-cleaning
- performance guarantee

High Temperature and Sanitary Flange Transducers

In response to the needs of industry, Milltronics has developed transducers with advanced technical features which allow wider application possibilities. The high temperature transducer ST25 HT in a SUPEC body with Teflon face, is designed to monitor processes with temperatures as high as to 150°C (300°F). The ST25 CST in a ferrule of 4 inches is designed for quick removal in sanitary applications where tank cleaning is important.
Construction of LR Transducers

Long Range LR Series Transducers
The patented LR series flexural mode transducers provide maximum acoustic coupling assuring efficient operation in ranges to 61 metres (200 ft) in the harshest applications across the range of industry. They perform with one standard face maximizing echo capture area on either bulk solids or liquids. In use, the vibrating action of the sonic pulse provides maintenance-free operation in applications characterized by dust, turbulence, steam and electrical interference. In addition to commonly providing for dry bulk level measurement of material such as coal, flour and grain in bins, silos and hoppers, the versatile LR transducers prove highly effective in rather unusual applications. These include positioning locomotives for loadout, monitoring tripper car position and controlling hopper fill, positioning ships in docking, and use on stacker/reclaimers as high limit switches to control the level stacking of material. They are used deep underground to monitor ore storage bins, used as anti-collision devices on heavy machinery, for monitoring sag on hydro lines, and for loop control of steel sheets in the steel fabrication industry.

Operating Advantages
1. High Efficiency: Comparison tests show the transmit/receive of the FM transducers to be 14 to 400 times higher than conventional units.
2. Narrow Beam Width: Typically 5.5° or better at −3db for maximum concentration of ultrasonic energy.
3. Sidelobes: Unwanted off-axis transmissions are suppressed by a very effective −19db.
4. Small Deadband: The more efficient coupling to the air path results in a shorter ring down period and therefore provides a shorter minimum range of .9 metres (3ft).
5. Maximum Range: Up to 61 metres (200 ft).
6. Impervious to Dust Buildup: Exclusive self-cleaning action provides reliable maintenance-free operation in dusty areas.
7. Effective operation in moist environments.

Principle of Operation
1. The diagram shows a cross section of a vibrating disc.
2. An expanded section of the disc shows adjacent antinodes. Note the out of phase motion which effectively cancels the sound wave and would result in a sonic pulse of little strength.
3. To produce an intense sonic pulse, we increase the radiation efficiency of the LR transducer by applying multiple layers of impedance-matching material to the disc face in a precisely determined pattern. Developed by, and patented solely to Millitronics, this technique results in the production of the most efficient sonic wave. This is the basis of the unmatchable superiority of the LR series in determining levels to 61 metres (200 ft).

Applications
1. Transducer oriented towards outlet.
2. Interpreting bin wall seems presents no problem.
1. Transducer too close to material inlet. Failing material will interact sound beam and cause erroneous readings or loss of echo.

Minimum Angle of Repose
1. On fluid like solids, aim transducer perpendicular to material surface.
On Dual Discharge Bins, aim each Transducer at the outlet point below and select average reading.
**ST Series Approvals:**

- **CSA**
  - Class I Gr. A, B, C, D
  - Class II Gr. F & G

- **FM**
  - For ST-25 and ST-50 Series
  - Class I, Div. 1, Gr. A, B, C, D
  - Class II, Div. 1 Gr. E, F, & G
  - For ST-100 series
  - Class II, Div. 1, Gr. E, F, & G

- **SAA**
  - Ex s IIB T6 Class I, Zone 0
  - DIP T6, IP65

- **BASEEFA**
  - EEx m II T5
  - Ex s II, Zone 0

- **CENELEC**
  - EEx m II T5
  - (T amb = 70°C)

- **3A**
  - Approved

**LR Series Approvals**

- **CSA**
  - Class I, Gr. D
  - Class II, Gr. E, F & G

- **FM**
  - Class I, Div. 1, Gr. A, B, C & D (outside tank)
  - Class I, Div. 1, Gr. D, Methane only (inside tank)
  - Class II, Div. 1, Gr. E, F, G

- **SAA**
  - Ex s, IIB, T6, Class I, Zone 0
  - DIP T6, IP65

- **BASEEFA**
  - EEx m II T5
  - Ex s II, Zone 0

- **CENELEC**
  - EEx m II T5
  - (T amb = 70°C)

---

**Specifications
STANDARD TRANSDUCERS**

<table>
<thead>
<tr>
<th>FACINGS</th>
<th>TEMPERATURE</th>
<th>APPLICATIONS</th>
</tr>
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<tbody>
<tr>
<td>ST25B/C</td>
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</table>

- # B denotes use in Canada, C international use
- * Denotes approvals pending on U series due to change in manufacture
- o Approvals pending

Condensed approval listing.
Consult agency approval guide for details.
Meridian Instruments

MultiRanger Plus: wanneer het om niveau gaat
Contactloos ultrasoon niveau meet- en regelsysteem
Ultrason niveaumeten

Voor het niveaumeten van vloeistoffen (water) en vaste stoffen staan ons veel meetprincipes ter beschikking. Hiervan onderscheidt zich het ultrasonse niveaumesysteem heel duidelijk, omdat het een contactloze meting is (de niveautransducer komt niet in aanraking met het medium).

De voordelen hiervan liggen voor de hand, nl. geen aangroei, geen gevaar voor electrochemische corrosie, schoonmaken niveautransducer overbodig; met andere woorden ONDERHOUDSVRIJ. Hierdoor heeft de ultrasonse niveameter een uitstekende lange termijn stabiliteit. Het meetprincipe is even simpel als zo'n voordelen: een uitgezonden geluidsgalmaal weerkaast tegen het te meten oppervlak, de tijdsduur dat de echo terugkeert is een maat voor de afstand. Steeds verbeterde elektronica-technieken (microprocessors) hebben de ultrasonse niveaumetingen binnen ons bereik gebracht.

Een en ander heeft bij de MultiRanger Plus als consequentie, ingenieusmechaniek, hoge nauwkeurigheid (<0,25%), kort blokafstand (<30 cm) en tot slot, onderdopenhoutzaag van de niveautransducer.

Bovendien is de ultrasonse niveautransducer geschikt voor het gebruik in een H2S gasomgeving.

Onderhoudsvrij en gunstig prijs/prestatieverhouding hebben bij de meer dan 35-jarige ervaring, model gestaan bij de ontwikkeling van de MultiRanger Plus.

Inmiddels is de MultiRanger Plus bij diverse departementen van het Ministerie van Verkeer en Waterstaat succesvol uitgetest.

MultiRanger Plus

Zonder enige twijfel is de MultiRanger Plus het meest geavanceerde ultrasonse niveaumeet- en regelsysteem, momenteel leverbaar.

De MultiRanger Plus meet tot een hoogte van 15 meter en is geschikt voor vaste stoffen en vloeistoffen.

Geavanceerde gepatenteerde software maakt de MultiRanger Plus ook toepasbaar voor reservoirs met roerwerken, rooilages met obstakels, maar ook niveaumeting in peilkokers en... verschijnheidsmeting, m.b.v. een 2e niveautransducer.

Door middel van de infrarode calibrator kan het gehele systeem via z.g. "stap voor stap" functies op een eenvoudige wijze worden geprogrammeerd.

Een toegangscode maakt bovendien het programmeren door onbevoegden, praktisch onmogelijk.

De infrarode calibrator is universeel en is geschikt voor meerdere MultiRanger Plus systemen (kostenbesparing).

De analoge meetwaarde van 0-20/4-20 mA, kan tijdens het meten, ter controle op het L.C.D. display worden weergegeven.

Door het grote L.C.D. display en de inbouwmogelijkheid van de MultiRanger Plus zijn separate afleesinstrumenten overbodig.

Bovendien kan direct en zonder schaalaanpassing iedere gewenste meetgroothoed op het display worden weergegeven in cm, m, % en... N.A.P. Eveneens geldt dit voor volumemetingen in m³, tonnen enz.

De MultiRanger Plus is voorzien van 5 potentiële lineaire relaiscontacten, die ieder onafhankelijk van elkaar kunnen worden geprogrammeerd op niveau, temperatuur, differentie, tijd/flow instelbare pulsen (t.b.v. monstername-apparatuur) en/of storingsalarm.

Bovendien zijn de relaisfuncties zodanig te programmeren, dat pompen opeenvolgend geschakeld kunnen worden, waardoor ongelijk bedrijfssure van de pompen onderling, wordt voorkomen.

Via de ingebouwde simulator kan vooraf een volledige systeemtest worden uitgevoerd van alle relaisfuncties en analoge uitgang.

Doordat een EEROM is toegepast, heeft nette onderbrekend brekend geen enkel invloed op de ingeregelde parameters en opgeslagen grootheden w.o. bedrijfssureregistratie per pomp, debiet enz.

Het gehele is ondergebracht in een slagvaste (lexan) kunststof behuizing en heeft een waterdichtheidsclassificatie volgens IP65. Door de universeel toepasbaarheid is de MultiRanger Plus geschikt voor praktisch alle waterhuishoudingstoppassingen.

Hierdoor kan het aantal reservoires tot een minimum beperkt blijven.

---

Polder/rioolgemaalregeling

- Geschikt voor 5 pompen
- Aan/uit hysteresis functies
- Bedrijfssureregistratie per pomp
- Flow totalisatie
- Meting L.O. N.A.P., m, cm of %
- Wissel- c.q. opeenvolgsfunctie van pompen

---

Krooshek

---

Differentiaalmeting sluizen

- Verschijnheidsmeting
- Verschijnheidsdetectie
- Hoogwateralarm
- Laagwateralarm

---

Open kana
Tijdens het meten heeft een aantal membraamtoetsen een z.g. dubbelfunctie.
Door een simpele druk op één van deze membraamtoetsen, verschijnt onmiddellijk de gevraagde informatie op het grote L.C.D.-display, zonder dat hierbij de meting wordt onderbroken.

- **H TOT** = Hoogste digits debietmeting
- **L TOT** = Laagste digits debietmeting
- **HEAD** = Opstuwhoogte flowmeting (h)
- **FLOW** = Momentele flowwaarde (Qh)
- **mA** = Analoge waarde (mA)
- **TEMP** = Temperatuur (°C)
- **RATE** = Snelheidverandering niveauhoogte (hoogte-eenheid/min)
- **CONF** = Echosignaalsterkte (dB)
- **HRS 1** = Bedrijfsurenregistratie pomp 1 t/m 5
- **READ** = Tegengepast functie naar meting
- **DIST** = "Vrije hoogte" meting t.o.v. meetoppervlak

### einiger
Verschijniveauametning en detectie
Hoog en laagwateralarm
Pompmeting - bedrijfsurenregistratie van verschijniveau en niveauametning
Temperatuur detectie (beveiliging krooshekreining bij vorst)

### Riolkelder of tankvolumemeting
- Volumameting 7 tankvormen (vb. kalksilometen in tonnen)
- Hoog/laag detectie
- Temperatuur detectie
- Geschikt voor zone 0 (explosieveilig)

### Waterstand/grondwaterpeilniveauametning
- Waterstandniveauametning
- Grondwaterpeilniveauametning
- Binnendiameter standpijp min. 30 mm
- Hoog/laag alarmdetectie
- Meting t.o.v. N.A.P., m, cm of %
Meridian Instruments is gespecialiseerd in de ontwikkeling en fabricage van hoogwaardige procesinstrumenten t.b.v. de chemische- en petrochemische industrie, waterhuishouding, voedingsindustrie enz. Kortom die tak van de industrie, die de allerhoogste eisen stelt met betrekking tot betrouwbaarheid en after sales service. Hierdoor bieden wij een 24-uurs service, die zowel op zon- als feestdagen bereikbaar is.

Het leveringsprogramma voor de waterhuishouding omvat:

* Capacitieve niveaumeting
* Drustransmitter niveaumeting
* Geleidsbaarheidsniveaumeting

* Open kanaalmeting
* Capacitieve doorstroommeting
* Monsternametapparatuur

Meridian Electronics Holland BV
Nieuw Mathenesserstraat 39-41
3029 AV Rotterdam
The Netherlands

Telefoon: 010 - 4739455
Telefax: 010 - 4264752
Telex: 26106

Foto's omslag: Landustie Sneek en Jansen Venneboer Wijhe.
Een contactloze, onderhoudsvrije vloestof-niveaumeting, zonder de problemen van traditionele niveaumeetapparatuur.

De naam Probe staat bij vele technologische ontwikkelingen vaak model als voorloper van een revolutionaire vooruitgang. De Probe is echter geen voorloper, maar is het meest innovatieve ultrasoneniveaumeetsysteem momenteel leverbaar. Microprocessors technieken, gecombineerd met geavanceerde software, geven de Probe een uitstekende prijs/prestatieverhouding.

De Probe is onderhoudsvrij, en wordt geadviseerd onder het motto:

**Installeer de Probe en vergeet hem.**

Kenmerkende eigenschappen

- Zeer concurrerend prijsniveau
- Contactloos niveau meten
- Geen mechanisch bewegende delen
- Onderhoudsvrij
- Eenvoudige montage
- Hoge reproduceerbaarheid en nauwkeurigheid
- Eenvoudige instelling
- Hoge chemische resistantie
- Niet afhankelijk van dichtheid, dieëtische constante en/of viscositeit

Genoemde kenmerkende eigenschappen maken de Probe bijzonder aantrekkelijk als beste alternatief voor andere meetprincipes, zoals druk, capacitive, geleidoordniveau metingen. Het transmettergedeelte van de Probe is uitgevoerd in Tetzel. Hierdoor wordt een zeer hoge chemische resistantie bereikt voor het niveau meten van de meeste agressieve vloestoffen.

Met slechts (2) waterdichte membraanschakelaars kan de Probe worden ingegeeld voor een meetbereik van 0,25 tot 5,0 m. Een grafische instructie, gecombineerd met een L.C.D. display, verschafft informatie over:

- Groen: normaal bedrijf!
- Geel: wordt gebruikt tijdens instelling, waarbij de beste montage/echoutechnieken worden weergegeven
- Rood: afwezigheid van een betrouwbare echo

Het meetbereik kan worden ingesteld van 4-20 of van 20-4 mA.

Toepassingsgebied

De Probe is geschikt voor praktisch alle niveau-applicaties in vloestoffen, sluiers en sludges. De unieke software van de Probe, maakt de Probe bovendien geschikt voor niveaumetingen waarin roerwerken zijn toegepast. Meer dan 100.000 contactloze niveaumetingen worden in de afgelopen 5 jaar, het resultaat van jarenlange ervaring (sinds 1954) van Micronics.

Innovatie! Eén meer de problemen van contactloze niveaumetingen
Montage
De Probe moet op een zodanige manier worden gemonteerd, dat de Probe rechtuit op het te reflecterende oppervlak is gericht. De minimaal afstand tussen de onderzijde van de Probe tot het maximale vloeistofoppervlak is 25 cm.

De Probe moet zodanig geplaatst worden, dat deze vrij is van obstakels tot het vloeistofoppervlak.

Bevestiging
Draad, 2 inch B.S.P.

Technische specificaties

<table>
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<tr>
<th>Specificatie</th>
<th>Details</th>
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<tr>
<td>Voedingsspanning</td>
<td>18 tot 30 Vdc (200 mA 24 Vdc)</td>
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<tr>
<td>Meetbereik</td>
<td>0,25 tot 5,0 m</td>
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<tr>
<td>Spredingshoek</td>
<td>10° (-3 dB)</td>
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<tr>
<td>Geheugen</td>
<td>EEPROM (batterijlaag)</td>
</tr>
<tr>
<td>Calibratie</td>
<td>2 stuk waterdichte membraanschakelaars</td>
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<tr>
<td>Toegestane omgevingstemperatuur</td>
<td>-20 tot 60 °C</td>
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<tr>
<td>- electronica</td>
<td>110 °C gedurende 30 min.</td>
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<tr>
<td>- transmitter</td>
<td>1,0 m/min.</td>
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<tr>
<td>Meet/Reactiesnelheid (demping)</td>
<td>3-voudig L.C.D. t.b.v. vrije hoogte uitlezing</td>
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<td>Uitlezing</td>
<td>- meervoudig multisegment t.b.v. bedrijfstatus</td>
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<td>Max. drukbestendigheid</td>
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<td>Uitgangssignaal - meetbereik</td>
<td>4-20 mA over niveaubereik of</td>
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<tr>
<td>- nauwkeurigheid</td>
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<td>- resolutie</td>
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<td>- belasting</td>
<td>≤ 3 mm</td>
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<td>- Relaisuitgang</td>
<td>750 ohm bij 24 Vdc</td>
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<td>- functie (storing detectie)</td>
<td>tijdens normaal bedrijf open</td>
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<td>- belasting</td>
<td>5 A, 220 Vac cos ϕ = 1</td>
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<tr>
<td>- Materiaal</td>
<td>PVC</td>
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<tr>
<td>- bedrading</td>
<td>Tefzel 210</td>
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<tr>
<td>- Kabelsoort</td>
<td>IP 65</td>
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<tr>
<td>- Processaansluiting</td>
<td>max. 2 stuk tot PG 16</td>
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<tr>
<td>- draadverbinding</td>
<td>2 inch B.S.P.</td>
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<tr>
<td>- flensverbinding</td>
<td>op aanvraag</td>
</tr>
<tr>
<td>- Gewicht</td>
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</tbody>
</table>
GENERAL PURPOSE PRESSURE TRANSMITTERS

Excellent linearity and hysteresis
±0.1 % - B.S.L. for all ranges

Encapsulated electronics

High overload and burst pressures

Good thermal stability
± 1" total error band –20° to +80° C

Baseefa approved as standard
The PTX 100 series of 4-20mA pressure transmitters has the combination of a small diffused silicon diaphragm together with a fully encapsulated advanced solid state integrated circuit, ensuring excellent reliability in adverse environments whilst retaining supreme accuracy and temperature stability. The operational ratings such as shock, vibration and overload are extremely high as is usual with microcircuit devices.

The transmitters will operate typically between 70mbar and 700 bar, being available as gauge, sealed gauge or absolute devices, and can be calibrated in many engineering units.

The series is available with many different media configurations ranging from compatibility with silicon, stainless steel and hastelloy. The stainless steel and hastelloy versions are manufactured by isolating the sensor from the pressure media by either a stainless steel or hastelloy diaphragm.

The entire range is certified as standard for use with barrier systems to EEX ia gas group IIC with a T4 rating at an ambient temperature of 80°C to BS5501 part 7 and Cenelec EN50 020.

These transmitters have integral zero and span controls which enables precise setting of the zero and full range outputs.

Many options available include depth, industrial and differential transmitters.

The type numbering system denotes the following details:

PTX 1XX/X

/W fitted with isolating diaphragm between the silicon diaphragm and pressure media

Backend construction & electrical connection

00 integral connector and free mating socket

07 integral vented cable and boot

15 detachable M20 x 1.5 conduit entry

*/0 100 transmitter series

*These are only available with ‘/W’ configuration.

Please refer to operating pressure ranges, overpressure, pressure media, temperature effects, electrical connection and installation drawings to fulfil your requirements.

STANDARD SPECIFICATION

Operating pressure ranges

PTX 100 Series

70mbar, 175mbar, 350mbar, 700mbar, 1, 1.5, 2, 3, 5, 7, 10, 15, 20, 35, 60, 70 and 135 bar gauge or sealed gauge.

Sealed gauge not available for ranges up to 10 bar.

PTX 100/W Series

350mbar, 700mbar, 1, 1.5, 2, 3, 5, 7, 10, 15, 20, 35, 60 and 70 bar gauge or absolute. 175mbar gauge only.

PTX 170/W & PTX 180/W Series

135, 200, 350, 500 and 700 bar sealed gauge or absolute.

Other pressure units can be specified, e.g. psi, kPa, etc.

Intermediate pressure ranges, depth and differential transmitters are available.

Overpressure

The rated pressure can be exceeded by the following multiples causing negligible calibration change:

PTX 100 Series

10x for 70 and 175mbar ranges

6x for 350mbar range

4x for 700mbar to 135 bar ranges.

PTX 100/W Series

10x for 175mbar range

6x for 350mbar range

4x for 700mbar to 15 bar ranges.

36 bar range and above maximum pressure 100 bar.

PTX 170/W & PTX 180/W Series

2x for all ranges

Burst pressure greater than 1380 bar.

Pressure media

PTX 100 Series

Fluids compatible with silicon and titanium.

PTX 100/W Series

Fluids compatible with 316 stainless steel.

115/W — N.A.C.E. specified materials.

110/W/Ti — Fluids compatible with titanium.

PTX 170/W & PTX 180/W Series

Fluids compatible with 316L stainless steel and hastelloy which are N.A.C.E. specified materials for hydrogen sulphide.

Conducting pressure media

When operating the PTX 100 Series with a conducting pressure media use a fully floating system or earth the +Ve supply.

If this method is not practicable please refer to manufacturer.

Transduction principle

Integrated silicon strain gauge bridge.

Transmitter supply voltage

9-30V d.c.

This voltage must appear across the transmitter terminals.

For other supply voltages please refer to manufacturer.

Supply sensitivity

0.005% F.S. /Volt and excellent 50Hz and 100Hz supply ripple rejection.

Output current

4mA at zero pressure

20mA at full range pressure.

Zero suppression can be incorporated such that 4mA output coincides with up to 20% of full range pressure.

Resolution

Infinite.

Combined non-linearity, hysteresis and repeatability

±0.1% F.S. for all ranges.

±0.06% B.S.I. available for ranges to 20 bar on request.

Please refer to manufacturer.

Zero offset and span setting

±5% F.S., sealed potentiometer adjustment.

Operating temperature range

–20°C ± 80°C standard.

This temperature range can be extended.

Temperature effects

PTX 100 Series

±0.5% total error band 10°C to 40°C for 70mbar range.

±0.5% total error band 0°C to 50°C for 175mbar ranges and above.

±1.5% total error band –20°C to +80°C for 175mbar ranges and above.

PTX 100/W Series

±0.5% total error band 10°C to 40°C for 175mbar range.

±0.5% total error band 0°C to 50°C for 350mbar ranges and above.

±1.5% total error band –20°C to +80°C for 350mbar ranges and above.

PTX 170/W & PTX 180/W Series

±1% total error band over –20°C to +80°C referred to +25°C calibration.

For special applications it is possible to give improved temperature compensation over a wider temperature range.
Acceleration sensitivity
0.044% F.S./g for 350mbar decreasing to
0.0003% F.S./g for 70 bar.

Mechanical shock
1000g 1ms half sine pulse in each of 3
mutually perpendicular axis will not affect
calibration.

Vibration
Response less than 0.05% F.S./g at 30g
peak 10Hz-2kHz, limited by 12mm double
amplitude (MIL-STD 810C Proc 514.2-2
Curve L).

Weight
400 gms. nominal.

Intrinsic safety
These transmitters are certified for use
with barrier systems to EEx ia gas group
IIIC with a T4 rating at an ambient
temperature of 80°C to BS5501 part 7 and
Cenelec EN50020.

Electrical connection
PTX 100, PTX 100/W & PTX 170/W
6 pin Bayonet fixed plug tested to
MIL-C-26482 or DEF 5325 Shell size 10
and mating socket Amphenol type
62GB-16F 10-55 supplied as standard.

PTX 110, PTX 110/W & PTX 180/W
1 metre integral vented cable supplied.
Longer lengths available on request.

PTX 115, PTX 115/W & PTX 185/W
Detachable M20 x 1.5 conduit entry to
Klippon MK8/2 terminal block (conductor
size 0.5 to 1.5mm).

Pressure connections
PTX 100 & PTX 100/W Series
G ¼" B 60° Internal cone
1 ¼" N.P.T. Flat end

G ½" B 60° Internal cone
¼" U.N.F. as MS 33656-4
M12 x 1.5 Ermeto
M14 x 1.5mm 6 DIN
Others available on request.

PTX 170/W & PTX 180/W
G ¼" B ¼" N.P.T. Flat end

PTX 115/W & PTX 185/W
¼"-14 N.P.T.

Options available
Differential transmitter PTX 120/WL
(see separate data sheet).
Depth transmitters PTX 110/D and
PTX 160/D (see separate data sheets).
Flush mounting transmitter PTX 110/F
(ref to manufacturer).
RFI protection — please refer to
manufacturer.

Ordering information
Please state the following:-
(1) Type number
(2) Pressure range
(3) Gauge, sealed gauge or absolute
(4) Temperature range
(5) Pressure connection
(6) Pressure media.

For non-standard requirements please
specify in detail.
Continuing development sometimes
necessitates specification changes without
notice.

TYPICAL INTRINSICALLY SAFE INSTALLATIONS. Full installation details available on request.
MODEL 1151DP ALPHALINE DIFFERENTIAL PRESSURE TRANSMITTER

Ranges from 0-5" H₂O to 0-750" H₂O
Compatible with any 2-wire system
Solid state, plug-in circuit boards
Compact, rugged, impervious to vibration
External span and zero adjustments
0.2% accuracy
On 4-20 mA output:
• Up to 600% elevation or
  500% suppression
• Adjustable damping

FEATURES

The Alphaline® Differential Pressure Transmitter* brings true precision to the measurement of flow, level, low gage pressure, vacuum, and specific gravity. Direct electronic sensing with the completely sealed δ-CELL™ capacitance sensing element allows significant improvement in differential pressure measurement. Because mechanical force transfer is eliminated, performance is dramatically improved and problems with shock and vibration are drastically reduced. Welded stress isolation clamping in the sensor housing prevents introduction of errors due to stresses and torques on the process flanges and minimizes effects of line pressure and overpressure to 2000 psi.

Installation, calibration, and commissioning are simplified by compact design, external span and zero adjustments, and explosion-proof, weather-proof construction with separate compartments for electronics and wiring connections. Volumetric displacement of less than 0.01 cubic inch prevents pumping of the process fluid and eliminates the need for condensate chambers and level pots. Tantalum, Hastelloy C-276 and Monel are available for corrosive service. Modular construction and plug-in printed circuit boards aid in trouble shooting and reduce parts stocking.

OPERATION

Process pressure is transmitted through isolating diaphragms and oil fill fluid to a sensing diaphragm in the center of the δ-CELL. The sensing diaphragm is a stretched spring element which deflects in response to differential pressure across it. The displacement of the sensing diaphragm a maximum motion of 0.004 inches, is proportional to the differential pressure. The position of the sensing diaphragm is detected by capacitor plates on both sides of the sensing diaphragm. The differential capacitance between the sensing diaphragm and the capacitor plates is converted electronically to a 2-wire, 4-20 mADC or 10-50 mADC signal.

*May be protected by one or more of the following U.S. Patent Nos. 3,618,390; 3,646,538; 3,752,885; 3,800,413; 3,975,719 and Re. 30,603.
MEXICO PATENTADO NO. 118,852. May Depend on Model. Other Foreign Patents Issued and Pending.
Functional Specifications

Service
Liquid, gas or vapor.

Ranges
0-5/30 inches H₂O
0-25/150 inches H₂O
0-125/750 inches H₂O

Outputs
4-20 mADC or 10-50 mADC

Power Supply
External power supply required.
4-20 mADC:
Transmitter operates on 12 to 45 VDC with no load.
10-50 mADC:
Transmitter operates on 30 to 85 VDC with no load.

Load Limitations
See Figure 1.

Indication
Optional meter with 1-3/4" scale. Indication accuracy is ±2%.

Hazardous Locations
Explosion proof: Approved by Factory Mutual (FM) for Class I, Division 1, Groups B, C and D; Class II, Division 1, Groups E, F and G; and Class III, Division 1. Certification by Canadian Standards Association (CSA) for Class I, Division 2, Groups A and B; Class I, Division 1, Groups C and D; Class II, Division 1, Groups E, F and G; Class III (Encl. IV).
Intrinsically safe: FM or CSA certification optional for Class I, Division 1, Groups A, B, C and D when used with approved barrier systems.
FM Explosion Proof tag standard. Appropriate tag will be substituted if optional certification selected.

Span and Zero
Continuously adjustable externally.

Zero Elevation and Suppression
Regardless of output specified, zero elevation and suppression must be such that neither the span nor the upper or lower range value exceed 100% of the upper range limit.
4-20 mADC Maximum zero elevation: 600% of calibrated span. Maximum zero suppression: 500% of calibrate span.
10-50 mADC Maximum zero elevation or suppression: 150% of calibrated span.

Temperature Limits
-20°F to +200°F Amplifier operating.
-40°F to +220°F Sensing element operating with Silicone fill.
+32°F to +180°F Sensing element operating with Fluorolube fill.
-60°F to +250°F Storage.

Static Pressure and Overpressure Limits
0 psia to 2000 psig on either side without damage to the transmitter. Operates within specifications between static line pressures of 1/2 psia and 2000 psig for silicone oil transmitters and between atmospheric and 2000 psig for Fluorolube transmitters. 10,000 psig proof pressure on the flanges.

Humidity Limits
0-100% RH.

Volumetric Displacement
Less than 0.01 cubic inches.

Damping
4-20 mADC: Time constant continuously adjustable between 0.2 and 1.67 seconds with silicone fill.
10-50 mADC: Time constant fixed at 0.2 second (0.4 second for range 3) with silicone fill.
Fluorolube fill: Higher time constant.

Turn-On Time
2 seconds. No warmup required.

---

FIGURE 1
LOAD LIMITATIONS

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| OPERATING REGION |

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| OPERATING REGION |

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Rosemount 3
Performance Specifications
(ZERO BASED SPANS, REFERENCE CONDITIONS, SILICONE OIL FILL, 316SS ISOLATING DIAPHRAGMS)

Accuracy
±0.2% of calibrated span. Includes combined effects of linearity, hysteresis and repeatability.

Linearity
±0.1% of calibrated span.

Hysteresis
0.05% of calibrated span (0.1% for range 5 or range 3 with Fluorolube).

Repeatability
0.05% of calibrated span (0.1% for range 3 with Fluorolube).

Dead Band
None

Stability
±0.2% of upper range limit for 6 months.

Temperature Effect
At Maximum Span (e.g. 0-150" H2O for 0-25/150" H2O range)
Zero Error: ±0.5% of span per 100°F. Total effect including span and zero errors: ±1.0% of span per 100°F.
Note: Double the specified effect for range 3.

At Minimum Span (e.g. 0-25" H2O for 0-25/150" H2O range)
Zero Error: ±3.0% of span per 100°F. Total effect including span and zero errors: ±3.0% of span per 100°F.
Note: Double the specified effect for range code 3.

Static Pressure Effect
Zero Error: ±0.25% of upper range limit for 2000 psi (±0.5% for range 3).
Span Error: For transmitters with silicone oil ±0.25% of reading per 1000 psi (1.5±0.25% for range 3). For transmitters with Fluorolube oil ±1±0.5% of reading per 1000 psi (1.5±0.5% for range 3). This is a systematic error which can be calibrated out for a particular pressure before installation.

Vibration Effect
±0.05% of upper range limit per g to 200 Hz in any axis.

Power Supply Effect
Less than 0.005% of output span per volt.

Load Effect
No load effect other than the change in power supplied to the transmitter.

Mounting Position Effect
Zero shift of up to 1" H2O which can be calibrated out. No span effect. No effect in plane of diaphragm.

Physical Specifications

Materials of Construction†
Isolating Diaphragms:
316SS, Hastelloy C-276, Monel or tantalum.

Drain/Vent Valves:
316SS, Hastelloy C, or Monel.

Process Flanges and Adapters:
Cadmium Plated Carbon Steel, 316SS, Hastelloy C or Monel.

Wetted O-Rings:
Viton.

Fill Fluid:
Silicone Oil or Fluorolube Oil.

Bolts:
Cadmium Plated Carbon Steel

Electronics Housing:
Low-copper aluminum (NEMA4)

Paint:
Epoxy-Polyester.

Process Connections
1/4-NPT on 2-1/8" centers on flanges. 1/2-NPT on 2", 2-1/8" or 2-1/4" centers with adapters.

Electrical Connections
1/2-inch conduit with screw terminals and integral test jacks compatible with miniature banana plugs (Pomona 2944, 3690 or equal).

Weight
12 pounds excluding options.

†Monel is a trademark of International Nickel Co.
Hastelloy is a trademark of the Cabot Corp.
Viton is a DuPont trademark.
Fluorolube is a trademark of the Hooker Chemical Co.
Terminology per SAMA Standard PMC20 1-1973

Rosemount 4
Typical Model 1151 Pressure Transmitter Assembly

Electrical Block Diagram

Wiring Connections

STANDARD ACCESSORIES All Models are shipped with flange adapters, vent/drain valves and one instruction manual per shipment.

TAGGING Alphaline Differential Pressure Transmitters will be tagged in accordance with customer requirements. All tags are stainless steel.

CALIBRATION Transmitters are factory calibrated to customer's specified range. If calibration is not specified, transmitters are calibrated at maximum range. Calibration is at ambient temperature and pressure.

Rosemount 5
### Ordering Information

**ALPHALINE DIFFERENTIAL PRESSURE TRANSMITTER**

#### CODE RANGES
- 3: 0-5 to 0-30 inches H₂O (0-127 to 0-762 mm H₂O)
- 4: 0-25 to 0-150 inches H₂O (0-635 to 0-3810 mm H₂O)
- 5: 0-125 to 0-750 inches H₂O (0-3175 to 0-19050 mm H₂O)

#### CODE OUTPUT
- E: 4-20 mA DC with adjustable damping
- B: 10-50 mA DC with fixed damping

#### MATERIALS OF CONSTRUCTION

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<th>CODE</th>
<th>FLANGES &amp; ADAPTERS</th>
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<th>ISOLATING DIAPHRAGMS</th>
<th>FILL FLUID</th>
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#### CODE OPTIONS (See Product Data Sheet 2360 for Additional Options)

- M1: Linear Meter, 0-100% Scale
- M2: Square Root Meter, 0-10 Scale
- B1: Mounting Bracket for Mounting to 2" Pipe
- B2: Mounting Bracket for Panel Mounting
- B3: Flat Mounting Bracket for Mounting to 2" Pipe
- D1: Side Vent/Drain, Top
- D2: Side Vent/Drain, Bottom
- E6: CSA Explosion Proof Certification for Class I, Division 2, Groups A and B; Class I, Division 1, Groups C and D; Class II, Division 1, Groups E, F, and G; Class III (Encl. IV).
- Other Options: Note: Insert the appropriate Option Codes to specify any of the additional Options described in Product Data Sheet 2360.

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**ADDITIONAL OPTIONS**

All Series 1151 Transmitter Options are described in Product Data Sheet 2360. These include optional materials, outputs, tests, etc. Any appropriate Option Code can be added to the basic 1151 Transmitter Model Number.

**ACCESSORY 3-VALVE MANIFOLD (Packaged Separately)**

Part No. 1151-150-1: 3-Valve Manifold, Carbon Steel

Part No. 1151-150-2: 3-Valve Manifold, 316SS

---

**Rosemount Inc.**

POST OFFICE BOX 35129 MINNEAPOLIS, MINNESOTA 55435

PHONE: (612) 941-5560 TWX: 910.576-3103 TELEX: 29-0183 CABLE: ROSEMOUNT

Revised 9/80
SYMmetrical Density Distribution
On the next page there is a table showing a symmetrical density distribution.
The following example illustrates the use of this table:

Assuming that 95% of all measurements fall within a specific limit (called a confidence interval) and that the standard deviation of the density distribution is known, this limit can be established.
95% means that 2.5% of the measurements have a value greater than the upper limit and 2.5% of the measurements have a value less than the lower limit.
In the table on the following page the value 0250 can be located and from this the appropriate value of 1.96 for the variable U can be subtracted.
Now the lower and upper limits found are:

lower limit = mean value - 1.96*standard deviation
upper limit = mean value + 1.96*standard deviation

When the maximum deviation from the mean value and a confidence interval are known it is also possible to use the table overleaf to estimate a standard deviation.
By using the confidence interval, a value for U can be read from the table. The standard deviation may now be estimated as

standard deviation = maximum deviation / U
TABEL VAN DE STANDAARD-NORMALE VERDELING

overschrijdingskansen:
waarden van $k \cdot 10^4$ voor $u = 0,00(0,01)3,49$

$$\int_{-\infty}^{u} \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx = k$$

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LIST OF SYMBOLS

$H$ = thickness of layer to be dredged [m]
$H_{in}$ = distance from reference level to the surface of the bottom, measured during in-survey [m]
$H_{out}$ = distance from reference level to the surface of the bottom, measured during out-survey [m]
$\sigma_{\Delta Hs}$ = standard deviation of the error in depth measurement, established during in- or out survey [m]
$\sigma_{\Delta Hin}$ = standard deviation of the error in depth measurement, established during in-survey [m]
$\sigma_{\Delta Hout}$ = standard deviation of the error in depth measurement, established during out-survey [m]
$\Delta H$ = error in measurement of thickness of layer, established during survey [m]
$A_D$ = surface of area to be dredged [m$^2$]
$\rho_{B}$ = average density of mixture in hopper [kg/m$^3$]
$\rho_{m}$ = mean density of pumped up mixture measured in time [kg/m$^3$]
$Q$ = flow in m$^3$/s of pumped mixture measured in time [kg/m$^3$]
$\rho_{W}$ = known density of in-situ water [kg/m$^3$]
$\text{Var}_{\rho W}$ = variation of known density of in-situ water [kg/m$^3$]
$\rho_{IS}$ = known density of in-situ material [kg/m$^3$]
$p$ = volume-percentage of in-situ material [-]
$100$
$d$ = the diameter of the pipe [m]
$V_m$ = mean velocity of the dredged mixture in the suction pipe [m/sec]
$\rho_{S}$ = specific density of dredged material [kg/m$^3$]
$\text{Var}_{\rho S}$ = variation of specific density of dredged material [kg/m$^3$]
$p_1$ = pressure difference between sensor 1 and floating sensor [N/m$^2$]
$p_2$ = pressure difference between sensor 2 and floating sensor [N/m$^2$]
$h$ = average height of the load [m]
$M$ = weight of the load [kg]
$V$ = volume of the load [m$^3$]
$\text{Var}_V$ = variation of volume of hopper-load [m$^3$]
$D_{Loaded}$ = draft of loaded ship [m]
$D_{Empty}$ = draft of empty ship [m]
$s$ = steepness of waves [-]
$L_o$ = wavelength applying on deep water [m]
$L_{1}$ = wavelength applying on shallow water [m]
$T_p$ = wave-peak period [sec]
$H_s$ = significant wave height [m]
$\alpha$ = angle between wave propagation direction and vessel propagation direction [°]
$T_1$ = wave period applying on shallow water [sec]
$g$ = earth gravity acceleration [m/s$^2$]
$\Delta p$ = maximum pressure difference during wave-passage [N/m$^2$]
$A_w$ = amplitude (half of wave height) [m]
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>z</td>
<td>distance from pressure-sensor to the water-surface [m]</td>
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<tr>
<td>(V_{b_{dapp}})</td>
<td>variation of draft at a.p.p. [m]</td>
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<tr>
<td>(V_{b_{dfpp}})</td>
<td>variation of draft at f.p.p. [m]</td>
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<tr>
<td>(V_{b_{dw}})</td>
<td>variation of draft due to wave influence [m]</td>
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<tr>
<td>(V_{b_{da}})</td>
<td>variation of aft draft measurement [m]</td>
</tr>
<tr>
<td>(V_{b_{df}})</td>
<td>variation of fore draft measurement [m]</td>
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<tr>
<td>(L_{av})</td>
<td>distance between pressure sensors [m]</td>
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<td>(L_{a})</td>
<td>distance from aft pressure sensor to a.p.p. [m]</td>
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<tr>
<td>(L_{f})</td>
<td>distance from fore pressure sensor to f.p.p [m]</td>
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<tr>
<td>(D_{av}_{vr})</td>
<td>average draft of a vessel [m]</td>
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<tr>
<td>(V_{b_{ eaten}})</td>
<td>variation of average draft of the vessel [m]</td>
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<tr>
<td>(Opp)</td>
<td>surface of hopper [m²]</td>
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<tr>
<td>(N_{a})</td>
<td>aft acoustic measurement [m]</td>
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<tr>
<td>(N_{f})</td>
<td>fore acoustic measurement [m]</td>
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<tr>
<td>(N_{bh})</td>
<td>acoustic level at back of hopper [m]</td>
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<td>(N_{fh})</td>
<td>acoustic level at front of hopper [m]</td>
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<tr>
<td>(B{L}_{av})</td>
<td>distance between acoustic sensors [m]</td>
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<tr>
<td>(B{L}_{a})</td>
<td>distance from b.h.w. to aft acoustic sensor [m]</td>
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<tr>
<td>(B{L}_{f})</td>
<td>distance from f.h.w. to fore acoustic sensor [m]</td>
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<td>b.h.w.</td>
<td>back of hopper</td>
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<tr>
<td>f.h.w.</td>
<td>front of hopper</td>
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<td>(A)</td>
<td>factor used to linearize the carène diagram [-]</td>
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<tr>
<td>(C)</td>
<td>factor used to linearize the carène diagram [-]</td>
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<tr>
<td>(B_{u})</td>
<td>mean value of symmetrical density distribution B used to linearize the carène diagram [m³]</td>
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<tr>
<td>(D_{u})</td>
<td>mean value of symmetrical density distribution D used to linearize the carène diagram [m³]</td>
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<tr>
<td>(B_{o})</td>
<td>standard deviation of symmetrical density distribution B, used to express the error in the carène matrix [m³]</td>
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<tr>
<td>(D_{o})</td>
<td>standard deviation of symmetrical density distribution D, used to express the error in the carène matrix [m³]</td>
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<td>(f)</td>
<td>maximum bend [m]</td>
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<td>(L_{e})</td>
<td>length between a.p.p. and f.p.p. [m]</td>
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<td>(y)</td>
<td>bending [m]</td>
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<td>(W)</td>
<td>displacement [m³]</td>
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<td>(A_{wres})</td>
<td>resulting wave-amplitude after averaging [m]</td>
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LIST OF REFERENCES
REFERENCES

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24. Korevaar C.G., North Sea Climate, based on observations from ships and lightvessels, Royal Dutch Meteorological Institute (KNMI), De Bilt, (1990).